PERFORMANCE PREDICTION MODEL FOR A HYBRID PVT SYSTEM

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Performance Prediction Model for

a Hybrid PVT System

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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ABSTRACT

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Photovoltaic cells convert, depending on the cell type, 6-18% of the incoming solar radiation into electricity with a higher percentage converted into heat. The heat in turn affects the cell temperature which has direct impact on its efficiency. In literature, both water and air have been used for PV cooling through a thermal unit attached to the back of the module yielding a photovoltaic-thermal (PVT) system. But the use of water requires more extensive modifications to prevent leakage and corrosion. Hence, an air channel operating on forced convection that would substantially improve the heat transfer aspects was chosen.

This study investigates the performance of a low-cost heat-extraction improvement in the channel of a PVT air system that achieves higher thermal output and PV cooling while keeping the electrical efficiency at acceptable level. This study presents the use of a "helical insert" along the air channel as heat transfer augmentation that improves the PVT system's overall performance. Based on energy balance of each component of PVT system, an analytical expression for the temperature of the PV module, back wall and the outlet air has been derived. The developed model was first validated with the experimental data obtained by researchers. By confirming a good agreement with the experimental data, simulations were carried out to optimize various operating parameters, like the channel hydraulics, air mass flow rate, twist angle of helical insert and number of inserts. Then the steady-state thermal efficiency of the modified system equipped with helical insert is compared with those of typical PVT air systems. The modification results in a substantial

increase in the overall thermal and electrical efficiencies to about 66.5% and 13.5%, respectively. Hence, these techniques would positively impact the applications of PV systems, more specifically Building Integrated Photovoltaics (BIPV).

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I am immensely grateful to my advisor - Dr. Sumathy Krishnan for her stimulated guidance, unwavering support and encouragement and above all her friendly attitude. Needless to say, the thesis would not be in the present form without her help, involvement and commitment towards the cause of renewable energy which is certainly inspirational. I would not have enjoyed this research program without her attention and direction, as well as the freedom I received from her.

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I take this opportunity to express deep sense of gratitude to my parents, who gave everything they could to make me what I am today. I also had the affection of my brothers and sisters all along. Their touching care and love provided me the necessary strength to withstand the pressures of my research program. Their contributions to this work, though invisible, are invaluable to me.

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NOMENCLATURE

A	= area (m^2)
A_i	= surface area of the insert (m^2)
b	= width (m)
C_p	= specific heat of air (J kg^{-1} C^{-1})
D_H	= hydraulic diameter (m)
f	= friction factor
$\bar{F}'$	= efficiency factor
$\bar{F}_R$	= heat removal factor for the PVT solar collectors
F_{PV_i}	= shape factor between PV cells and the insert
F_{PV_w}	= shape factor between PV cells and the back wall
F_{i_w}	= shape factor between insert and the back wall
G	= mass flow rate per unit area (kg s^{-1} m^2)
h_{r,PV_w}	= radiative coefficient between PV cells and the back wall (W m^{-2} $^oC^{-1}$)
h_{r,PV_i}	= radiative coefficient between PV cells and the insert (W m^{-2} $^oC^{-1}$)
h_{r,g_amb}	= radiative heat transfer between the glass panel and the ambient air (W m^{-2} $^oC^{-1}$)
h_{r,i_w}	= radiative coefficient between insert and the back wall (W m^{-2} $^oC^{-1}$)
h_c	= convective heat transfer coefficient in the air channel (W m^{-2} $^oC^{-1}$)
h_{p1}	= penalty factor
I	= solar irradiation on the PVT system (Wm^{-2})
K	= thermal conductivity (W m^{-1} $^oC^{-1}$)
$\dot{m}$	= air mass flow rate inside the air channel (kg s^{-1})
n	= total data points
P_m	= pumping power (watt)
Pr	= Prandtl number
Q_u	= heat gain (W m^{-2})
Re	= Reynolds number
T	= temperature (°C)
T_f	= average temperature of the air in the air channel (°C)

T_{in}	= inlet air temperature (°C)
T_{out}	= outlet air temperature (°C)
T_s	= reference temperature of PV cell (taken as 25°C)
U_b	= overall heat transfer coefficient from back wall to ambient through insulation (W m^{-2} °C^{-1})
U_e	= edge heat loss coefficient (W m^{-2} °C^{-1})
U_L	= overall heat loss coefficient (W m^{-2} °C^{-1})
U_t	= top heat loss coefficient (W m^{-2} °C^{-1})
U_T	= conductive heat transfer coefficient from solar cell to air through tedler (W m^{-2} °C^{-1})
U_{tT}	= an overall heat transfer coefficient through top from tedler to glass (W m^{-2} °C^{-1})
v	= wind velocity (m s^{-1})
X	= theoretical value
X_i	= theoretical value of ith term
Y	= twist ratio
Z	= experimental value
Z_i	= experimental value of ith term

Subscripts

amb	= ambient
el	= electrical
g	= glass panel
i	= insert
in	= insulation
PV	= PV cell
t	= thickness
th	= thermal
T	= tedler
w	= back wall

Greek letters

α	= absorptivity
β	= temperature coefficient of PV cell
ϵ	= emissivity
σ	= Stefan-Boltzmann constant (W m^{-2} K^{-4})
ρ	= density
τ	= transmissivity
η_s	= standard electrical efficiency of PV cell
δ_{PV_g}	= spacing between the PV cell and the glass panel (m)
θ	= angle of inclination
ϕ	= twist angle
ν	= kinematic viscosity of the air inside the air channel (m^2 s^{-1})
Δp	= pressure drop (N m^{-2})

CHAPTER 1. INTRODUCTION

1.1. General

"As the energy crisis escalates - and the price of gas and electricity with it –International Energy Agency (IEA) predicts an inevitable shift to solar energy that will transform everyday life as radically as did the last century's revolutions in Information and Communication technologies [1]". However, the key drawback is their relatively poor efficiency. Typically, the efficiencies of PV cells today range from 6 to 18% commercially. This is because , PV cells have the ability to use only a part of the incident radiation from the sun, depending on the band gap of the semi-conductor material used. The remaining part of the radiation is either reflected or increases the sensible heat of the PV surface.

In general, PV systems are produced with either mono or polycrystalline silicon cells. The efficiency of these PV panels degrades due to the increased temperature. This undesirable effect can be partially avoided by a heat recovery unit in which fluid is circulated to keep the electrical efficiency at a satisfactory level. A PV panel provided with a heat recovery unit is more commonly referred as photovoltaic thermal (PVT) system or hybrid PVT system.

In PVT system applications, the optimization of the electrical output is the main design priority; therefore it is essential to maintain the surface of PV panels at relatively low temperature to ensure high electrical efficiency. Current literature suggests that PV cooling with air and/or water heat extraction from PV modules contributes to improved electrical efficiency. Hybrid systems with air heat extraction are more extensively studied, not only because of their easier construction and operation, but also can provide an economical solution to building integrated PV units (BIPV). In the Netherlands, calculation done by ECN (Energy research Centre of the Netherlands) [2] showed that it was possible to reduce the collector area by 40% with the use of PVT collectors while generating the same amount of energy. Moreover, PVT modules share the aesthetic advantage of PV.

Several studies refer to theoretical and experimental results of air cooled hybrid PVT system, most reporting a maximum thermal efficiency of about 45% . Several possibilities for enhancing the thermal efficiency of both buoyancy-driven and forced air-flow exist, and the main research objective of this study is to explore the effectiveness of two new low cost techniques in the air channel for decreasing the PV module temperature and increasing system thermal performance. The proposed methods are: (i) to provide a metallic back-wall at the bottom of the air-channel duct to enhance the radiative heat transfer and (ii) to use selectively coated helical inserts in the air duct which can enhance convective heat transfer. It is expected that these proposed techniques will modify the duct hydraulics and it will result in increasing convection heat transfer coefficient. By this, it is possible to transfer more heat to the air stream in the duct. Therefore, these effects can ensure better PV cooling and heat production. Any method that could enhance the performance of the system even marginally would positively impact the economics of such systems.

A basic configuration of PVT system is shown in Fig. 1.1, which is a combination of photovoltaic panel integrated to a solar thermal collector, forming a single device that converts solar radiation into electricity and heat concurrently.

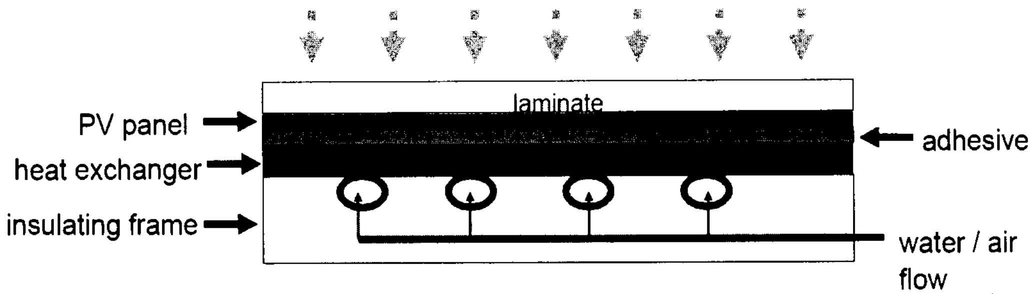


Figure 1.1. Cross sectional view of a basic PVT collector

1.2. System description

Figure 1.2 shows the schematic of the modified solar PVT system considered in this work. The PVT system consist of the following components: (i) PV panel; (ii) air channel duct integrated to the PV panel; (iii) metallic back-wall provided at the bottom end of the air channel; (iv) selectively coated helical insert provided inside the air channel duct along the air flow.

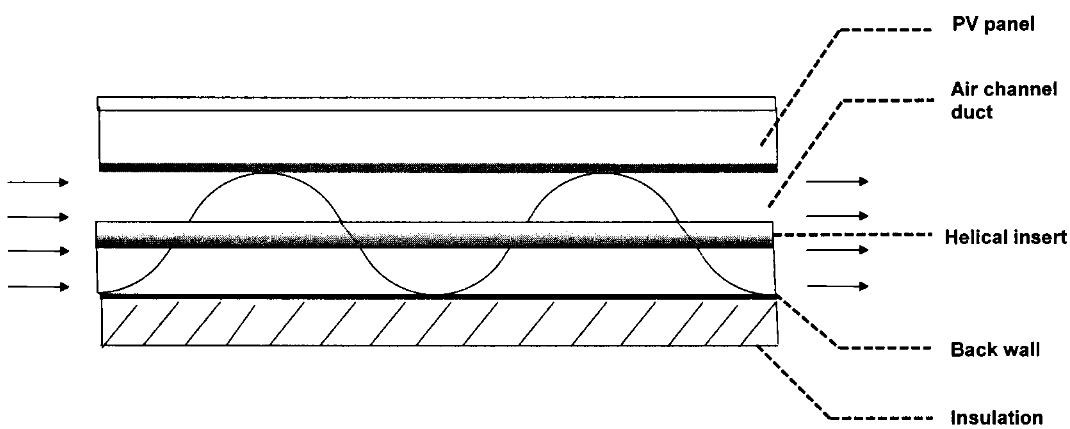


Figure 1.2. Cross sectional view of the modified PVT system

The incoming solar radiation is converted into electricity by PV panel and the waste heat from the PV panel is utilized by the collector to produce useful heat output. This heat can be utilized for several low temperature applications. The attractive features of the PVT system can be summarized as follows:

- it is dual-purpose: the system can cogenerate both electricity and thermal output;
- it is efficient and flexible: the combined efficiency is always higher compared to two independent systems;
- it has a wide application: the heat output can be used both for heating and cooling (desiccant cooling) applications depending on the season and practically is suitable for domestic applications;
- it is cheap and practical: can easily be retrofitted/integrated to a building without any major modifications.

1.3. Outline of thesis

In the current study, a detailed theoretical investigation has been performed to analyze the performance of the modified air cooled PV module, with helical insert as a mode to increase the heat transfer to the working fluid. Based on the energy balance of each component of PVT system, an analytical expression for the temperature of PV module, back wall and the outlet air has been derived. The developed model is validated with the experimental data obtained by Tiwari et al [3]. Further, simulations have been carried out to optimize various operating parameters that influence the performance of the PVT system, such as: channel depth, mass flow rate, twist angle of insert and number of inserts. The entire study is presented in 6 chapters:

* Chapter 2 presents literature review of the technologies related to the present research work and provides an in-depth understanding of numerous scopes of the photovoltaic thermal (PVT) system, recent trends of PVT technology, and various PVT

devices. Each review includes theoretical, numerical and experimental investigation of system performance and their applications.

* Chapter 3 describes a new PVT module design and the introduction of a new heat transfer promoter, "Helical Insert," in order to attain a higher system performance in terms of both electrical and thermal efficiencies.

* Chapter 4 covers the theoretical modeling of the modified PVT system based on air as the working fluid and the use of helical insert to extract enhanced heat from the PVT system.

* Chapter 5 presents the model validation and parametric study both for the reference and modified PVT system. Based on the optimum values of the various parameters, the year around performance of the modified PVT system is shown.

* Chapter 6 highlights the summary of this study and the merits of the proposed system. Suggestions for future research are also given.

CHAPTER 2. LITERATURE REVIEW

This chapter reviews the relevant research work and provides an in-depth understanding of the different technologies of the PVT system. The purpose of the review is to identify the key points in each technology that affect its performance in order to achieve the best possible integration between them.

2.1. Energy from the Sun

North Dakota has a higher number of sunshine hours annually. "Annually, North Dakota receives 58 to 62 percent of total possible sunshine hours [4]." On an annual basis, North Dakota registers 2,600-2,800 sunshine hours and averages 350 to 370 langleys (1 langley is 41840 J m^{-2}) of solar radiation per day. One interesting fact about Fargo is that, although the length of daylight between January and June varies significantly, the percentage of possible sunshine hours within any given month, especially January to June, remains uniform, around 55 % (Fig 2.1).

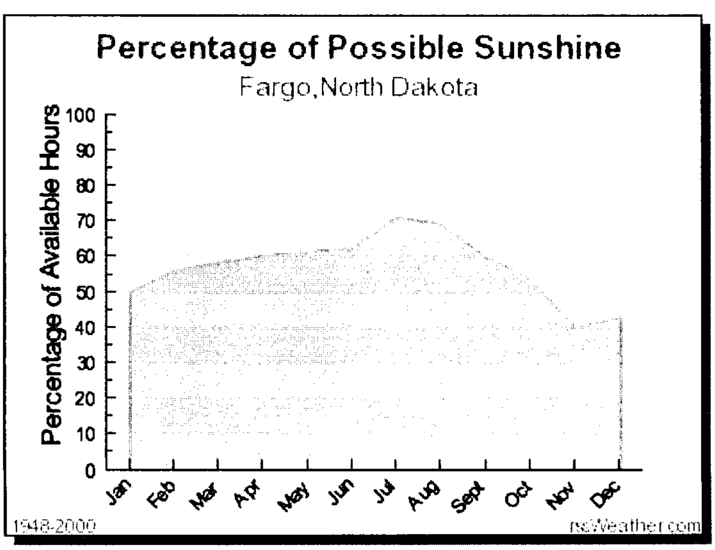


Figure 2.1. Solar radiation in Fargo [4]

2.2. Technologies for conversion of solar energy

Solar energy can be utilized in three main ways: solar thermal collectors, photovoltaic and photovoltaic-thermal cogeneration systems. Solar thermal collector is a type of heat exchanger which converts solar radiation to thermal energy. Other than being converted into heat, the solar energy can be directly converted into electrical energy by means of a photovoltaic effect. A single cell is termed as a "solar cell" or, more generally, a photovoltaic cell; and combinations of such cells are designed to increase the electric power output and is called a "Solar Module" or "Solar Array" (Fig. 2.2).

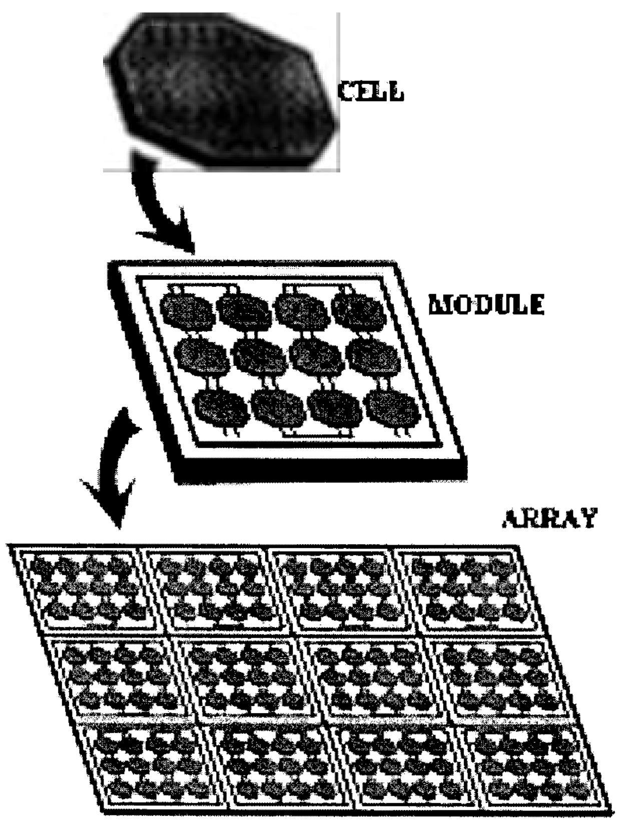


Figure 2.2. PV cells, modules and arrays

Photovoltaic cells are made of semiconductors that generate electricity when they absorb light. As photons are received, electricity is generated. Because solar cells are not heat engines, they do not require to operate at higher temperature. In general, these devices have a maximum theoretical efficiency in the order of 25%. Actual operating efficiencies are less than half this value, and decrease fairly rapidly with the rise in temperature.

Unlike solar thermal collectors or PV collectors, hybrid photovoltaic thermal (PVT) collectors can simultaneously convert solar energy into electricity and heat (Fig. 2.3).

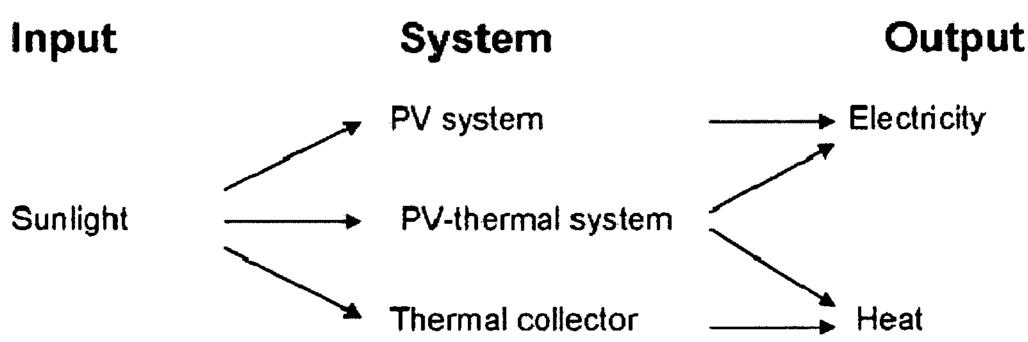


Figure 2.3. Comparison between PV, PVT and solar thermal systems

The concept of PVT system has been used and investigated by various researchers both experimentally and numerically. During 1970's, the research on PVT started, with an aim to increase the overall efficiency. Initially the focus was on glazed type air or liquid type collectors, however, soon the unglazed collector also received attention. A detailed description of PVT collectors with its various aspects, current status and future context, are presented in a recently published Roadmap [5].

2.3. PVT devices

PVT devices can vary in design for various applications, from PVT domestic systems to commercial buildings. The markets of solar thermal collectors and PV systems are growing rapidly and have reached a very substantial size. For PVT a similar growth can be expected, since the technical feasibility is proven and can be integrated with other domestic applications. PVT has a broad range of applications, that is, it is not only suitable for domestic hot water heating (glazed PVT collectors), but also for commercial buildings. Hence, the market for PVT might even be larger than the market for thermal collectors.

The thermal demand can be met by choosing appropriate PVT system. There exist various forms of PVT system which depend on the type of PV module as well as its design, and the type of heat removal fluid (water/glycol or air).

Therefore, the PVT products can be classified as:

- Liquid PVT collector
- Air PVT collector
- Ventilated PV with heat recovery.

Irrespective of the type of collector, the absorber of each PVT collector may have a glass cover over the absorber to reduce the thermal losses. If such a cover is present, the collector is referred to as "glazed", otherwise as "unglazed".

- Glazed collectors have smaller thermal losses, especially at higher collector fluid temperatures. For medium to high temperature applications, this results in a much higher annual thermal yield.

- Glazed collectors result in high stagnation temperatures that may be critical for certain types of PV encapsulant (risk of yellowing and delamination) and glazing makes the module more sensitive to hot spots. In addition, bypass diodes may get overheated due to the additional insulation. Reflection losses at the glazing further reduce the electrical performance of the module. Increased temperature levels lower the electrical yield.

In summary, while choosing a glazed collector, it is important to find a good balance between the increased thermal yield on one hand, and the reduction in electrical yield and the issues related to possible degradation on the other hand. The relationship is given in Table 2.1.

2.3.1. Liquid PVT collector

To improve the performance of the PVT system, much effort has gone into research using water as the coolant. The liquid PVT collectors are similar to conventional flat-plate liquid collectors. An absorber with a serpentine tube or a series of parallel risers is applied, on which PV has been laminated or glued as an adhesive epoxy joint.

Two common configurations used in PVT systems are: "The parallel plate configuration", and "The tube-in-plate configuration". Prakash [6], Huang et al. [7], Tiwari et al. [3, 8] have worked on the parallel plate design, while Zondag et al. [9], Chow [10, 11], Kalogirou [12], Huang et al. [6], Tiwari and Sodha [13] have carried out an in depth study on the tube-in-plate design. Among the first works on PVT water system, Bergene and Lovvik [14] initially carried out a theoretical study on PVT water system composed of flat plate collector with PV cells. They suggested their proposed PVT system might be useful particularly to preheat the domestic hot water.

Table 2.1. Recommendation of the collector type based on the type of demand

Demand		Recommendation
Water	High temperature	Use glazed liquid collector. Also, an unglazed collector can be used if PVT has to be integrated to a heat pump.
	Low temperature	To meet only summer demand, use unglazed liquid collector. On the other hand, to meet both summer and winter demands, use glazed liquid collector; an unglazed collector can be chosen if PVT has to be integrated to a heat pump.
Air	High temperature	Use glazed air collector or unglazed collector. Ventilated PV can be used as heat source if PVT has to be integrated to a heat pump.
	Low temperature	To meet only summer demand or for the place receiving high irradiation in winter, use unglazed air collector or ventilated PV. On the other hand, to meet both summer and winter demands, use glazed air collector; an unglazed collector can be a choice if PVT has to be integrated to a heat pump.

More recently, Zondag et al. [15] classified the concepts of water PVT collectors into four main types: "sheet and-tube collectors, channel collectors, free-flow collectors, and two-absorber collectors." All of these PVT collectors are designed for forced mode of operation. Based on analysis it was concluded that providing a channel below the transparent PV module could be the suitable option from the efficiency viewpoint [11].

However, in the case of good overall performance, the single glazing sheet and tube hybrid PVT collector is the most suitable design.

Dubey and Tiwari [16] designed an integrated PV (glass-to-glass) thermal (PVT) water PVT system and tested it under outdoor conditions of India. Similarly, Erdil et al. [17] constructed and tested a hybrid PVT system for energy collection at the geographical conditions of Cyprus, where they used water as the cooling fluid. It was reported that the payback period for their PVT system with the proposed modification was less than 2 years which made their hybrid system economically attractive.

Chow et al. [11] developed a numerical model of a PV-thermosyphon PVT system using water as a working fluid and verified the model accuracy by comparing with measured data. According to them the PV-thermosyphon PVT system is capable to extend photovoltaic applications in the domestic market.

Apart from the above study, Chow et al. [18] also carried out analytical simulation to investigate the performance of BIPV-water system for the geographical region of Hong Kong and found that the annual thermal and cell conversion efficiencies were about 37.5% and 9.39%, respectively. Based on the results, they confirmed that PVT systems could be applicable even to hot-humid regions.

Though the liquid collectors have proven to be technically feasible, economical feasibility is yet questionable. Compared to the air heating PVT system, not much of developments are seen in the literature, on the liquid-heating system due to its inherent limitations such as: additional cost of the thermal unit pipes for the water circulation, and the inherent freezing problem of working fluid when used in low temperature regions, etc.

2.3.2. *Air PVT collector*

The PVT air collectors are similar to a conventional air collector heater with a PV laminate functioning as the top cover or bottom layer of the air channel. PVT air collectors are cheaper than the PVT liquid collectors because of the flexibility that conventional PV modules can be easily converted to a PVT system, with very few modifications. PVT air collectors can either be glazed or unglazed. In general, air collectors are mostly applied if the end-users have a demand for hot air, space heat, dry agricultural products, or to condition the indoor air (air cooling).

Presently, air heating systems that directly use the air for space heating are mainly designed. However, the demand for this application depends directly on the market share of air heating systems, which is low in most countries. A niche market is given by preheating of ventilation air for large volume buildings (stores, sport halls, schools and other commercial buildings) where temperatures in the range of 15 to 25°C are desirable. With the very same air systems, hot water preparation is often possible through an air/water heat exchanger, which is generally done during the summer season in order to improve the overall performance of the system.

The application of air as a heat transport medium compared to water, has significant advantages along with a few inevitable disadvantages.

Advantages:

- No freezing and no boiling of the collector fluid.
- No damage if leakages occur.

Disadvantages:

- Low heat capacity and low heat conductivity, which result in a low heat transfer.

- Low density, which results in a high volume transfer.
- High heat losses through air leakage.

As the heat transfer in the air cooled PVT system is much more critical than in the liquid cooled PVT system, it is important to model the heat transfer properly. Eicker [19] presented an synopsis of entrance region effect heat transfer relation for air PVT system, reported that for a wide air-channel, the hydraulic diameter should be two times of the air-channel height.

The impact of air flow, induced by buoyancy (natural flow), on the PVT system performance was investigated numerically and experimentally by Moshfegh and Sanberg [20, 21]. The study reports that the induced air flow velocity increases the heat flux non-uniformly inside the channel duct and according to them its impact depends on the exit size and design. More analysis and modeling on passively cooled PVT air systems continue to appear [8, 13, 22-25] and a substantial amount of research has been specifically carried out [26-31] to improve heat transfer to the air of both buoyancy-driven and forced air flow systems. Their studies were focused generally on channel geometry, to create more turbulence in the channel and to increase the convective heat transfer surface area in the flow channel. Most of these studies used simulation model for their experimental work where the PV module was modeled as a heated foil.

Similar to the liquid collectors, various types of solar air systems exist and an overview has been given by Hastings and Morck [32]. The main air-cooled PVT system concepts were presented in the works of Kern and Russel [33], Hendrie [34], Florschuetz [35], Raghuraman [36], and Cox and Raghuraman [37]. The exclusive theoretical aspects of PVT systems with air as the heat extraction fluid are detailed by Bhargava et al [38], Prakash [5], and Sophian et al [39].

2.3.3. Ventilated PV with heat recovery

In conventional PV facades or PV roofs, an air gap is often present at the rear in order to allow the air to cool the PV by means of natural convection (ventilated PV). If this heat can be recovered from the PV and used in the building, then the same PV is considered to function as a PVT collector. Such PV facades, apart from providing electricity and heat, have additional benefits as well:

- A PV-facade may limit the thermal losses by infiltration. Also it shields the building from the solar irradiance, thereby reducing the cooling load. Hence, such facades are especially useful for retrofitting poorly insulated offices.
- If there is no demand for the generated heat, then air collectors and PV-facades can use their buoyancy induced pressure difference to assist the ventilation,
- Facade integration of PV has an additional cost incentive of substituting expensive facade cladding materials.

Because of the hybrid PVT systems easier construction and operation, this PVT system with air as a heat extraction medium is more extensively studied, commonly as an alternative and cost effective solution to building integrated PV systems (BIPV). Test results on PVT collectors with an improvement in air heat extraction were given by Ricaud and Roubeau [40] and from roof integrated air cooled PV panels by Yang et al. [41].

Posnansky et al. [42], Ossenbrink et al. [43] and Moshfegh et al. [44] have worked extensively on the building integrated PVT systems. Later, Brinkworth et al. [45-47], Moshfegh and Sandberg [20] and Krauter et al. [48] presented the performance and design studies of air BIPV systems. Also, Eicker et al. [49] gave results of a building integrated photovoltaic thermal system.

Yet another comprehensive examination of PV and PVT in building environments was presented by Bazilian et al. [50]. The study has highlighted that the PVT systems are well suited for low temperature applications. Furthermore, they noted that the integration of PV systems into the built environment could achieve ''a cohesive design, construction and energy solution". Finally, they suggested that there is a need for further research in the said field, before combined PVT systems become successful commercial reality.

The building integrated PV is going to be a sector of a wider PV panel application and the works of Hegazy [51], Lee et al.[52], Chow et al. [53] as well as Ito and Miura [54] has given interesting modeling results on air cooled PV modules. Recent work on BIPV air PVT system includes the study on the multi-operational ventilated PV's [55], the ventilated building PV facades [56 - 58] and the design of cooling air channel to reduce the efficiency loss [25].

According to Elazari [59], smaller size PV and PVT systems, using aperture area of approximately 3-5 m^2 and water storage tank of 150-200 litres, could be installed on single family houses. They have suggested that, larger size systems of about 30-50 m^2 and 1500-2000 litres of water storage are more suitable for multi story residential buildings, hospitals and various food processing industries.

Charalambous et al. [60] suggested that the building integrated PVT collectors are most suited for cold conditions to lower the temperature of the PVs and supply the hot air for space heating. Battisti and Corrado [61] investigated the EPBT (energy payback period) for a conventional multi crystalline BIPV system for the yearly total insolation as

1530 kWh/m^2.year in Rome. The study reports that the EPBT gets reduced from 3.3 years to 2.8 years by integrating the PV to the building.

A difference between ventilated PV with heat recovery and PVT collectors is that the PVT system is typically designed for a specific building and is not manufactured as a standardized system. Due to the current strong link between this type of PVT and specific building projects, it is very difficult for a non-specialist architect to provide this option for a specific project. However, this situation may change since several institutes and manufacturers are making an effort to standardize these systems [62].

2.4. PV module types

The performance of the PVT system depends on the PV module types as well. PV module can be constructed with crystalline silicon (c-Si), poly crystalline silicon (pc-Si) and the newly developed thin films of amorphous silicon (a-Si) types of cells. Crystalline silicon has by far the largest market share of all PV technologies. Although c-Si cells are highly efficient, they are expensive because of the slow manufacturing processes, laborious and energy intensive. A number of approaches to reduce the cost of c-Si cells and modules have been under development during the last 20 years or so. The newly developed thin film a-Si cells, have a significant market share since they are much cheaper to produce and are cost effective for low temperature applications.

2.5. PVT applications

The photovoltaic integrated thermal systems can be widely used for various applications. Large scale applications include power generation, where the PVT system can either be mounted on the rooftops of houses or in large fields connected to the utility grid. These systems are not only promising but also provide clean, safe and strategically sound alternatives to current methods of electricity generation. Grid connected PV energy offers consumers economic as well as environmental benefits. Consumers can use a grid connected PV panel to supply a portion of the energy they need while using utility generated power at night and cloudy days. The heat extracted can be utilized to meet the heating needs of the domestic and commercial buildings.

A vast majority of autonomous or stand alone PVT systems are used to supply electricity in regions with no electricity, no telephone coverage, and often with difficult accessibility. There are no moving parts, so the system's lifetime is very long and it is virtually maintenance free. It is more popularly used for rural electrification.

2.6. Performance analysis

A PVT collector basically combines the functions of a flat-plate solar (thermal) collector and those of a photovoltaic panel.

2.6.1. Modeling and simulation

Analytical expressions have been derived in terms of design and climactic factors to predict the instantaneous thermal efficiency of the PVT system. Within the earlier works on the theoretical analysis of the PVT system, Florschuetz [35] did an extension of Hottel-Whillier equation to model PVT collectors by adopting simple modifications to the conventional parameters used in the original model and all other existing relations in predicting the collector performance were unaltered. He developed a simple linear relationship to predict the effect of cell operating temperature on the PVT system efficiency. Raghuraman [36] also carried elaborate numerical model both for liquid and air type PVT flat-plate collector and found that the system with air as the working fluid could achieve a thermal efficiency of about 42%.

Jones and Underwood [63] also derived an expression for PV module temperature in terms of irradiance and ambient temperature. The transient model derived in their study was based upon the theoretical description of module temperature described by Schott [64]. According to Jones and Underwood, there were several parameters that were responsible for the PV module electrical efficiency reduction such as packing factor (PF), ohmic losses between two consecutive solar cells and the temperature of the module. Among the above mentioned factors, increasing the packing factor could improve the efficiency considerably by removing the thermal energy.

To predict the temperatures of the PV panel and the working fluid during fluctuating irradiance or intermittent flow under transient conditions, Chow [10] developed an model based on the "control-volume finite-difference" approach for a glazed water heating PVT system. He used a thin adhesive layer made of an EVA layer and Tedlar layer to fix the PV plate on to the absorber plate. He found "two key manufacturing defects in PVT collectors: (i) the imperfect adhesion between the PV plate and the absorber plate, and (ii) the imperfect bonding between the absorber plate and the metallic tubes." He has reported the maximum combined efficiency of a perfect collector could be over 70% and might decrease to less than 60% for a low-quality collector.

Yet another physical model was developed by Bergene and Lovvik [65] to make quantitative performance predictions of a hybrid PVT system. Their model was purely based on analyzing different modes of heat transfer such as conduction, convection and radiation encountered in the energy transfer process. This model could predict the amount of heat as well as the theoretical power output. Their proposed model predicted the performance of the system well with thermal and electrical efficiencies, between 60% to 80%.

Sopian et al. [39] also developed a steady state model to analyze the thermal performance of single-pass and double-pass PVT air systems. The study shows that the "double-pass" PVT air system had better efficiencies (both the thermal and combined) compared to the "single-pass" (typical) system due to the efficient cooling of the PV cells.

An extensive investigation of the thermal, electrical, hydraulic and overall performances of flat-plate PVT air collectors was carried out by Hegazy [51]. In his analysis, he considered four designs: air flowing on top or under the absorber, or on both sides. Based on the performance results, he suggested that the design in which air was allowed to pass on both sides of the absorber, was the most suitable design for converting solar energy into low quality heat and high quality electrical energy. Also such a system was simple to be built by local craftsmen in the rural areas of developing countries.

Recently, following the work of Hegazy [51], Othman et al. [66] designed and fabricated a prototype double-pass photovoltaic thermal solar air collector with CPC with fins in 2005. The system was tested for its performance over a wide range of operating conditions, and it was reported that the electricity production decreased with increasing temperature of the air flow, implying that the air temperature should be kept as low as possible. However, if hot air is required for some end-uses, a trade-off between maximizing electricity production and producing hot air of useful temperature is necessary.

Sandnes and Rekstad [67] developed an analytical model for the PVT collector which could simulate the temperature distribution and the performances of both thermal and PV units. The simulation results showed that by pasting PV cells on the absorbing surface, the solar energy absorbed by the panel could be significantly reduced (10% of incident energy).

Tiwari et al. [8] derived an analytical expression for the overall efficiency (electrical and thermal) in order to evaluate the performance of the PV module integrated with air duct for the composite climate of India. They found a fair agreement between their experimental and theoretical results for back surface, outlet air and top surface temperatures with correlation coefficient of about 0.97 - 0.99 and root mean square percent deviation of about 7.54 - 13.89%. The overall efficiency of the hybrid PVT system was to be increased by about 18% due to thermal energy output in addition to the electrical energy production.

Apart from the above mentioned work, Joshi and Tiwari [68] also studied the performance of a hybrid PVT parallel plate air collector for four different climatic conditions and carried out exergy analysis for the cold climatic condition of India (Srinagar). They observed the instantaneous energy and exergy efficiency of PVT air heater varied between 55 - 65 % and 12 - 15%, respectively which were very close to the results predicted by Bosanac et al. [69]. They found an increase of about 2 - 3% exergy due to thermal energy output in addition to its 12% electrical output from PVT system.

The impact of climatic conditions on the PVT system was further investigated by Dubey and Tiwari [16]. They designed and tested an integrated system of a photovoltaic (glass-to-glass) thermal (PVT) solar water heater under outdoor conditions for three typical days during the month of February to April, 2007. They also derived an analytical expression to characterize the performance of PVT flat-plate collector as a function of design and climatic parameters. The developed thermal model was validated with their experimental results and reported that when flat-plate collector is covered partially with PV module it resulted in better thermal and average cell efficiency. The modified system could attain an increase in the instantaneous efficiency by about 33% to 64% mainly due to the increase in glazing area.

The above mentioned theoretical model was used to evaluate the performance of the modified PVT system under four distinct climatic conditions of New Delhi, India. The analytical model could predict the monthly average electrical efficiency by considering different weather conditions of New Delhi for glass-to-glass type PV module with and without duct and was found to be 10.41% and 9.75%, respectively [70]. The glass-to-glass type PV module with duct gave a higher efficiency than the glass-to-tedlar type. This is because the radiation falling on non-packing area of glass-to-glass module is transmitted to the air flow in the duct, whereas in case of glass-to-tedlar entire radiation is absorbed by the tedlar. The reported results are in agreement with the other researchers' investigations [10, 15].

As an extension of the above mentioned study, Dubey and Tiwari [71] evaluated the theoretical performance of partially covered flat-plate water collectors connected in series. The performance was simulated for five different locations (New Delhi, Bangalore, Mumbai, Srinagar, and Jodhpur) in India reflecting different seasons. The study reported that collectors partially covered by PV module were beneficial in terms of annualized uniform cost if the primary requirement of user is thermal energy yield. On the other hand, if the primary requirement of user is electrical energy yield then fully covered collectors are beneficial. The results also showed that the outlet water temperature increased considerably from 60 to 86°C as the number of collectors connected in series increased from four to ten. The useful thermal energy yield was about 4.17 to 8.66 kWh and the electrical energy yield increased from 0.052 to 0.123 kWh depending on the number of collectors. This type of configuration is very useful in the urban and rural areas, where the hot water and electricity are required simultaneously along with some carbon credits. The study predicted that, if the proposed type was installed even only in 10% of the total residential buildings in Delhi, the total carbon credit earned by PVT water heater in terms of thermal energy was USD $144.5 million per annum and in terms of exergy was about USD $14.3 million per annum.

An attempt was made by Joshi et al. [72] to analyze the performance characteristics of a PV and PVT system based on energy and exergy efficiencies. First the "fill factor" was determined experimentally to evaluate the effect of the fill factor on the efficiencies. The energy and exergy efficiencies of the PV and PVT systems were evaluated for a typical day (27th March) in New Delhi and was found that the energy efficiency varied from a minimum of 33% to a maximum of 45% respectively. The corresponding exergy efficiency for PVT system was found to be 11.3% to 16%, while for PV it varied from a minimum of 7.8% to a maximum of 13.8%.

Apart from evaluating the PVT system performance in terms of thermal and electrical efficiencies, several researchers have carried out simulation studies to identify and analyze various performance parameters.

Garg and Adhikari [73] made a numerical model for PVT air system to analyze the effect operational and design parameters on the PVT system performance. Parametric studies show that the increase in mass flow rate, collector length and cell density has a positive impact on efficiency and increase in duct depth have a negative impact.

A novel heat pump system was proposed by Jie et al. [74] in which the PVT collector was coupled to a solar assisted heat pump and worked as an evaporator. They developed mathematical model to analyze the complex energy conversion processes and performed a numerical simulation based on the distributed parameters approach. The Simulation results were validated with experimental data. Results indicated that the photovoltaic solar assisted heat pump (PV-SAHP) as a combined unit could yield better coefficient of performance (COP) and photovoltaic efficiency than being treated as separate units. The system COP of the PV-SAHP could attain a maximum value of about 8.4 while the average value was around 6.5 along with an average photovoltaic efficiency of about 13.4%.

Extensive work on PVT systems have been initiated and carried out at the University of Patras in Greece by Kalogirou and Tripanagnostopoulos [75]. They had constructed and tested hybrid PVT systems consisting of pc-Si and a-Si PV modules with water heat extraction, which were modeled and simulated with the TRNSYS program. Simulation study was carried out for three geographical locations of different latitudes, Nicosia (35°), Athens (38°) and Madison (43°). The results showed that the electrical output of the system with pc-Si cells was more compared to the one with a-Si cells, but the thermal output was slightly lower.

Cox and Raghuraman [37] explored two main areas: (i) increasing the solar absorptance and (ii) reducing the infrared emittance of PVT collectors with the use of computer simulation to explore the effectiveness and interaction on overall system performance. The work focused on the air-type collectors employing single crystal silicon PV cells. Simulation results showed that when the total collector area is covered by about

65% with PV cells providing a selective absorber and gridded-back cell, the thermal efficiency actually reduced.

2.6.2. Experimental work

Various PVT prototypes were designed and tested by several researchers, with the objective of developing an efficient system which could yield a higher electrical efficiency, and a satisfactory thermal output. He et al. [76] constructed and tested a water type PVT system with a polycrystalline PV module on an aluminum-alloy flat-box absorber which functioned as a thermosyphon system. The results showed that if the initial temperature of the working water was the same as the daily mean ambient temperature, then the maximum thermal efficiency could reach 40%, which is about 1.8 times that of a conventional solar thermosyphon collector system. This product design is simple and has a high potential for serving the domestic market.

Robles-Ocampo et al. [77] constructed and studied an experimental model of a PVT hybrid system with bifacial PV module to enhance the electric energy production. Further, making use of both active surfaces of the bifacial PV module, they designed and fabricated an original water-heating planar collector with a set of reflecting planes. The hybrid system implemented with a bifacial module produced a higher amount of electrical energy than a conventional PVT system and the estimated overall solar energy utilization efficiency for the system was in the order of 60%, for which the electrical efficiency turned out to be 16.4%.

Towards low cost improvements of building integrated air cooled hybrid PVT systems, Tripanagnostopoulos et al. [78] tested experimental models consisting of three different modifications in the air channel. That is, the modified system was designed and tested for the following modifications: "(i) varying the air channel depth, (ii) inserting fins/tubes in the air channel; (iii) suspending a selectively coated flat-plate in the air channel." The results of the modified system were compared with those of the reference system. The modified system consisted of an air channel with 15 cm depth. The comparative study was carried out both for vertical and inclined positions, corresponding to building facade and inclined roof PV integration modes. Based on the results, they suggested a simple and efficient heat extraction mode. That is, providing a roughened opposite channel surface with a metallic sheet inside channel could serve as a low cost system improvement.

In addition to the above studies, Tripanagnostopoulos et al. [79] further designed and fabricated a PVT system with dual heat extraction function, which could use water as well as air as the cooling fluid. The proposed PVT system was meant to be used either for water or air heating. Their experimental model consisted of a pc-Si PV module which had been integrated to an air channel, in which the heat exchanger element was carefully designed for flexibility in boosting inside the air channel.

A practical and efficient system particularly suitable for PV installations on buildings was investigated by Tripanagnostopoulos et al. [80]. Two types of PVT prototypes, one with a commercial pc-Si PV module, termed as "reference system", and the second with a newly fabricated pc-Si PV module with transparent tedlar on the front and normal glass on the back of PV surface, termed as "modified system" were investigated. Their results showed that their suggested modifications could satisfactorily cool the PV module and improve the PVT system's energy performance.

Further, the possibility of generating electrical power and heat from a commercially available PV panel, was discussed by Tonui and Tripanagnostopoulos [30]. They constructed two identical prototype models using commercial pc-Si PV panels having a rated power output of 46 W_p, as absorber-plates and an air-channel of depth 15 cm attached at the rear surface of each module. The systems were mounted at a tilt angle of 40^o (approximate optimum tilt angle for Greece). In order to augment the heat transfer, certain modifications such as suspending a thin flat metallic sheet (TMS) in the middle of the air channel or providing fins at the back wall of an air duct were tested for their impact on thermal output. The suggested modifications lowered the back wall temperature considerably when compared with the usual PVT system without any modification. The pumping powers required were also less and were in agreement with the results of Choudhury and Garg [81]. The additional power required by the modified systems was about 0.54mW and 0.51 mW for thin metal sheet and FIN systems, respectively. The power generated by the photovoltaic modules was about 35W. Hence, the additional required power (less than 1%) is less enough that it does not degrade its electrical output power appreciably.

In order to evaluate the overall performance of hybrid PVT air collector under forced mode of operation, Tiwari and Sodha [82] carried out experiments for four different configurations such as, unglazed and glazed PVT air heaters, with and without tedlar. The results showed that for glazed PVT system irrespective of the provision of tedlar, the temperature of the outlet air, back surface of module as well as solar cell was significantly higher than the unglazed system, which was due to a reduction in the top loss coefficient. They also noted that the solar cell temperature for the single module is significantly higher compared to that of the two-module system due to an increase in the inlet temperature of the second module. However, the outlet air temperature increased only marginally.

A hybrid PVT system of a PV module with thermal collector was experimentally studied by Erdil et al. [17]. A vent pipe is used to avoid the breaking of the glass plate. Bakker et al. [83] solved that problem by using a glass plate.

Joshi et al. [85] studied the performance of unglazed hybrid PVT glass-to-glass system for the composite climate of New Delhi and compared with glass-to-tedlar (PVT) system for the forced mode of operation. They found that compared to a glass-to-tedlar system, the thermal efficiency of glass-to-glass PVT air collector was higher because its outlet air temperature was slightly higher.

Solanki et al. [86] carried out experiments on a PVT solar air heater system under indoor conditions. The experimental system consisted of three PV modules (mono crystalline silicon cells) of glass-to-tedlar type, each rated at 75 Wp having 0.45 m width and 1.2 m length and mounted on a wooden duct. The study reported that the thermal, electrical and overall efficiency of the solar heater obtained under indoor conditions was 42%, 8.4% and 50%, respectively. These results were in agreement with those obtained by other researchers for outdoor conditions [8].

2.7. Scopes and objectives of the present study

Information gathered from the literature reveals that the performance of various PVT systems, particularly the glazed type PVT air collector varies over a wide range. Most of the works reported in the literature are experimental in nature under widely varying conditions. The comprehensive theoretical analysis to assess the performance of the PVT system applied to BIPV is very much limited.

In view of these observations, in this study, a glazed PVT air collector used as a BIPV system is selected for details analysis. One of the main advantages of this system is that the well established conventional PV systems can be easily retrofitted as a PVT system, which would be fairly inexpensive and also easy to maintain.

The objectives of the present study are: (i) to perform a thorough analysis of the PVT collector which includes various PVT modules and heat transfer enhancement promoters. (ii) Most of the existing PVT systems either have a glass or tedlar integrated beneath the PV panel. The maximum achievable efficiencies of both the said types of systems are only about 45%. Hence in this study, an attempt would be made to develop/design a new configuration (model concept) to achieve higher efficiency. (iii) Though there exist several heat transfer promoting techniques in the literature, in this study a new technique would be introduced to increase the turbulence in the air flow channel, which in turn could increase the thermal efficiency. (iv) An analytical model would be developed based on the energy balances of different subsystems of the chosen PVT configuration. Further the results obtained from the model, would be compared with the experimental data available in the literature [3] in order to validate the proposed model. (v) To gain an insight into the air channel hydraulics as well as kinetics in the air channel, the effect of various design and operating parameters on the overall system performance would be carried out.

CHAPTER 3. PVT CONCEPTS AND HEAT EXTRACTION IMPROVEMENT

In this chapter, a new PVT module concept is proposed with an aim to improve the performance of a PVT system in terms of its electrical efficiency. Further, the techniques to improve the heat transfer in air channel of the PVT system are detailed in this section.

3.1. PVT module concepts

Most of the PVT systems reported in the literature typically consist of a PV module on the back of which an absorber plate (a heat extraction device) is attached and the working fluid flows over the PV panel or beneath the PV panel. Figure 3.1 shows that the working fluid channel has been placed over the PV panel and the working fluid is circulated between the glazing and the PV panel [17].

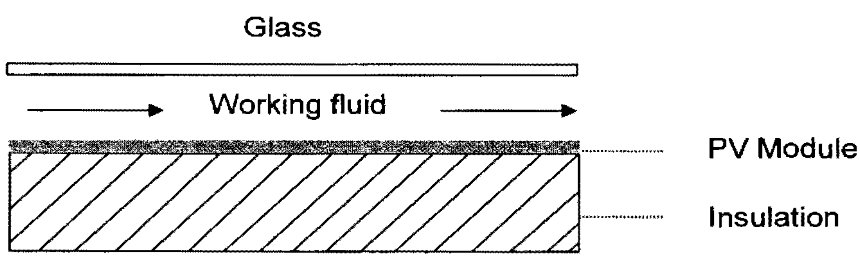


Figure 3.1. Liquid flowing on top of the PV panel

Figure 3.2 shows that the cooling medium being used beneath the rear surface of the PV module [24, 30, 31, 75, 78-80, 86]. This configuration is most suitable for building integrated photovoltaic systems and also it has been shown to provide optimum thermal performance. Hence, in the present study, the working fluid channel is placed beneath the PV panel.

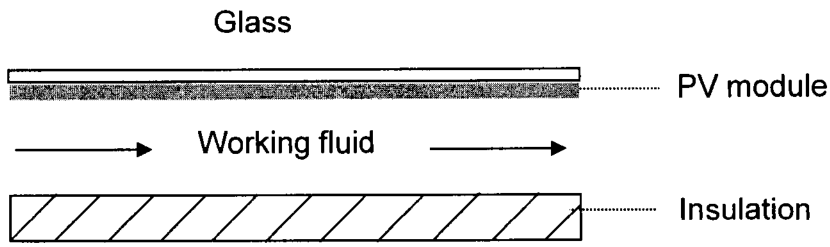


Figure 3.2. Liquid flowing beneath the PV panel

Further, literature shows that there exit two types of PVT module configurations:

- Type 1: PV module is integrated to glass-to-tedlar (Fig. 3.3). In this case, solar radiation is absorbed by the solar cells as well as EVA (Ethylene Vinyl Acetate) and it is then conducted to the base of the tedlar for heating the air flowing below it.
- Type 2: Conventional PV module with glass-to-glass (Fig. 3.4). In this case, solar radiation is absorbed both by the solar cells and the back surface. The air flowing underneath the base is heated by both the convective heat from back surface as well as the heat conducted from solar cell.

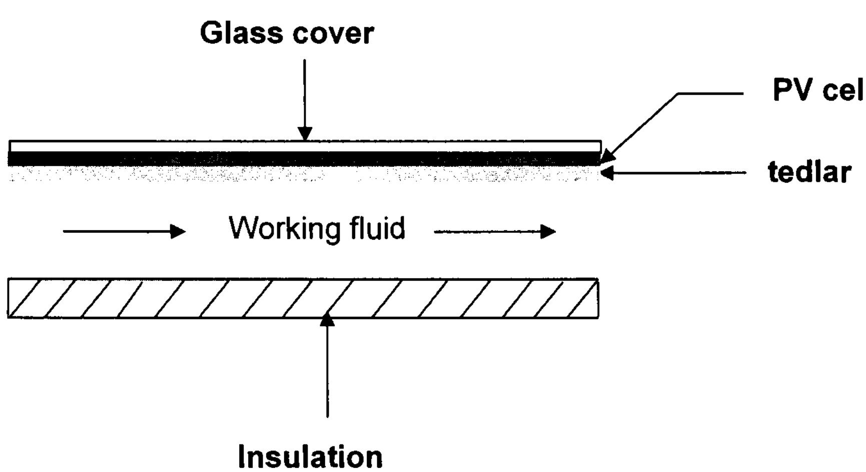


Figure 3.3. Glass-to-tedlar PVT module

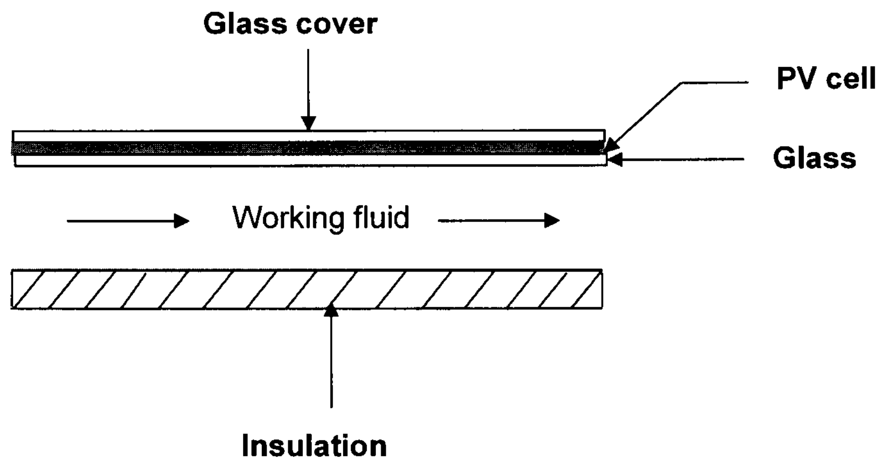


Figure 3.4. Glass-to-glass PVT module

In the case of glass-to-tedlar system, a lower value of thermal efficiency is experienced. The reduction in thermal efficiency is due to the increase in the heat resistance between the absorbing surface and the heat transfer medium caused by the additional layer of material, i.e. tedlar. Tedlar becomes a barrier for extracting thermal energy, in turn reducing both the electrical and overall efficiency of the system. In the case of glass-to-glass system, though there is a marginal increase in the thermal efficiency of PVT system, it has a negative impact on the cooling load requirement of the building, because of an increase in the back surface temperature. Hence, in order to keep all layers between the PV panel and the absorber as thin as possible, in this current research, a new PVT module design is proposed (Fig. 3.5). Here, a plate is integrated to the back surface of the PVT system and it is termed as the "back wall." By doing so, it is expected that not only the thermal efficiency would increase, but also the thermal load requirement of the building would decrease. This is due to the fact that, it is possible to extract more thermal energy both from the PV panel and the back wall by the air that is being circulated in the duct.

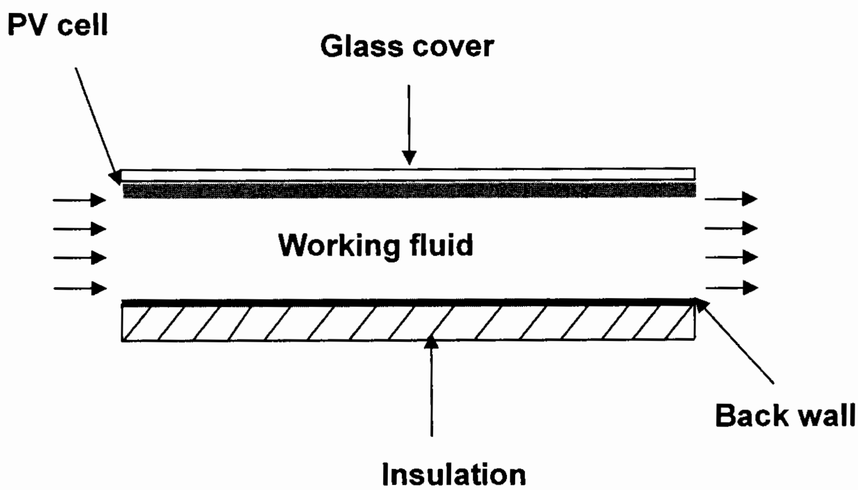


Figure 3.5. Cross-sectional view of the proposed PVT air collector model

3.2. Techniques to increase PVT performance

There exists numerous methods to enhance the performance of air PVT system: using fin to the rear surface of the PV system, thin metal sheet or corrugated sheet placed in the air channel or providing fluid circulation on top and bottom of the PV panel. Elements of various types of configuration can be placed inside the channel between the PV panel and opposite wall, as well as can be placed on back surface, through which heat extraction can be made more efficient [31]. The opposite wall can be roughened with ribs which is considered as a low cost heat extraction method (Fig. 3.6a).

Also, corrugated sheet can be placed inside the channel between the PV panels rear surface (Fig. 3.6b). Alternatively, light pipes can also be placed along the air flow (Fig. 3.6c). The conduction, convection and radiation can take place from PV surface to these pipes, which can enhance higher heat extraction.

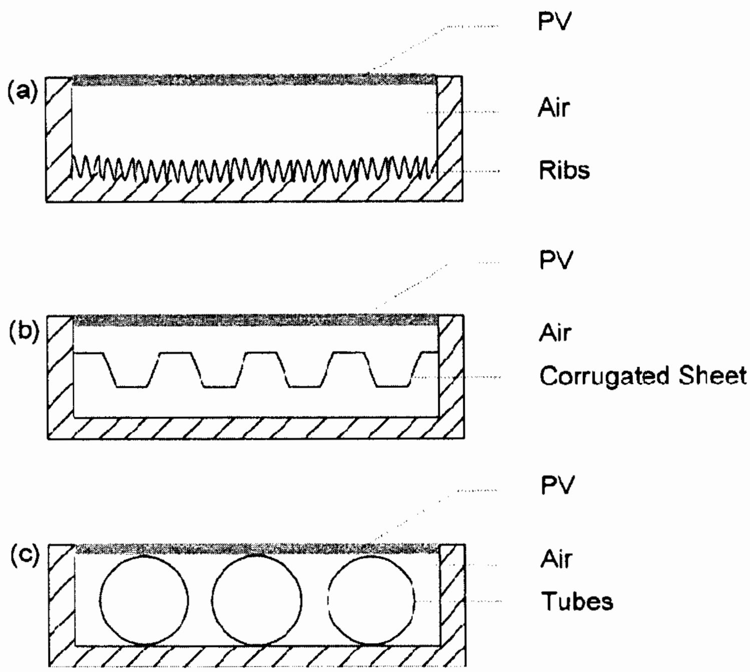


Figure 3.6. Improvement of heat extraction of the PVT air system with (a) ribs, (b) a corrugated sheet and (c) tubes

Researchers have conducted experiments to enhance the heat transfer dynamics and kinetics in the channel of a PVT system. Tripanagnostopoulos et al. [30, 88, 89] have investigated the performance improvement modifications by using either finned back wall or flat TMS sheet placed in the PVT system. The cross-sectional views of their models are shown in Fig. 3.7.

The models resemble with air collectors where a PV panel works as the absorber plate. The system consists of a channel, which is attached with the PV panel and for the improved systems they modify the air channel by suspending a flat TMS in the channel or by attaching fin of rectangular shape on the back surface of the wall to the PV rear surface.

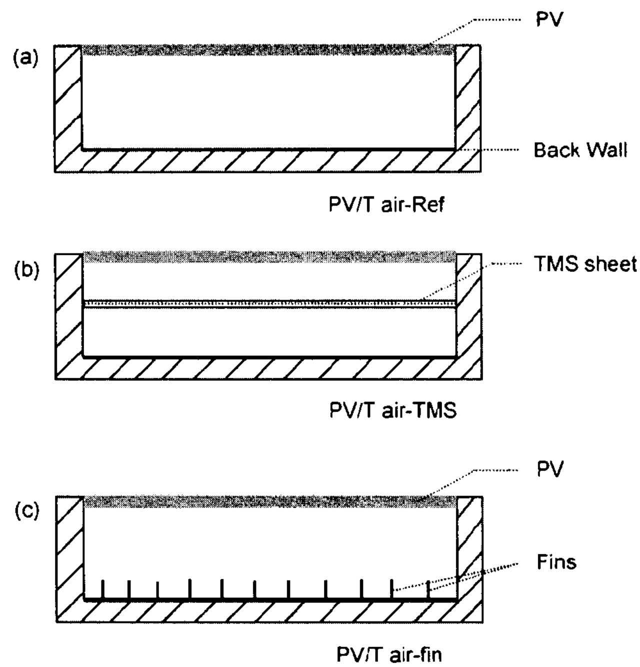


Figure 3.7. PVT air collector equipped with different heat transfer promoters

Othman et al. [66] have also confirmed that by attaching fin with the PV module, the heat transfer to the working fluid as well as the overall efficiency was enhanced.

Apart from using fins in the air channel duct, an attempt was made to use metallic cylindrical tubes, using 0.5 mm thick aluminum sheet, to study the effect of geometry on the heat transfer mechanism [78]. Tubes were installed along the air channel pressed fit by PV rear surface and opposite wall. For the given duct width, two tubes were used instead of three, in order to have low weight, cost and pressure drop. The study showed that though the temperature drop at the PV laminate surface is not much higher compared to the system using fins, it has better advantage since the back wall temperatures are much lower. Hence, using tubes in air channel duct is more suitable for BIPV.

However, studies with the above listed modifications have shown to increase the air cooled PVT system's thermal efficiency increase by only about 45% [46]. Hence in the present system, in order to attain a higher thermal efficiency, helical inserts (thickness 2 mm) are used to enhance the heat extraction in the channel (Fig. 3.8) and the PVT system incorporated with helical inserts is termed as a "modified PVT" system. It is expected that not only the thermal efficiency of the system would improve but it will also be a low cost technique. The PVT system with the suggested improvement is simple to manufacture since helical inserts can be fabricated from locally accessible low-cost materials like aluminum or galvanized iron sheets. Further, they can be easily incorporated in the channel, presenting a practical design for the air PVT system. This technique would considerably change the air channel hydraulic because the hydraulic diameter will be lower, as a result the convective heat-transfer coefficient will be higher and higher heat-transfer surface area. The final effect would be higher heat is transferred to the working fluid (air stream) in the air channel. Hence, it is expected that the described system would perform better in terms of PV cooling as well as heat producing compared to the conventional/reference PVT types (PVT without insert). Further, the insert can be selectively coated to increase heat absorption and to minimize reflective losses from the air channel.

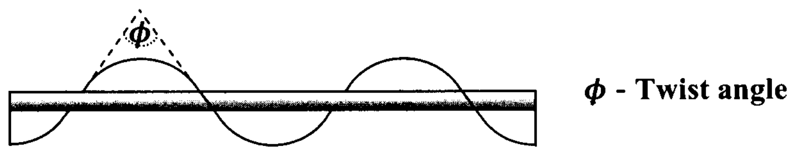


Figure 3.8. Schematic drawing of Helical Insert

3.3. Summary

In this chapter, various PVT module concepts and the advantages as well as disadvantages of each module concept were highlighted. As a part of the present research, a new PVT module design had been introduced which can be implemented in a building integrated photovoltaic (BIPV) system. Also, the existing types of heat transfer promoters were listed. Further in this chapter, details on some new low-cost heat extraction methods had been elaborated.

CHAPTER 4. THERMAL ANALYSIS

Thermal and electrical performances of the PVT collector have been evaluated by means of a steady state simulation model. The model is based on the thermal balances of the different sections of the modified collector, such as the PV panel, air gap, insert, and the back wall [Fig. 4.1]. The convective and/or radiative coefficients in the energy balance expressions were evaluated using appropriate correlations. The energy balance equations are organized in a numerical matrix, whereas the radiative coefficient equations are solved by means of an iterative procedure.

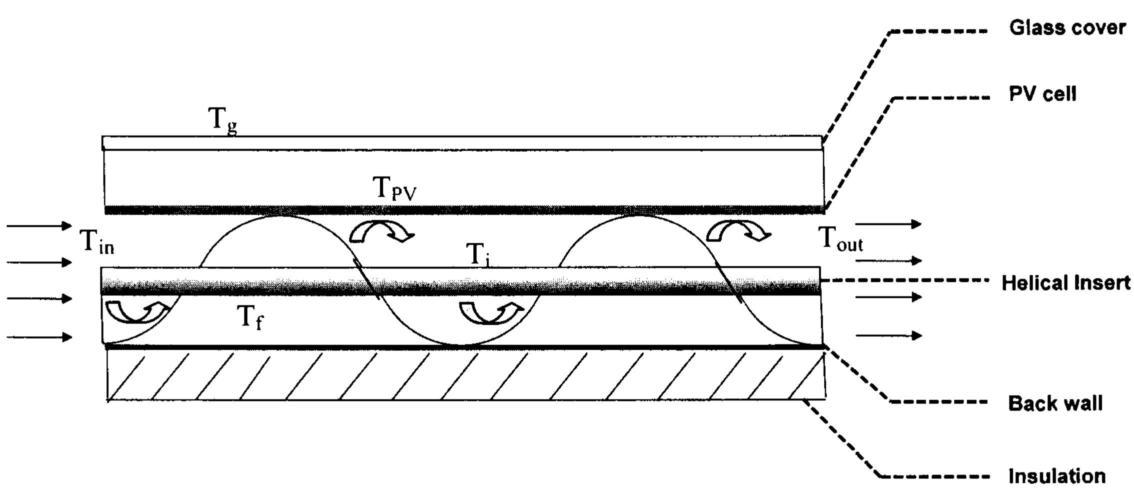


Figure 4.1. Temperature nodes of the modified PVT system

Figure 4.1 shows the cross sectional view of the glazed type of PVT system with insert, termed as a "modified system," showing the essential temperature nodes. For this system, T_i is the node which is representing the helical insert, T_g and T_{PV} refers to the nodes at the glass cover and PV panel respectively. Also, the fluid node is denoted by T_f with the outlet temperature T_{out} and the inlet temperature T_{in}.

The following assumptions have been made to keep the procedure simple:

(i) One dimensional (1D) steady state heat transfer,

(ii) negligible thermal capacitance of the sub-systems of the PVT collectors,

(iii) convective heat transfer coefficient, $h_{c,}$ is of the same value between the air-channel surfaces, the helical insert and the flowing air, and

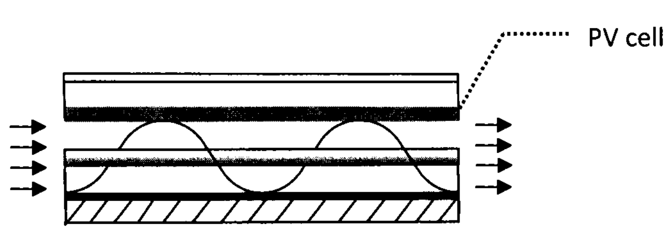
(iv) heat loss from the PVT system outer surfaces are to the ambient.

The energy balance equations for the modified PVT system in Fig. 4.1, are framed based on the assumptions specified.

4.1. Thermal equilibrium of the PV panel

The solar energy gained by the PV panel ($\tau_g \alpha_{PV} I$) generates the electrical power of the PVT system. The remaining energy that is not being converted to electricity generates heat. The remaining energy of the PV panel, $\tau_g \alpha_{PV} (1 - \eta_s) I$, gets distributed as top loss as well as heat transfer to the Insert, to the working fluid and to the back wall. The orientation of surfaces has an influence on the net radiation exchange between the heat transfer surfaces. This is computed by taking into account the "shape factor" or "view factor," which gives the proportion of radiation leaving the PV surface that strikes the helical insert of back wall of the PVT system.

Energy balance equation for PV cell can be given as:



$$\begin{bmatrix} \text{The net rate} \\ \text{of solar energy} \\ \text{available for heating} \end{bmatrix} = \begin{bmatrix} \text{An overall heat loss} \\ \text{from top surface} \\ \text{of PV cells to ambient} \end{bmatrix} + \begin{bmatrix} \text{The rate of heat} \\ \text{transfer from} \\ \text{cell to flowing fluid} \end{bmatrix}$$

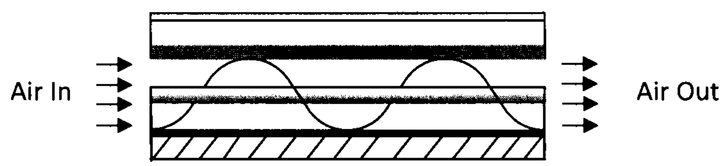
$$+ \begin{bmatrix} \text{The rate of heat} \\ \text{transfer from} \\ \text{cell to Insert} \end{bmatrix} + \begin{bmatrix} \text{The rate of heat} \\ \text{transfer from} \\ \text{cell to back wall} \end{bmatrix}$$

$$\begin{aligned} A_{PV}\, \tau_g \alpha_{PV}\, (1 - \eta_{el}) I = {} & A_{PV}\, U_t\, (T_{PV} - T_{amb}) \\ & + A_{PV}\, h_c\, (T_{PV} - T_f) \\ & + A_{PV}\, h_{r,PV\_i}\, (T_{PV} - T_i) F_{PV\_i} \\ & + A_{PV}\, h_{r,PV\_w}\, (T_{PV} - T_w) F_{PV\_w} \end{aligned} \tag{4.1}$$

where, A_{PV} is the PV cells area (m^2); τ_g is the solar transmittance of the glass panel; α_{PV} is the solar absorptance of PV cells; η_{el} is the electrical efficiency of PV cells; I is solar irradiation on the PVT system (W m^{-2}); U_t is the top heat transfer coefficient from PV cells to ambient through glass cover (W m^{-2} °C^{-1}); T_{PV} is the temperature of the PV cells (°C); T_{amb} is the ambient air temperature (°C); h_c is the convective heat transfer coefficient in the air channel (W m^{-2} °C^{-1}); T_f is the average temperature of the air in the air channel (°C); h_{r,PV_i} is the radiative coefficient between PV cells and the insert (W m^{-2} °C^{-1}); T_i is the temperature of the insert (°C); F_{PV_i} is the shape factor between PV cells and the insert; h_{r,PV_w} is the radiative coefficient between PV cells and the back wall (W m^{-2} °C^{-1}); T_w is the temperature of the back wall (°C); F_{PV_w} is the shape factor between PV cells and the back wall.

4.2. Thermal equilibrium in the air channel

The working fluid (air) passing through the channel beneath the PV panel gains heat from the PV panel, from the insert as well as from the back wall simultaneously. In this study, it is intended to set the air flow in the channel to be in the forced convection mode, and hence the energy balance equation can be expressed as:



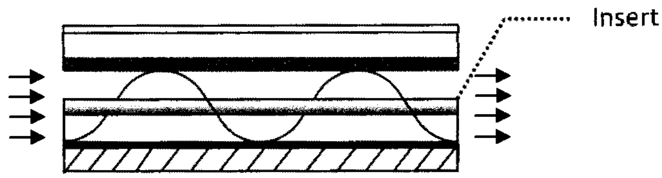
$$\begin{bmatrix}\text{The rate of heat} \\ \text{transfer from} \\ \text{cell to flowing fluid}\end{bmatrix} + \begin{bmatrix}\text{The rate of heat} \\ \text{transfer from} \\ \text{Insert to Fluid}\end{bmatrix} + \begin{bmatrix}\text{The rate of heat} \\ \text{transfer from} \\ \text{wall to fluid}\end{bmatrix} = \begin{bmatrix}\text{The mass flow} \\ \text{rate of} \\ \text{flowing air}\end{bmatrix}$$

$$A_{PV}\, h_c \left(T_{PV} - T_f\right) + A_i\, h_c \left(T_i - T_f\right) + A_w\, h_c \left(T_w - T_f\right) = \dot{m}\, C_p \left(T_{out} - T_{in}\right) \tag{4.2}$$

where, A_i is the surface area of the insert (m^2); A_w is the area of the back wall (m^2); $\dot{m}$ is the air mass flow rate inside the air channel ($kg\ s^{-1}$); C_p is the specific heat of air ($Jkg^{-1}K^{-1}$); T_{out} is the outlet air temperature (°C); T_{in} is the inlet air temperature (°C).

4.3. Thermal equilibrium of insert and back wall

The helical insert in the channel mainly gets heated from the PV panel through the mode of radiation heat transfer. This heat gets distributed as convection heat transfer to the working fluid and radiation heat transfer to the back wall simultaneously and the energy balance equation for insert can be written as:

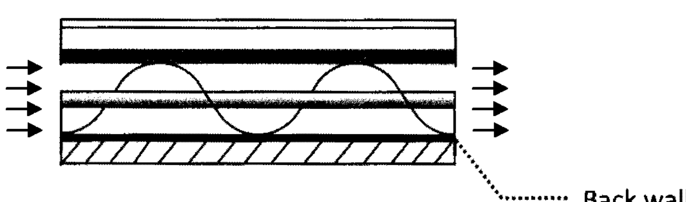


$$\begin{bmatrix}\text{The rate of heat}\\ \text{transfer from}\\ \text{cell to Insert}\end{bmatrix} = \begin{bmatrix}\text{The rate of heat}\\ \text{transfer from}\\ \text{Insert to flowing fluid}\end{bmatrix} + \begin{bmatrix}\text{The rate of heat}\\ \text{transfer from}\\ \text{Insert to back wall}\end{bmatrix}$$

$$A_{PV}\, h_{r,PV\_i}\, (T_{PV} - T_i) F_{PV\_I} = A_i\, h_c \left(T_i - T_f\right) + A_i\, h_{r,i\_w}\, (T_i - T_w) F_{i\_w} \qquad (4.3)$$

where, h_{r,i_w} is the radiative coefficient between insert and the back wall (W m^{-2} °C^{-1}); F_{i_w} is the shape factor between insert and the back wall.

Similar to Eq. (4.3), the energy balance equation of back wall can be expressed as:



$$\begin{bmatrix}\text{The rate of heat}\\ \text{transfer from}\\ \text{cell to back wall}\end{bmatrix} + \begin{bmatrix}\text{The rate of heat}\\ \text{transfer from}\\ \text{Insert to back wall}\end{bmatrix}$$

$$= \begin{bmatrix}\text{An overall heat loss}\\ \text{from back wall}\\ \text{to ambient}\end{bmatrix} + \begin{bmatrix}\text{The rate of heat}\\ \text{transfer from}\\ \text{back wall to flowing fluid}\end{bmatrix}$$

$$h_{r,PV_w}\,(T_{PV} - T_w)F_{PV\_w} + A_i\,h_{r,i_w}\,(T_i - T_w)F_{i\_w}$$
$$= A_w\,U_b(T_w - T_{amb}) + A_w\,h_c\,(T_w - T_f) \qquad (4.4)$$

where, U_b is the overall heat transfer coefficient from back wall to ambient through insulation (W m^{-2} °C^{-1}).

4.4. PV effective conversion efficiency as a function of cell temperature

As discussed earlier, the electrical efficiency of the PVT system is dependent on its temperature, i.e. the higher the cell temperature the lower is its cell efficiency, which is graphically shown in Fig. 4.2.

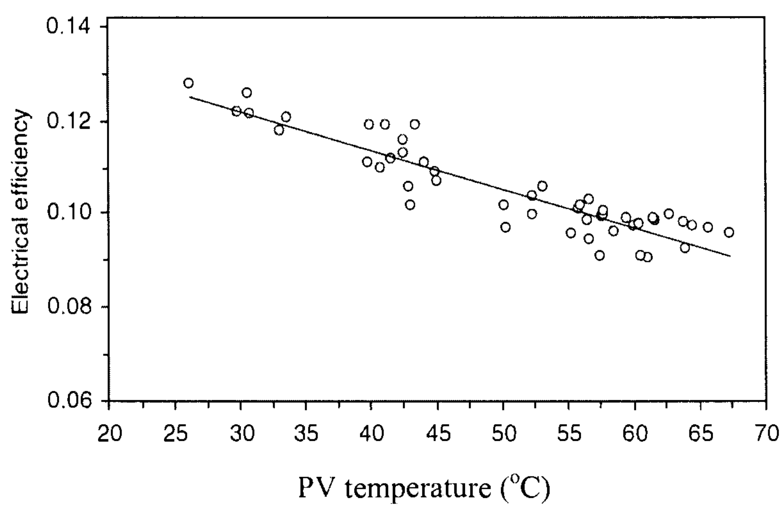


Figure 4.2. Electrical efficiency as a function of PV cell temperature

Hence, the temperature dependent electrical-efficiency of a PV cell [9, 64, 90] can be expressed as:

$$\eta_{el} = \eta_s\,[1 - \beta\,(T_{PV} - T_s)] \qquad (4.5)$$

where, β = 0.0045°C^{-1} is the temperature coefficient; T_{PV} is the temperature of the PV cell, T_s is the reference temperature (taken as 25°C) and η_s is the efficiency of the PV cell at the reference temperature.

The specifications of the silicon solar cells, at 1000 Wm^{-2} at 25 °C (standard test conditions) used in the PV module of the present work are as follows:

- fill factor (FF) = 0.72
- short circuit current (I_{sc}) = 4.8 A
- open circuit voltage (V_{oc}) = 21.7 V
- length, L = 1.0 m
- width, b = 0.45 m
- efficiency, η_s= 0.12.

4.5. Estimation of heat transfer coefficients

The heat transfer characteristics of a PVT system are described by Eqs. (1) - (4) respectively. The PVT system can be divided into numerous sections as described earlier. Calculations were performed section by section along the length of PVT system. In order to solve the energy equations, the following heat transfer parameters are first evaluated:

4.5.1 Overall heat loss coefficients

The overall heat loss coefficient is denoted by U_L. It combines the top losses U_t, bottom losses U_b and edge losses U_e. Usually, the edge losses are negligible, giving:

$$U_L = U_t + U_b \tag{4.6}$$

The top heat loss coefficient (U_t) from PV cells to ambient can be defined as follows:

$$\frac{1}{U_t} = \left(\frac{1}{h_1} + \frac{t_g}{K_g} + \frac{1}{h_2}\right) \tag{4.7}$$

The heat loss coefficient from PV cells to glass panel (h_1) can be defined as the sum of the convective heat transfer coefficient from PV cell to glass panel (h_{1c}) and the radiative heat transfer coefficient (h_{1r}) as

$$h_1 = h_{1c} + h_{1r} \tag{4.8}$$

Buchberg et al. [91] have recommended the following three region correlation for the convective heat transfer losses (h_{1c}) for an inclined surface:

$$Nu = \frac{h_{1c} * \delta_{PV\_g}}{K_{air}} = 1 + 1.446 \left[1 - \frac{1708}{Ra\cos\theta}\right] \text{for } 1708 < Ra\cos\theta < 5900 \tag{4.9}$$

$$Nu = \frac{h_{1c} * \delta_{PV\_g}}{K_{air}} = 0.229\ (Ra\cos\theta)^{0.252}\ \text{ for } 5900 < Ra\cos\theta < 9.23\ x\ 10^4 \tag{4.10}$$

$$Nu = \frac{h_{1c} * \delta_{PV\_g}}{K_{air}} = 0.157\ (Ra\cos\theta)^{0.285} \qquad \text{for } 9.23 \text{ x } 10^4 < Ra\cos\theta < 10^6 \tag{4.11}$$

where, θ is the angle of inclination; Ra is the Rayleigh number and is given by

$$Ra = Gr\,\mathrm{Pr} = \frac{g\,\acute{\beta}\,(T_{PV} - T_g)\,\delta_{PV\_g}^3}{\nu^2} \tag{4.12}$$

In equ (4.12), δ_{PV_g} is the spacing between the PV cells and the glass panel; K_{air} is the thermal conductivity of the inside air; ν is the kinematic viscosity of the air inside the air channel.

The radiative heat transfer coefficient (h_{1r}) can be expressed as:

$$h_{1r} = h_{r,PV\_g} = \sigma \frac{(T_{PV}^4 + T_g^4)}{\left(\frac{1}{\epsilon_{PV}} + \frac{1}{\epsilon_g} - 1\right)(T_{PV} - T_g)} \tag{4.13}$$

where, T_g is the glass panel temperature (°C); ϵ_g is the emissivity of the glass panel; ϵ_{PV} is the emissivity of the PV panel.

Also, the conduction heat transfer in the glass panel can be expressed as follows:

$$\frac{K_g}{t_g} \tag{4.14}$$

where K_g is the thermal conductivity of glass panel and t_g is the thickness of glass panel.

Finally, the heat transfer coefficient from the glass panel to ambient (h_2) can be expressed as:

$$h_2 = h_{2c} + h_{2r} \tag{4.15}$$

where, h_{2c} is convective heat transfer coefficient from glass panel to ambient and h_{2r} is the radiative heat transfer coefficient from glass panel to ambient.

The convective heat loss coefficient from the glass panel to the ambient (h_{2c}) can be estimated using the following expressions [30]:

$$h_{2c} = 5.7 + 3.8 * v \tag{4.16}$$

where, v is the air velocity.

Similarly, the radiative heat loss coefficient from the glass panel to the ambient (h_{2r}) can be expressed as [92]:

$$h_{2r} = h_{r,g\_amb} = \epsilon_g \, \sigma \frac{(T_g^4 - T_{sky}^4)}{(T_g - T_{amb})} \tag{4.17}$$

where,

$$T_{sky} = T_{amb} - 6 \tag{4.18}$$

The bottom heat loss U_b is the conduction heat loss from the back surface of the PVT system and can be expressed as:

$$U_b = \frac{K_{in}}{t_{in}} \tag{4.19}$$

where, K_{in} is the thermal conductivity of insulation and t_{in} is the thickness of insulation.

4.5.2 Film convection heat transfer coefficient

The air in the air-channel receives heat from air-channel surface through convection heat transfer and is characterized by convective heat transfer coefficient h_c. To ease the calculation, the forced convective (film) heat transfer coefficient in the channel of the PVT system is assumed to be uniform for all walls in the air-channel.

Heaton et al. [93] proposed the following convection heat transfer coefficient relation for laminar-flow ($Re < 2300$):

$$Nu = Nu_{\infty} + \frac{0.00190\left[Re\,\mathrm{Pr}\left(\frac{D_e}{L}\right)\right]^{1.71}}{1 + 0.00563\left[Re\,\mathrm{Pr}\left(\frac{D_e}{L}\right)\right]^{1.71}} \tag{4.20}$$

where, Nu is the Nusselt number, $Nu_{\infty} = 5.4$, and D_e is the hydraulic diameter of the channel given by:

$$D_e = \frac{4 \text{ x free flow area}}{\text{wetted perimeter}} \tag{4.21}$$

For the transition flow region (2300< Re <6000), the following correlation is used to predict the heat transfer coefficient:

$$Nu = 0.116\left(Re^{2/3} - 125\right) Pr^{1/3}\left[1 + \left(\frac{D_e}{L}\right)^{2/3}\right]\left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (4.22)$$

Tan and Charters [94] proposed the following correlation for the turbulent flow region to predict the heat transfer coefficient, h_c:

$$Nu = 0.0182\, Re^{0.8}\, Pr^{0.4}\left[1 + S\,\frac{D_H}{L}\right] \quad (4.23)$$

where, $S = 14.3 \log\left(\frac{L}{D_H}\right) - 7.9$ for $0 < \frac{L}{D_H} \leq 60$ and S is constant and will have a value of 17.50 for $\frac{L}{D_H} > 60$. The convective heat transfer coefficient can be calculated based on the hydraulic diameter as the characteristic dimension for the given air channel duct as

$$h_c = \frac{K_{air}}{D_H} Nu \quad (4.24)$$

As such, studied model is applicable for short length (=1 m) tubes or ducts. Hence, Tan and Charters [94] correlation is used to compute the forced convective heat transfer coefficient h_c for the reference system. Also, this relationship takes care of the thermal entrance effect of the air channel duct. The Reynolds number, hydraulic diameter and Prandtl number are determined using the respective standard expressions. While calculating the hydraulic diameter of the PVT system with insert (modified PVT), the thickness of insert is assumed to be very small so there is no significant effect on the cross sectional area of the air-channel. It only contributes on the wetted-perimeter; hence D_H

values are generally lower for the modified system. To evaluate the value of h_c for the modified PVT system (with insert), equ (3.24) is used except h_c is replaced by $\frac{h_c}{sin\frac{\Phi}{2}}$ [95].

4.5.3 PV cell - insert radiative coefficient

Radiation heat transfer coefficient in the air-channel between the PV cell and the insert is determined by using the Stefan-Boltzmann's linearized coefficient:

$$h_{r,PV\_i} = \sigma \frac{(T_{PV}^2 + T_i^2)\,(T_{PV} + T_i)}{\left(\frac{1}{\epsilon_{PV}} + \frac{1}{\epsilon_i} - 1\right)} \tag{4.25}$$

where, σ is the Stefan-Boltzmann constant $[W/m^{-2}K^{-4}]$; ϵ_{PV} is the emissivity of the PV cells; ϵ_i is the emissivity of the insert.

Similarly, the radiation heat transfer coefficient from PV cell to back wall and from insert to back wall have also been predicted.

4.5.4 PV cell - back wall radiative coefficient

Radiation heat transfer coefficient in the air-channel between PV cell and back wall is determined based on the linearized coefficient evaluated using Stefan-Boltzmann equation:

$$h_{r,PV\_w} = \sigma \frac{(T_{PV}^2 + T_w^2)\,(T_{PV} + T_w)}{\left(\frac{1}{\epsilon_{PV}} + \frac{1}{\epsilon_w} - 1\right)} \tag{4.26}$$

where, ϵ_w is the emissivity of the back wall.

4.5.5 Insert-back wall radiative coefficient

Similarly, radiation heat transfer coefficient in the air-channel between insert and back wall is determined by using the following equation:

$$h_{r,i\_w} = \sigma \frac{(T_i^2 + T_w^2)\,(T_i + T_w)}{\left(\frac{1}{\epsilon_i} + \frac{1}{\epsilon_w} - 1\right)} \tag{4.27}$$

4.6. Thermal efficiency of the PVT system

Thermally, a photovoltaic-thermal (PVT) system is similar to the thermal collector. By using good solar absorption and good heat transfer, good efficiency can be achieved in the case of thermal collector. Hence, in this PVT design, a glass cover is placed on the top of PV panel, termed as a "glazed" system to reduce the thermal losses. Also a helical insert is placed in the air channel to enhance the heat transfer between the PV panel and the working fluid. The thermal performance of the flat plate solar collector is described by the Hottel-Whillier-Bliss [95] thermal efficiency equation. This is further modified by Florschuetz [35] and is used here to compare the thermal efficiencies, η_{th}, of both the "reference" and the "modified" PVT system. The equation for thermal efficiency is given by

$$\eta_{th} = \bar{F}_R \left[\tau_g \alpha_{PV} \,(1 - \eta_{el}) - \bar{U}_L \left(\frac{T_{in} - T_{amb}}{I}\right)\right] \tag{4.28}$$

where, η_{el} is the PV module efficiency. The parameter $\bar{U}_L$ is the modified overall heat-loss coefficient and $\bar{F}_R$ is the modified heat removal factor for the PVT system [35].

In the case of reference PVT system, $\bar{F}'$ is estimated by using following modified-equation from Duffie-and Beckman [95]:

$$\frac{1}{\bar{F}'} = \left[1 + \frac{\overline{U_L}}{\frac{A\, h_c}{A_{PV}} + \frac{1}{\frac{1}{h_c} + \frac{1}{h_r}}} \right] \tag{4.29}$$

The ratio, $\frac{A}{A_{PV}}$ represents the heat transfer of the collector to its aperture area. In the above expression, h_c is the convective heat transfer coefficient and h_r is the radiative heat transfer coefficient of the air channel. For the case of modified PVT collector with inserts, the same equ. (23) is used, however h_c is replaced by $\frac{h_c}{sin\frac{\phi}{2}}$ [95].

Florschuetz [35] has given the relationship between $\bar{F}'$ and $\bar{F}_R$ is given by as

$$\frac{\bar{F}_R}{\bar{F}'} = \frac{G\, C_p}{\overline{U_L}\bar{F}'} \left[1 - exp - \left(\frac{\overline{U_L}\bar{F}'}{G\, C_p} \right) \right] \tag{4.30}$$

where, $G = \frac{\dot{m}}{A_{PV}}$ is the mass flow rate per unit area [kg s^{-1} m^{-2}].

4.7. Friction factor

The values of friction factor in a PVT collector equipped with helical insert have been found using the equations of Smithberg and Landies [96], Date and Singham [97], which have been written here as:

$$f = 4\, [\, 0.046 + 2.1 * (Y - 0.5)^{-1.2}] * Re^{-N} \tag{4.31}$$

where, $N = 0.2 * [1 + 1.7 * (Y)^{-1/2}]$ for $5\text{x}10^3 < \text{Re} < 10^5$ and $1.81 < \text{Y} < \infty$ (4.32)

and,
$$Y = \frac{4}{tan\left(90 - \frac{\phi}{2}\right)} \tag{4.33}$$

4.8. Pressure drop and pumping power

It is well known that while using air as a working fluid, pressure drop experiences in the air channel duct. Hence, it becomes crucial to dictate the required pumping power to maintain forced-flow conditions. Higher pressure drop requires higher pumping energy for flowing of a fluid. Relatively, for rough surface the drop of pressure is high. Pressure drop in a duct has been evaluated by using the following expression:

$$\Delta p = \left(\frac{f\,G^2}{\rho_{air}}\right)\left(\frac{L}{depth}\right)^3 \tag{4.34}$$

Similarly, pumping power has been evaluated by using the following expression:

$$P_m = \frac{\Delta p * \dot{m}}{\rho_{air}} \tag{4.35}$$

4.9. Error analysis

To compare the calculated result of the present proposed PVT system with the experimental result, the coefficient-of-correlation, r, and root-mean-square-percent-deviation, e, have been calculated by using the following expression:

$$r = \frac{n\,(\sum X * Z) - (\sum X) * (\sum Z)}{\sqrt{n(\sum X^2) - (\sum X)^2} * \sqrt{n(\sum Z^2) - (\sum Z)^2}} \tag{4.36}$$

and,

$$e = \sqrt{\frac{\sum(e_i)^2}{n}} \tag{4.37}$$

where, $$e_i = \frac{X_i - Z_i}{X_i} * 100 \tag{4.38}$$

In the above expressions, X is the theoretical value; X_i is the theoretical value of ith term; Z is the experimental value; Z_i is the experimental value of ith term; and n is the total data points.

The correlation coefficient and root mean square percent deviation are used to measure as to how well the predicted values of the proposed PVT design correlates to the experimental results of the work of Tiwari et al. [3]. The correlation coefficient is a factor whose values varies between 0 to 1. The strength of the relation between the predicted and actual data is reflected by higher values of the coefficient of correlation. That is, a perfect fit gives a coefficient of 1.0, so a higher coefficient of correlation is desirable.

CHAPTER 5. MODEL VALIDATION AND PARAMETRIC STUDIES

The theoretical model of a PVT system is developed based on the equations listed in Chapter 4. The solar insolation, ambient temperature, wind speed, and inlet air temperature values are the input to the MATLAB program. To fix the air properties, the initial values of the PV panel temperature and air inlet temperature are assigned. To compute the temperature at the unknown node and heat-transfer coefficient accurately, the program carries out an iterative process. The mathematical model is validated first with Tiwari et al. [3] experimental data. Further, the validated reference model was used to carry out the comparative study with the modified PVT system (with insert) to check the effectiveness of the insert. The modified model was used to simulate the effectiveness of various operational and design parameters on the PVT system performance.

5.1. Simulation of the system

A MATLAB computer program has been compiled to simulate the behavior of the modified PVT system described in Chapter 4. Since the governing equations of the thermal analysis comprising of a set of nonlinear equations, they are solved simultaneously using Newton-Raphson method. In this study, we have approximated the analysis to a steady state model, and hence the time-step is set to 3 sec (which case, the variations in solar intensity are negligible). During each time step, iterations are performed to obtain a converged solution. The simulation is carried out based on the four main components of the modified PVT system, namely PV panel, helical insert, back-wall and the working fluid. The only meteorological data required for the program are the daily global insolation, ambient temperature and wind velocity values. In the simulation, to begin with, the inlet air temperature is assumed to be equal to the ambient temperature.

5.2. Model validation

To validate the model developed in this study, the results of the present study is compared with the work of Tiwari et al. [3]. The model of Tiwari et al. [3] is chosen, as this model closely matches to the configuration of the system proposed in this study. Parameters such as PV surface temperature and working fluid outlet temperature are compared to check the validity. These parameters are selected because, only the above said data are published by Tiwari et al. [3]. The design parameters and various heat transfer coefficients of the photovoltaic-thermal system used in the present study are listed in Tables 5.1 and 5.2. They correspond to the experimental system described by Tiwari et al. [3]. Figure 5.1 shows a schematic of the experimental set-up of Tiwari et al. which comprises of a PV module, a channel through which the cooling air flows, and insulation material provided at the bottom of the channel.

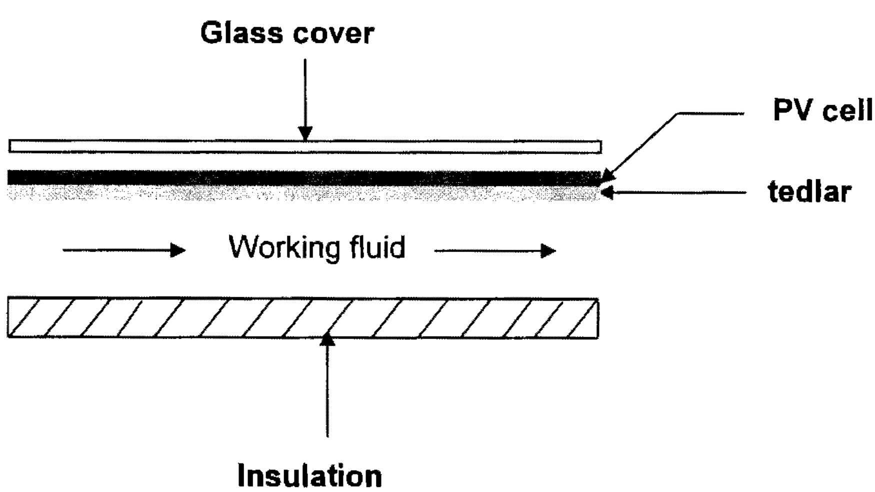


Figure 5.1. Cross-sectional view of Tiwari et al. Model

The uniqueness of this work is that a tedlar film is provided beneath the PV module, to separate it from the air channel.

Table 5.1. Design parameters of PVT system with air as the heat removal medium [3]

Parameters	**Values**
A_{PV}	0.54 m^2
b	0.45
h_{p1}	0.88
K_{PV}	0.039 $W\ m^{-1}\ {}^{o}C^{-1}$
K_g	1.0 $W\ m^{-1}\ {}^{o}C^{-1}$
K_{in}	0.035 $W\ m^{-2}\ {}^{o}C^{-1}$
K_T	0.033 $W\ m^{-2}\ {}^{o}C^{-1}$
L	1.2 m
t_{PV}	0.0003 m
t_g	0.003 m
t_{in}	0.05 m
t_T	0.0005 m
U_b	0.62 $W\ m^{-2}\ {}^{o}C^{-1}$
U_t	2.8 $W\ m^{-2}\ {}^{o}C^{-1}$
U_T	66 $W\ m^{-2}\ {}^{o}C^{-1}$
U_{tT}	8.11 $W\ m^{-2}\ {}^{o}C^{-1}$
α_{PV}	0.90
α_T	0.50
β_{PV}	0.83
η_{PV}	0.12
τ_g	0.95

Table 5.2. Hourly variation of climatic parameter and various temperatures [3]

Time (h)	Intensity ($W\ m^{-2}$)	Inlet air T (°C)	Ambient T (°C)	PV T (°C)	Outlet air T (°C)	Air velocity ($m\ s^{-1}$)	
						Air channel	Above panel
8	43	10.1	9	11.2	10	1.6	0
9	222	14.2	12	20.7	15.5	1.7	0
10	433	19.1	15	31	22.6	1.8	0
11	558	21.5	18	36.4	26	1.9	0
12	677	23.1	20	40.1	28.8	2	0
13	602	24	22	41.1	29.8	2.4	0
14	283	23.4	22	33.5	26.4	1.9	0.3
15	261	23.4	22	31.8	25.9	1.9	0.08
16	104	22.5	21	26.9	23.7	1.9	0.08

In their study, channel depth has not been specified in the literature and hence it is assumed to be of 0.03m for the comparative study. This may influence the convective heat transfer coefficient, and in turn the heat flow from the PV cell to the insert. It should be pointed out here that, while carrying out the parametric study (Section 5.3), simulation is carried out exclusively to check the effect of channel depth on the modified system's performance.

The design and climatic data given in Tables 5.1 and 5.2 have been used to evaluate the PV cell temperature and air outlet temperature. The simulated analytical results are plotted in Figs. 5.2 & 5.3, respectively. It is observed from Figs. 5.2 & 5.3 that there is a fair agreement between the experimental values and the theoretical values. The trend in the variations of the PV cell temperature, $T_{pv}(th)$, and the increase in air outlet temperature, $T_{out}(th)$, of the proposed model, are in accordance with the experimental data reported by Tiwari et al. [3].

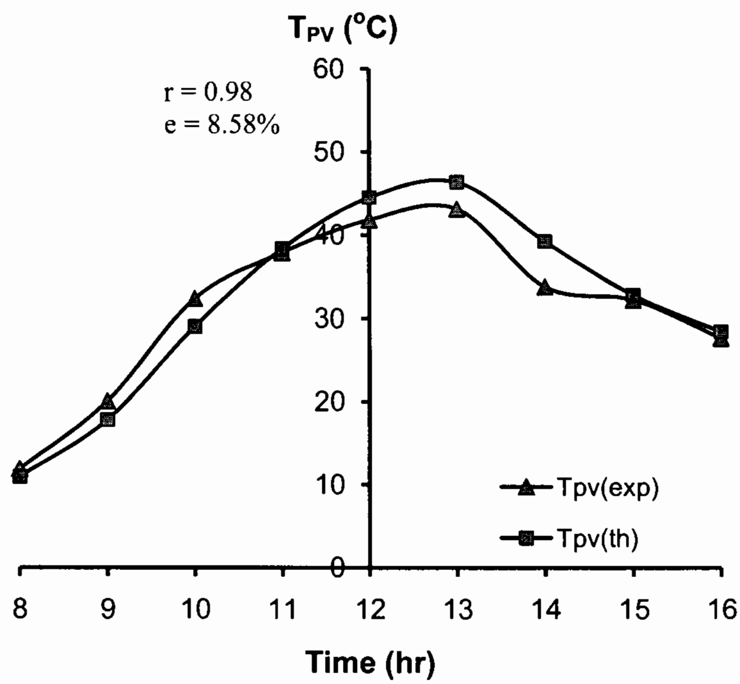


Figure 5.2. Variation of PV cell temperature

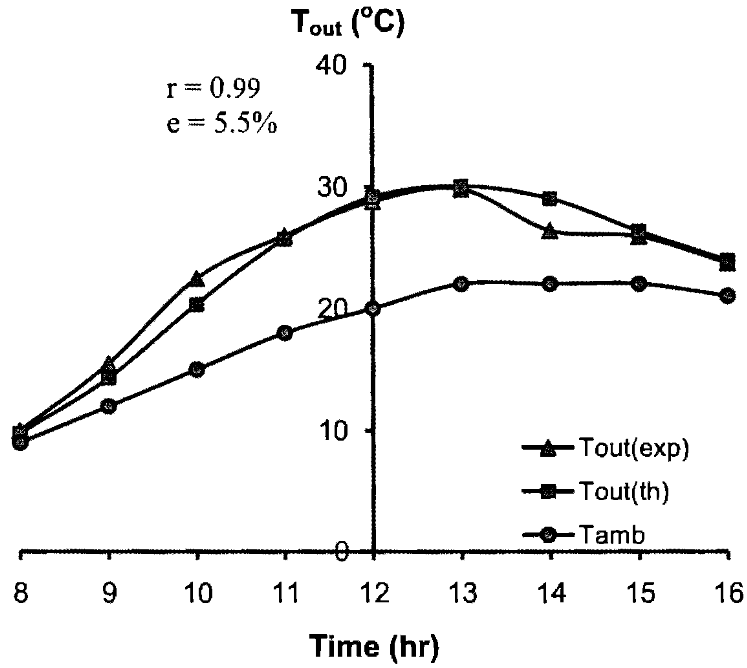


Figure 5.3. Variation of air outlet temperature

It is evident from Figs. 5.2 and 5.3 that the PV cell temperature is higher than the air outlet temperature, as expected. Also, there is an increase in air outlet temperature by about 9°C with respect to the ambient air temperature. Further, it can be observed that the theoretical and experimental values of air outlet temperature (T_{out}) correlates well with each other (Fig. 5.3), while the model overestimates the PV surface temperature by about 2°C or less as shown in Fig. 5.2 . This may be due to the fact that, unlike in the experimental study, tedlar has not been used in the reference model (present study). The correlation coefficient (r) and root mean square percent deviation (e) have also been evaluated using Eqs. (36) to (38), and are indicated in Figs. 5.2 and 5.3. The coefficient of correlation and root mean square percent deviation are found 0.98 & 8.58% respectively for PV cell temperature. Similarly, for air outlet temperature, the coefficient of correlation and root mean square percent deviation are found 0.99 & 5.5% respectively. As the value of correlation coefficient is nearly 1.0 for both two cases, which support the validity of the developed model. Also, the good agreement found among the experiment value and numerical results, suggests that the air channel depth of 0.03m assumed in the calculations is reasonable.

5.3. Heat transfer enhancement study

To confirm the effectiveness of using helical inserts in a PVT system, in this study to the proposed modified system configurations, helical inserts were placed inside the air-channel duct. Simulation was carried out to study and compare the performance of both modified PVT system with inserts (PVT/M) and the reference (conventional) system without inserts (PVT/R). The cross sectional views of the reference and the modified PVT systems are shown in Figs. 5.4 and 5.5, respectively.

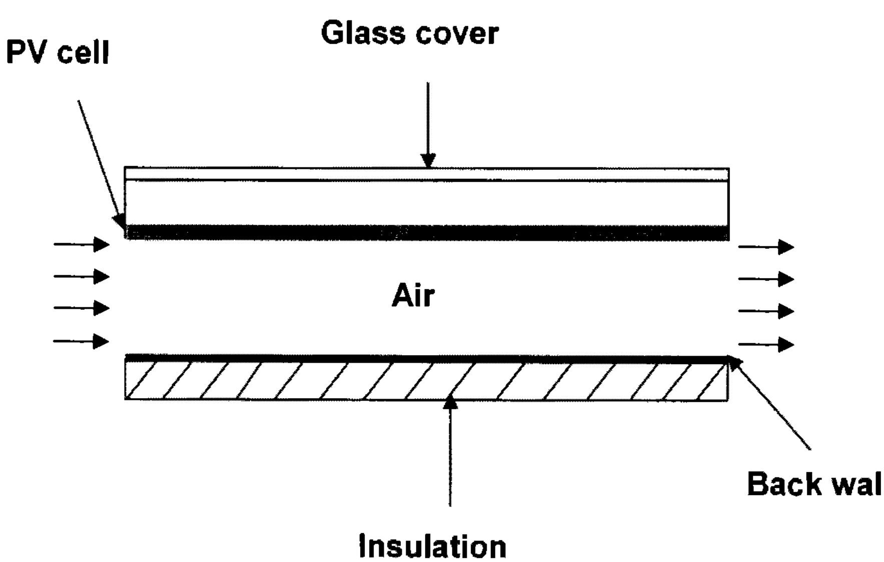


Figure 5.4. Cross-sectional view of the reference PVT system

Helical Insert

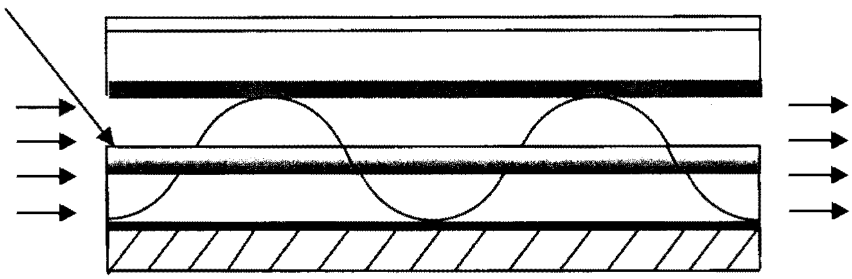


Figure 5.5. Cross-sectional view of the modified PVT system with insert

Commercially available PV module (1.0 m * 0.45 m) is chosen for the present study. By adding one insert, the heat exchanging surface area for the air heat extraction can be increased by about 92% compared to the reference system. The system is designed to have additional thermal insulation to reduce the heat loss from the air channel duct. The effectiveness of using helical inserts in a PVT system in terms of PV surface temperature, back wall temperature and working fluid outlet temperature are shown in Figs. 5.6 to 5.8.

It can be clearly seen from Fig. 5.6 that, the PV cell temperature of the modified system [T_{pv}(PVT/M-th)], is lower than that of the reference system [T_{pv}(PVT/R-th)], by up to 7°C, at given time of operation. Similar results can be seen in Fig. 5.7, with respect to the back wall temperature, as well. These results confirm that, the provision of inserts in a PVT system influences turbulence in the air flow, resulting in a lower PV cell temperature.

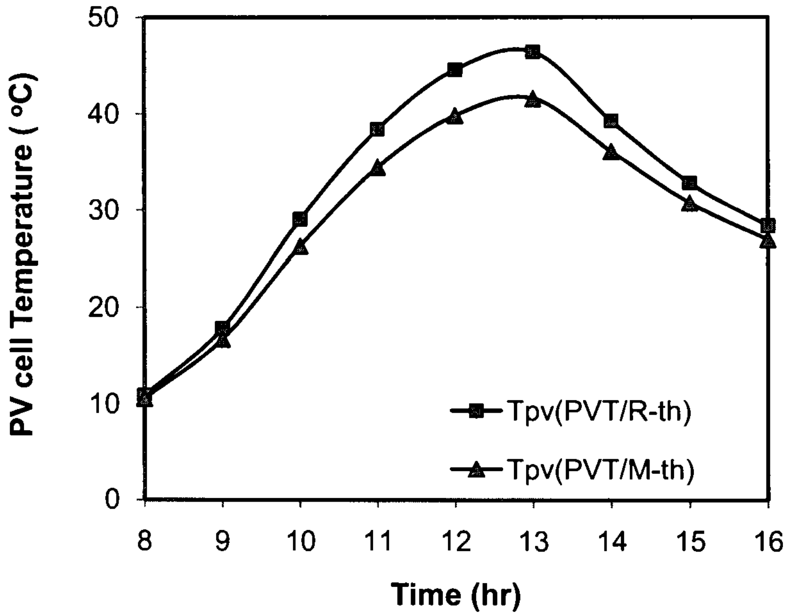


Figure 5.6. Variation of PV cell temperature

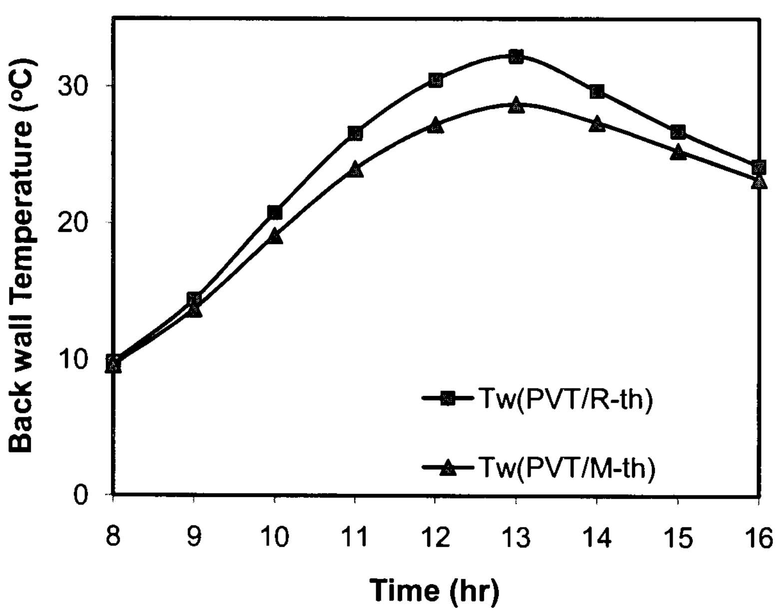


Figure 5.7. Variation of back wall temperature

This has a positive impact on the air outlet temperature (T_{out}) as shown in Fig. 5.8. Hence, the inclusion of inserts not only lowers the required PV panel temperature, but also increases the air outlet temperature because of an increase in heat exchange surface area and turbulence effect.

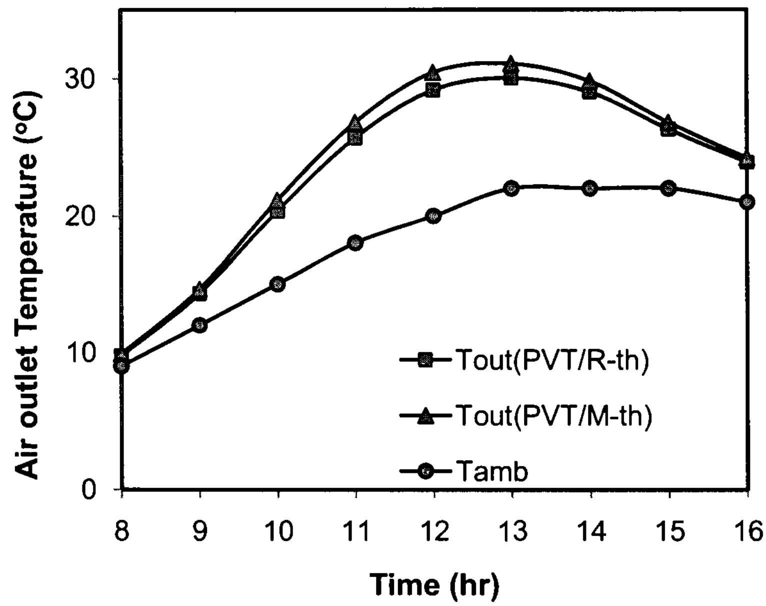


Figure 5.8. Variation of air outlet temperature

5.4. Parametric study

Helical inserts have shown to give promising outcomes in terms of lowering the PV panel temperature as well as the air outlet temperature. Further, to study the effect of various design and operational parameters on the modified system's performance, air-channel depth, mass flow rate, "Helical Insert" twist ratio and number of inserts were varied. These parameters were chosen, since they are important in dictating the performance of a given size of a PVT system under forced flow conditions. For the results of the simulation presented here, the initial conditions are: typical meteorological data corresponding to July 1, 2010, irradiance of 6.5 kWh m^{-2} day^{-1} for the, air speed of 1.5 m s^{-1} and ambient temperature of 20°C. The initial value of the air inlet temperature was set to the same value as that of the ambient temperature. The effectiveness of the parameters were measured in terms of PV surface temperature and the thermal output of the working fluid.

In order to check the impact of channel hydraulics, the dimensions of the air channel duct can be varied. As indicated earlier, in this study, it is intended to utilize the commercially available PV panel, hence the width and the length of the channel cannot be varied and it will have the same dimensions as that of the chosen PV panel. Therefore, only the channel depth is varied simultaneously with the air mass flow rate to identify the optimum values of channel depth and air mass flow rate.

Figure 5.9 shows the effect on air channel depth on the PV panel temperature (T_{pv}) and back wall temperature (T_w), where both the reference system (PVT without insert) and the modified system (PVT with insert) temperatures are increases with an increase in channel depth. This is due to the fact that, with an increase in channel depth, the air velocity reduces resulting in a low heat transfer coefficient. However, the pumping power is generally high for narrow channel depth because of higher pressure drop. It is observed from Fig. 5.9 that beyond channel depth of 0.15 m, the variation in PV surface and back wall temperatures are not significant. Hence, an optimized channel depth value of 0.15 m is selected here.

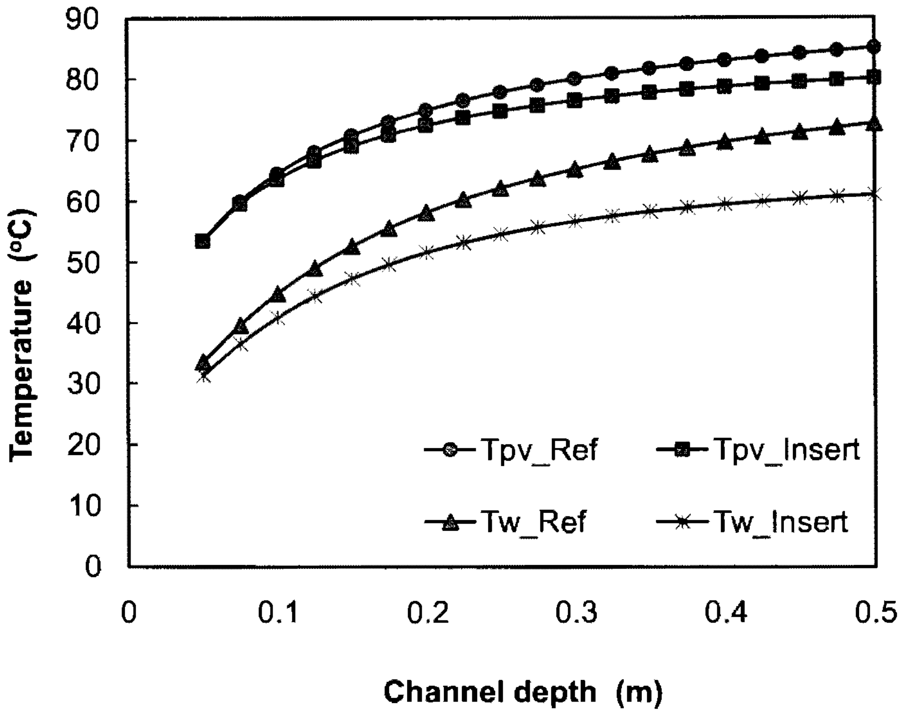


Figure 5.9. Effect of channel depth on the T_{pv} and T_w

Further, it can be seen that PV panel temperature of the modified PVT system (T_{pv}_Insert) is lower than that of the reference system (T_{pv}_Ref) by upto about 7°C. Also, the back wall temperature for the case of modified system is lower by upto about 12°C than the reference system. These results confirm that the inserts could affect turbulence as well as provide additional shading effect to the back wall, resulting in lower back surface temperatures.

The lowering of surface temperatures, in turn influences the air outlet temperature (T_{out}). Hence, as shown in Fig. 5.10, for any given channel depth, the modified system attains a higher air outlet temperature compared to the reference system. This is due to the fact that, for the modified system, with the presence of the helical inserts, the effective heat exchanging surface area is much higher facilitating higher heat extraction by the working fluid.

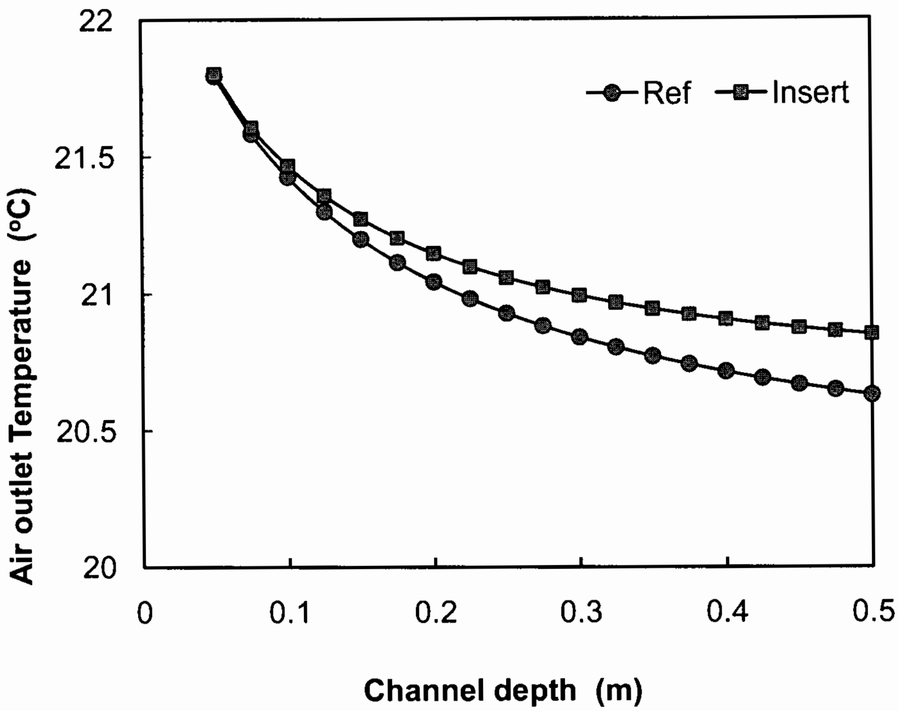


Figure 5.10. Effect of channel depth on the T_{out}

The effect of channel depth on the thermal and electrical efficiencies of the PVT system is illustrated in Fig. 5.11. It is observed that, both thermal and electrical efficiencies reduce with an increase in channel depth. This is because, as the depth increases, the flow velocity reduces resulting in a reduction in thermal efficiency; and also a reduction in electrical efficiency is observed because of prevailing higher PV surface temperatures. One point to note here is (Fig. 5.11) that such a negative impact on the system performance is less pronounced for the modified system compared to the reference system.

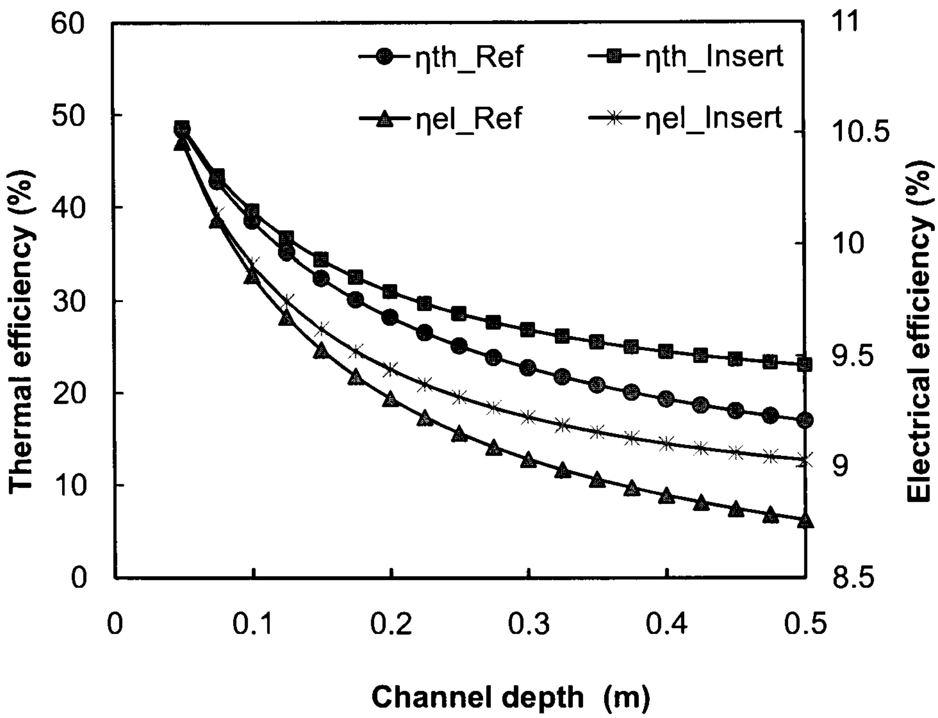


Figure 5.11. Effect of channel depth on thermal (η_{th}) and electrical (η_{el}) efficiency

Figure 5.12 shows the effect of mass flow rate on PV surface temperature (T_{pv}) and back wall temperature (T_w). It can be seen clearly that these temperatures decline with an increase in air mass flow rate, because for the given volume, more air is available to extract the heat from the channel walls, which helps lowering the PV and back wall temperatures. Checking the comparative performance, it can be seen from Fig. 5.12 that, the modified system has lower PV and back wall temperatures compared to the reference system, for any given mass flow rate.

The effects of mass flow rate on the thermal and electrical efficiencies are illustrated in Fig. 5.13. The trend shows that, electrical as well as thermal performance improves rapidly with air mass flow rate until around 0.20 kg s^{-1}. Further increase in mass

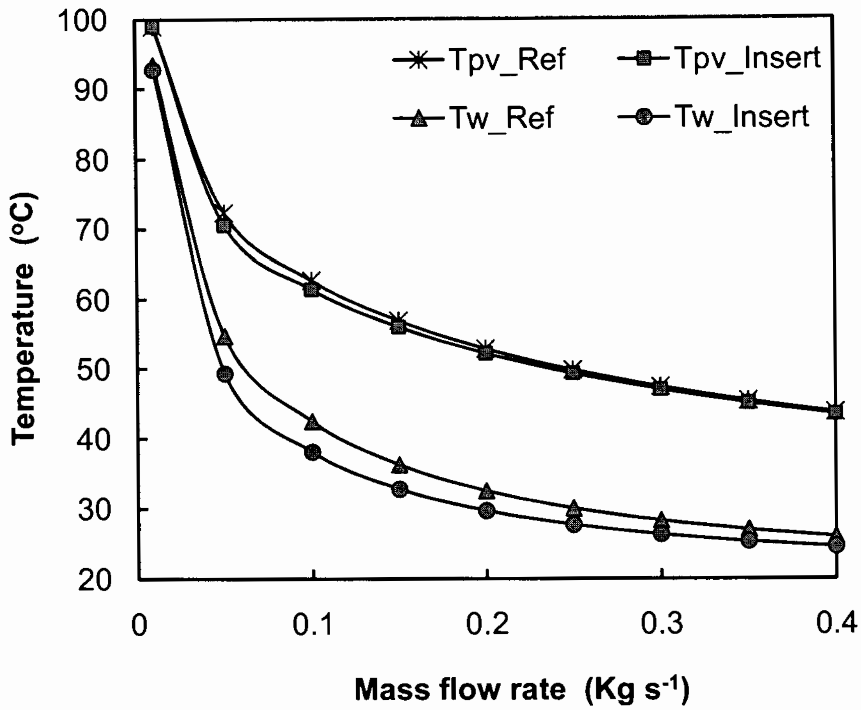


Figure 5.12. Effect of air mass flow rate on T_{pv} and T_w

flow rate does not influence the performance of the system substantially. Also Fig. 5.13 shows the comparative performance of the modified system with that of the reference system. The modified system could only have a marginal improvement in performance compared to the reference system.

The combined effect of air channel depth and air mass flow rate on the PVT system thermal efficiency is shown in Fig. 5.14. It can be found that the trend in thermal efficiency variation is different with air channel depth compared to the air mass flow rate. Also it can be noted that, the combination of low channel depth and high air mass flow rate results in a higher thermal performance. In applications with natural air circulation, a small channel depth reduces air flow which eventually increases the PV cell temperature.

For such systems, a large air channel depth (minimum 0.1 m) is necessary to reduce its impact on the PV cell temperature [38].

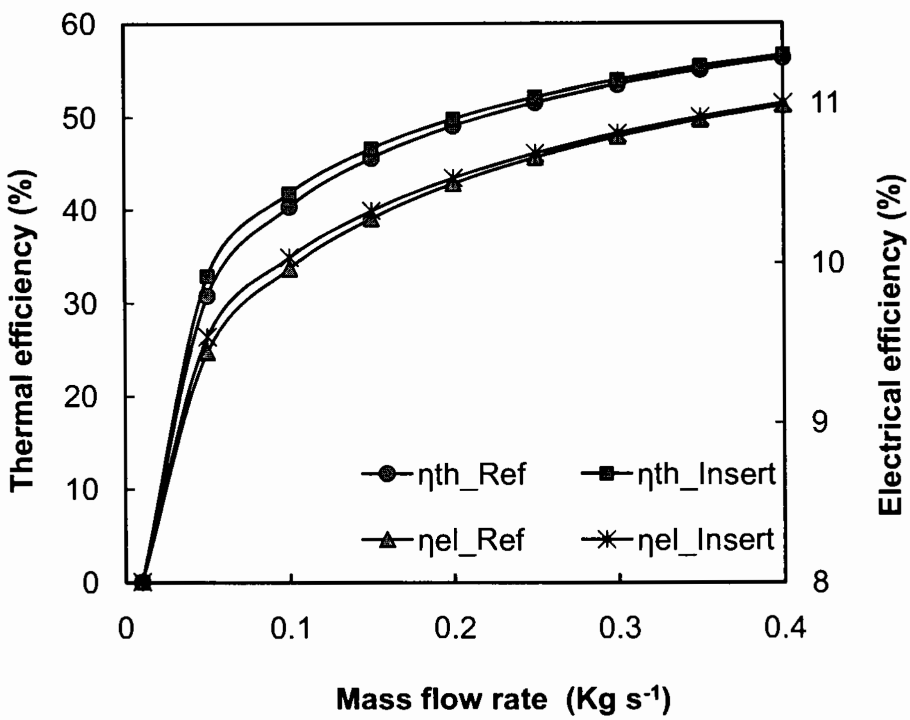


Figure 5.13. Effect of air mass flow rate on thermal (η_{th}) and electrical (η_{el}) efficiency

This combined effect of channel depth and air mass flow rate will especially be a useful data for building integrated photovoltaic (BIPV) systems. Based on this study, an optimized flow rate can be recommended for the chosen depth from the exterior wall of the building being integrated with PV panels. For the proposed system, the optimum channel depth and air mass flow rate turns out to be 0.15 m and 0.2 kg s^{-1}, respectively (Fig. 5.14).

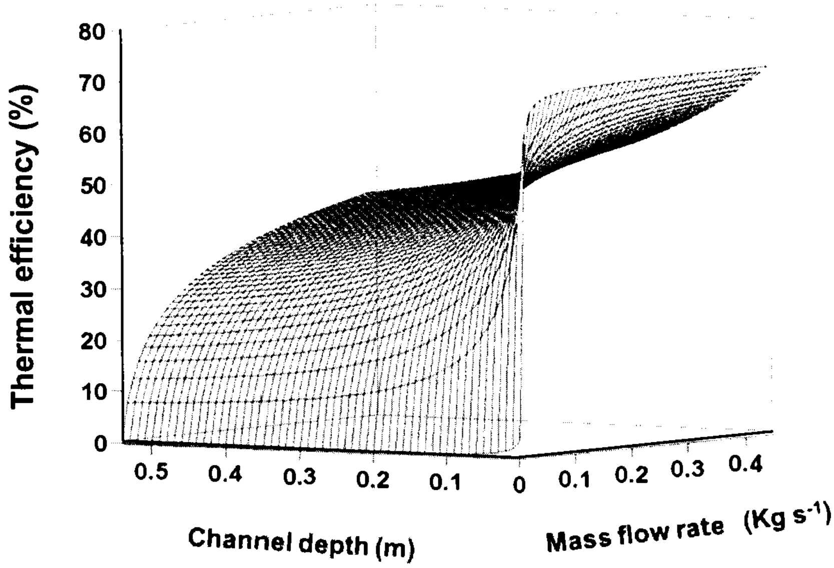


Figure 5.14. Combined effect of the mass flow rate and collector depth on thermal efficiency

Yet another parameter that can influence the system performance is the twist angle of the helical insert. To find its effectiveness on the PVT system's performance, the simulation program was run for various twist angles, keeping the mass flow rate and the channel depth at their optimized values. Figure 5.15 shows the variation in thermal and electrical efficiencies with twist angle.

Twist angles are varied from 20 to 160 degree and it can be seen that, as the twist angle of the insert is reduced, the thermal efficiency improves. This may be due to the fact that, lesser the twist angle, higher would be the helical insert surface area, which positively impacts the heat gain between the insert and the fluid (air) flow. However, it should be pointed out that, lower twist angles result in higher friction factor which in turn results in higher demands for pumping power.

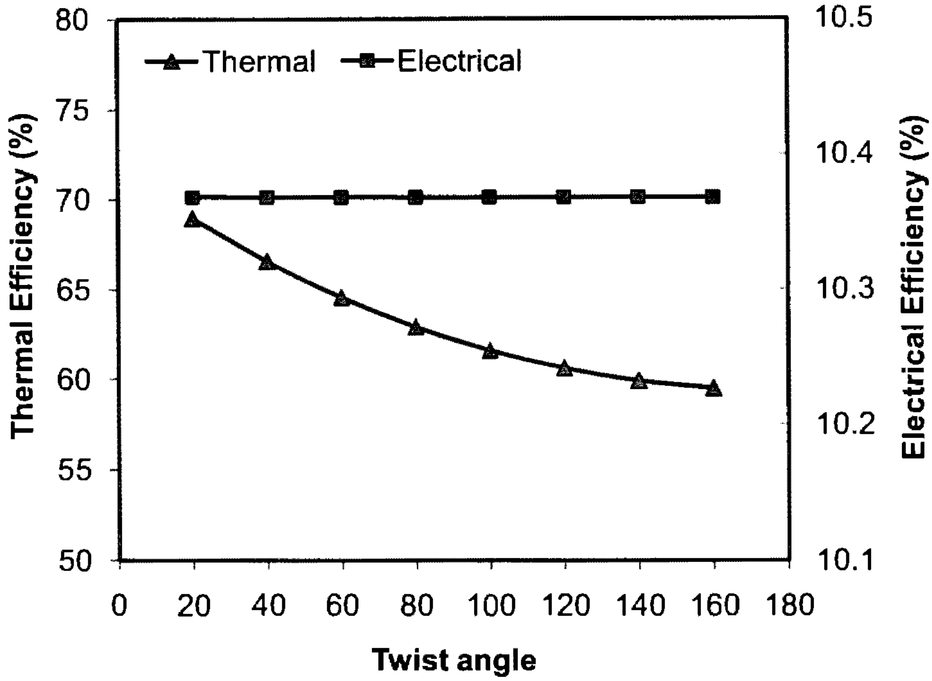


Figure 5.15. Variation of electrical and thermal efficiency with twist angle of insert

It can be seen from Fig. 5.16 that the friction factor values substantially decreases from 0.98 to 0.15 for twist angle 20 to 40 degrees and after that the changes are not much noticeable. Hence, in this study, a twist angle of 40 degree is chosen as the optimized value in order to attain a higher thermal efficiency at the expense of lower friction factor.

Also, shown in the Fig. 5.15 is the effect of twist angle on the electrical efficiency and there exists no significant effect. This is because, an increase in surface area of insert does not contribute much to the reduction in the PV cell temperature; hence only a negligible variation is noticed.

For the optimized twist angle, analysis was carried out to check the influence of the number of inserts on the PV cell temperature for various air mass flow rates.

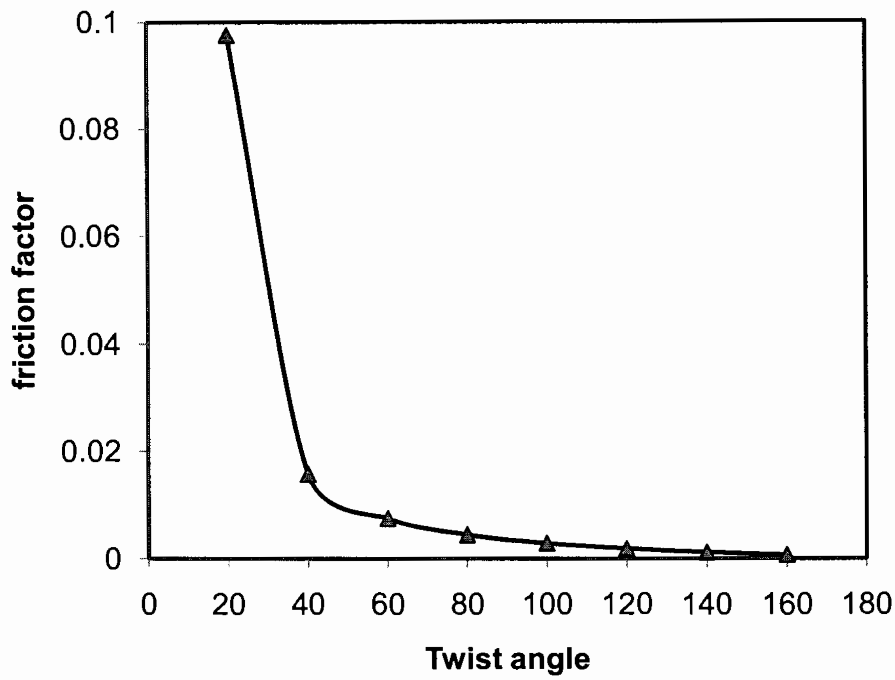


Figure 5.16. Variation of friction factor with twist angle of insert

It can be clearly seen from Fig. 5.17 that, irrespective of the number of inserts, the PV temperature decreases substantially with an increase in air mass flow rate until around 0.2 kg s^{-1}, and thereafter only a marginal decrease is observed. This is because, with an increase in air mass flow rate, more air per unit volume is available to remove the heat from the PV surface area thereby lowering the PV cell temperature. Hence, a mass flow rate of 0.2 kg s^{-1} is reconfirmed to be the optimized value for the proposed system. In this study, for the chosen channel depth and twist angle, the number of inserts can be varied up to a maximum of three. Also shown in the Fig. 5.17 is the effect of the number of inserts on the electrical performance. It can be seen that for a given flow rate, only a marginal decrease (about 4°C) in the PV cell temperature is observed with an increase in the number of inserts, hence only one insert is chosen for the proposed PVT design.

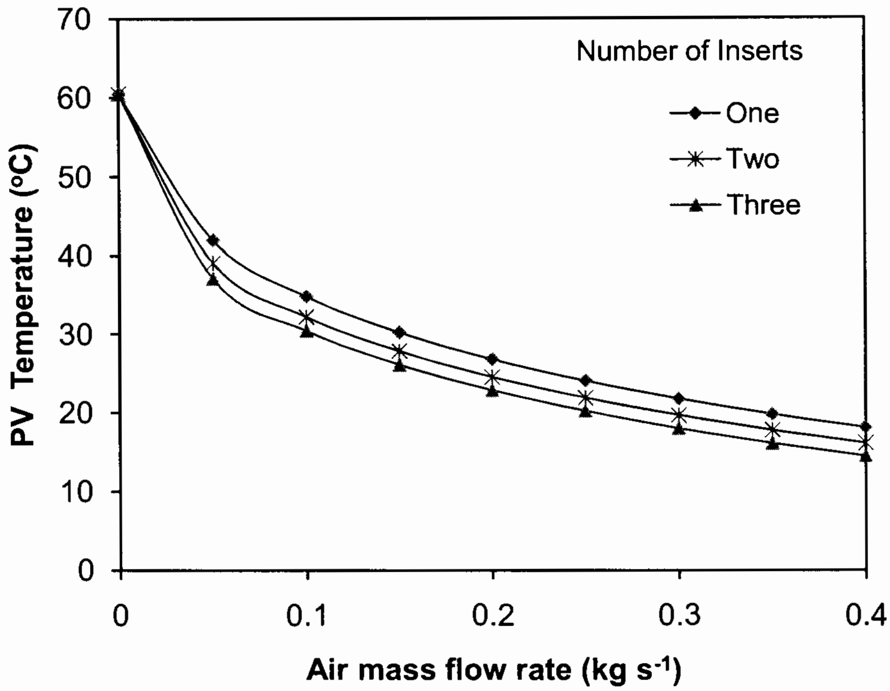


Figure 5.17. Variation of PV cell temperature with air mass flow rate

Further, with the above stated optimum values of channel depth, air mass flow rate, twist angle and number of inserts, simulation was carried out to analyze the hourly performance in terms of thermal (Fig. 5.18) and electrical efficiency (Fig. 5.19) for both the reference (PVT/R) and the modified (PVT/M) PVT systems.

Figure 5.18 shows that, the thermal efficiency ranges between 50 - 67% throughout the day, and the electrical efficiency (Fig. 5.19) ranges between 7-11%, which are higher in the case of modified system compared to the reference PVT system. In summary, the proposed modified system can increase both the thermal and electrical efficiency by about 17% and 2%, respectively.

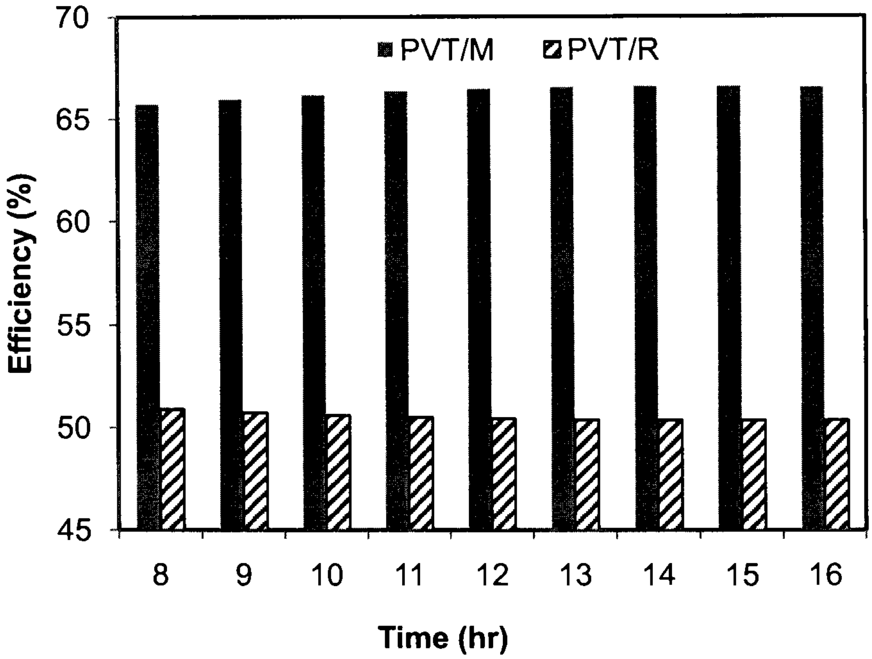


Figure 5.18. Hourly variation of thermal efficiency

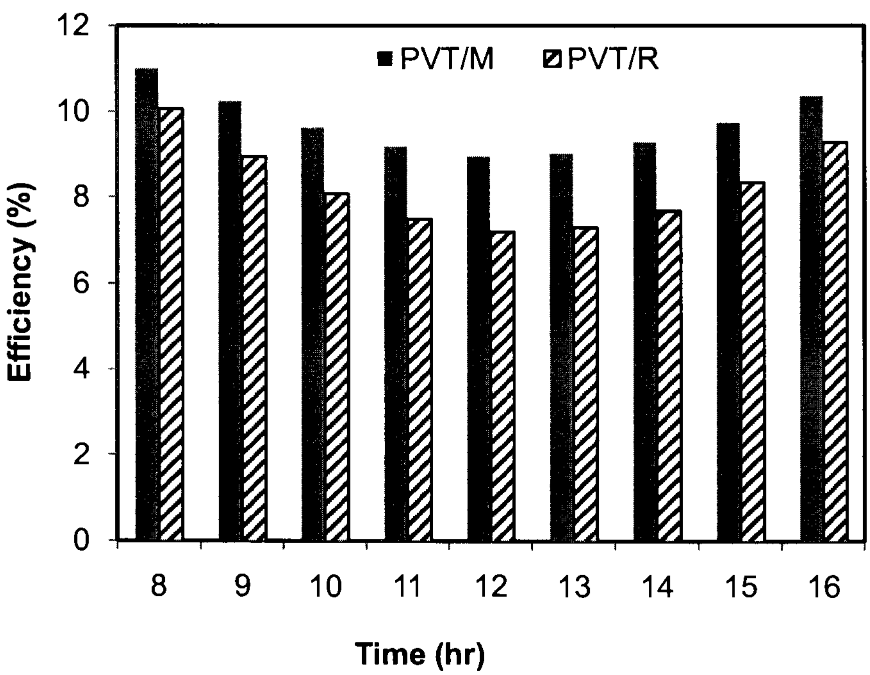


Figure 5.19. Hourly variation of electrical efficiency

In order to analyze the year around performance simulation was carried out, with the respective weather data. For each month, the average values of solar insolation, ambient temperature and wind velocity were input into the simulation to obtain the performance of the modified PVT system. It can be seen from Fig. 5.20 that in general, the thermal efficiency value is higher for the summer season compared to the winter. This is due to the fact that higher solar insolation are registered during summer, for example in Fargo, it receives 6 kWh/m^2.day during summer and 3.5 kWh/m^2.day during winter. These directly influence the thermal efficiency. Further, Fig. 5.21 shows that the electrical efficiency is higher in winter compared to summer. This is due to the fact that, in Fargo although daylight hours between January and June vary significantly, the percentage of possible sunshine hours within any given month remains uniform, around 55% (Fig. 2.1). Moreover, during winter the PV temperature is generally low because of low ambient temperatures. The maximum thermal and electrical efficiencies that can be achieved by using the proposed configuration is about 66.5 % and 13.5 % respectively.

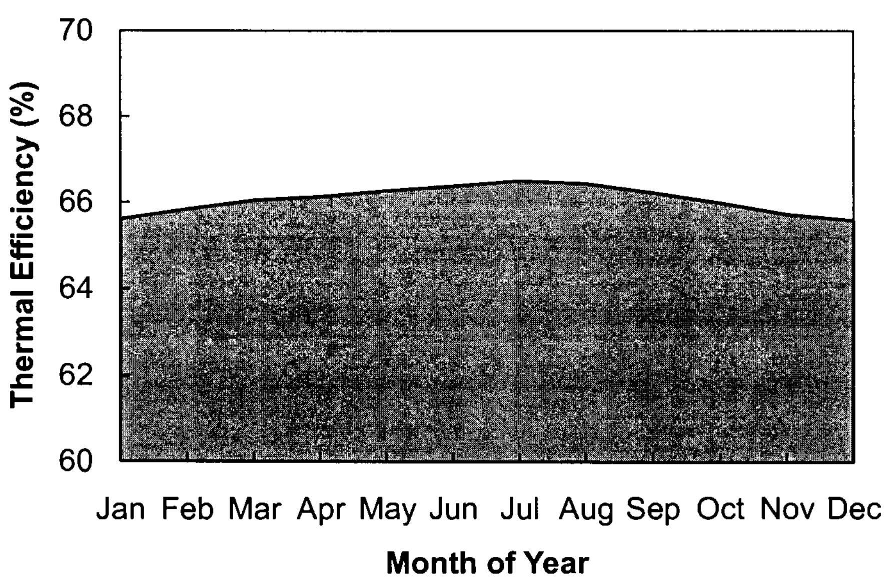


Figure 5.20. Seasonal variations of thermal efficiency

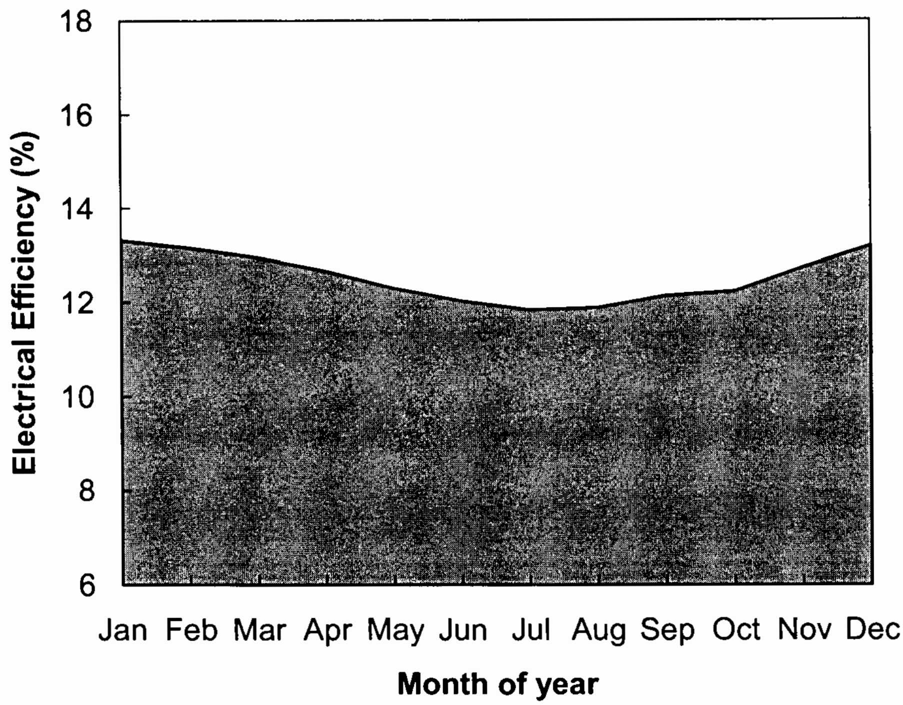


Figure 5.21. Seasonal variations of electrical efficiency

Figure 5.22 shows the power generated by the PV module and power consumed by the air pump during the sunshine hour in the case of a modified PVT system with insert for the optimized channel depth, air mass flow rate, twist angle of insert, and with one insert only. The total electrical power generated by the PV module is about 85.2 kWh/year and the power required for air pump is only 5.96 kwh/year. Hence, the modified PVT system can generate a net power of about 79 kwh/year, indicating clearly the proposed configuration is a self sustained system. Any marginal energy gain will go a long way in improving the economics of such renewable energy system.

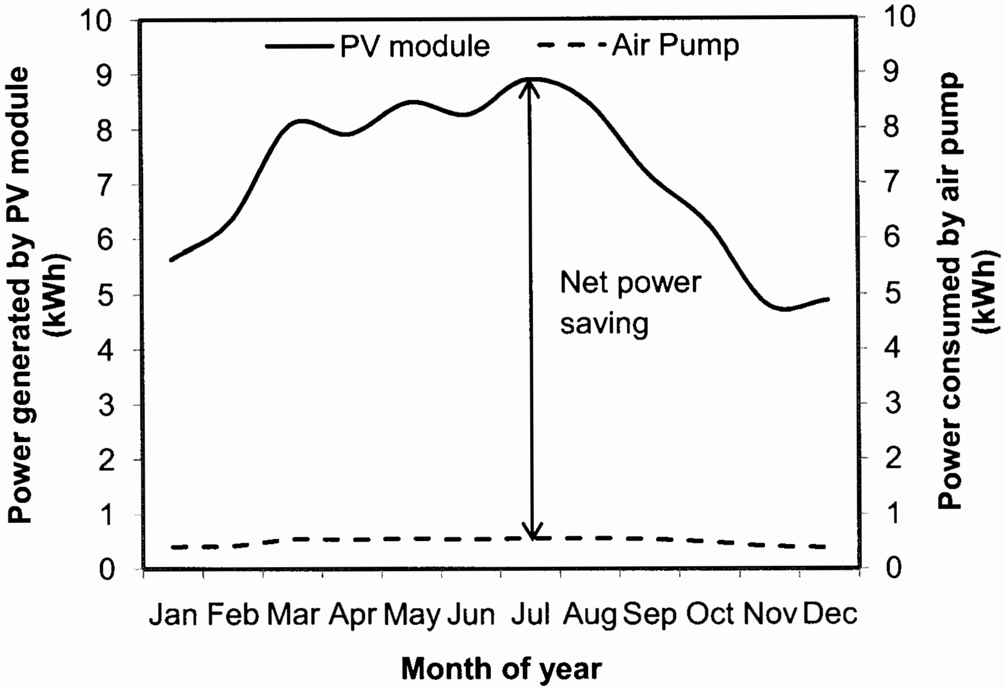


Figure 5.22. seasonal variations of power generated by PV module and power consumed by air pump

5.5. Summary

The model detailed in chapter 3 was validated with experimental data [Tiwari et al.]. Further, using the said model, a comparative study was carried out varying the design and operating parameters. Results show that the modified PVT system performs better towards enhancing the heat extraction from the PV panel for better electrical and thermal power output. Further, the parametric results showed that there exist optimum values for channel depth, air mass flow rate, twist angle and number of inserts at which both thermal and electrical efficiency values were maximum and for the studied system, the optimum values were reported to be 0.15m, 0.2 kg s^{-1}, 40 degree twist angle for the proposed PVT system. Also, it is recommended to use one insert for the proposed size with an intention to have the system to be cost effective.

CHAPTER 6. CONCLUSIONS AND FUTURE RESEARCH

This chapter describes the conclusion of current study as well as future research as a follow up to this investigation.

6.1. Conclusions

The focus of the present study is to theoretically investigate the performance of a modified PVT system provided with inserts. The entire work that has been done can be summarized as follows:

- In order to identify an optimal design of a photovoltaic-thermal (PVT) solar system, a detailed review of literature has been carried out. Investigations that specifically contribute to PVT improvements have also been carried out. Three main modifications are proposed in this study in order to further enhance the performance of the existing PVT module and a new PVT module design is proposed based on these modifications. The modifications include:

  (i) employing an air channel beneath the PV panel which can be applied for a building integration system without compromising the thermal efficiency;

  (ii) eliminating the additional glass or tedlar, provided beneath the PV panel in a conventional PVT system, to effect higher the heat transfer rates between the PV panel and the working fluid;

  (iii) providing an absorber plate ("back wall") at the back surface of the air channel duct, in order to avoid additional thermal load requirement by the building, which is relevant to building integrated PV systems.

- An analytical model has been developed and was used to carry out detailed studies on the newly proposed PVT system. The developed theoretical model could predict the air outlet and the PV module temperatures, which are in good agreement with the experimental values [Tiwari et al.] and hence confirming that the simulated results of the developed analytical model can represent the measured data with a good accuracy.
- The study presents a new concept of using a helical insert as a heat transfer promoter inside the air channel of an air cooled PVT. The helical insert increases the heat transfer surface area hence can enhance the heat transfer by convection to the airflow. This heat extraction enhancement method can simply be equipped in a building envelope (facade or roof). The additional element (insert) is less expensive from the material point of view, because it can be fabricated using locally available low cost materials, and hence can be easily adopted in any application that involves a working fluid as the medium to transport heat.
- To compare the effectiveness of the helical insert, theoretical analysis has been carried out to analyze both configurations, such as the modified system (with insert) as well as the usual (reference) system with no insert.
- The use of insert in the air channel presents superior results with regard to thermal power, electrical power, and better PV surface cooling compared to the reference system. Apart from ensuring better performance, the modified system with insert also presents better shielding to the building structure from undesirable overheating.

- The parametric studies have given more insight into the effect of various design and operational parameters in terms of thermal efficiencies and PV surface and air outlet temperatures. The results show that a combination of low channel depth and high fluid flow rate results in higher electrical efficiency and higher thermal output. The maximum thermal and electrical efficiencies that can be achieved by using the modified PVT system is about 66.5 % and 13.5 % respectively, which are higher than the ones for the reference system. Further, this increased electrical efficiency compensates the additional pumping power required in operating the modified system. Also, along with the improved electrical efficiency, an increase in the thermal efficiency makes the modified system cost effective in terms of energy production and operation.
- The heat produced by this system, can be channeled through proper ducting system into the building for space heating or any other low temperature applications.
- In order to identify the year-round performance of the modified system, simulation was carried out for different seasons. Obviously, the solar gain varies with different seasons, and therefore the thermal and electrical efficiencies change accordingly. In Fargo, sunshine is abundant, and although the length of daylight between January and June varies significantly, the percentage of possible sunshine hours within any given month remains uniform. The simulation results show that the system is more efficient during summer (because of high solar intensities) in terms of thermal efficiency and performs better during winter in terms of electrical efficiency (low ambient temperature).

6.2. Future research

This study comprises attaching an air-channel beneath the PV panel to make it as an air cooled PVT system and also a heat extraction device is placed in the air-channel. The feasibility of the PVT system will be dependent upon its technical and economical competitiveness with respect to other alternatives. Future potential research in the said field includes:

- Technical feasibility of this system must be confirmed by carrying out experimental studies and must be evaluated by comparing the electrical module efficiency and thermodynamic efficiency of such systems with those of the conventional ones.
- The economical feasibility (energy metric analysis) of the study can be carried out by balancing the capital cost of the solar system against the saving in conventional fuel costs. As the economic feasibility is heavily dependent on the financial parameters based on some assumptions (e.g. the inflation rate of conventional fuel costs), it is certain that the viability of such solar systems will be more pronounced when the environmental costs of conventional electricity production are factored in.
- Design and analysis of a PVT system with dual heat extraction, providing heated air and water at the same time can be attempted.
- Literature shows, PVT collectors can be combined with low, medium or high concentration devices. Though the focus of the present study was on low temperature output, there exists lots of scope for high concentration devices as well. A part of the expensive PV area is replaced by an inexpensive mirror area in a

concentration system, which will be a promising way to reduce the payback period.

- For PVT type air collectors, attention should be paid to improve the thermal contact between the PV and the thermal absorber. This problem can be solved by applying thin adhesive layers that have sufficiently high thermal conduction. It is also important to reduce the thermal losses, one way to achieve which is to use double layers of highly transparent glazing that improves the thermal insulation. Hence, there exist several areas of PVT which require further research and development efforts.

REFERENCES

[1] A dazzling future for solar power? – CNN.Com, http://www.cnn.com/2010/TECH/05/12/solar.energy.iea.report/index.html

[2] IEA Solar Heating and Cooling Programme, 2007.

[3] Tiwari A, Sodha MS, Chandra A, Joshi JC, "Performance evaluation of photovoltaic thermal solar air collector for composite climate of India," *Solar Energy Materials and Solar Cells* 2006;90(2):175-89.

[4] http://www.rssweather.com/climate/North%20Dakota/Fargo/

[5] Zondag H, Bakker M, van Helden WGJ, Affolter P, Eisenmann W, Fechner H, et al, "PVT Roadmap: A European guide for the development and market introduction of PVT technology," *Proceedings of (CD) 20th European Photovoltaic Solar Energy Conference*, 6-10 June 2005, Barcelona, Spain.

[6] Prakash J, "Transient analysis of a photovoltaic-thermal solar collector for co-generation of electricity and hot air/water," *Energy Conversion and Management* 1994;35:967-72.

[7] Huang BJ, Lin TH, Hung WC, Sun FS, "Performance evaluation of solar photovoltaic/thermal systems," *Solar Energy* 2001;70(5):443-8.

[8] Tiwari A, Sodha MS, "Performance evaluation of hybrid PV/thermal water/air heating system: a parametric study," *Renewable Energy* 2006;31(15):2460-74.

[9] Zondag HA, de Vries DW, van Helden WGJ, van Zolengen RJC, Steenhoven AA, "The thermal and electrical yield of a PV thermal collector," *Solar Energy* 2002;72(2):113-28.

[10] Chow TT, "Performance analysis of photovoltaic-thermal collector by explicit dynamic model," *Solar Energy* 2003;75:143-52.

[11] Chow TT, He W, Ji J, "Hybrid photovoltaic-thermosyphon water heating system for residential application," *Solar Energy* 2006;80:298-306.

[12] Kalogirou SA, "Use of TRYNSYS for modeling and simulation of a hybrid PV-thermal solar system for Cyprus," *Renewable Energy* 2001;23:247-60.

[13] Tiwari A, Sodha MS, "Performance evaluation of solar PV/T system: an experimental validation," *Solar Energy* 2006;80(7):751-9.

[14] Bergene T, Lovvik OM, "Model calculations on a flat-plate solar heat collector with integrated solar cells," *Solar Energy* 1995;55:453-62.

[15] Zondag HA, de Vries DW, van Helden WGJ, van Zolengen RJC, Steenhoven AA, "The yield of different combined PV-thermal collector designs," *Solar Energy* 2003;74(3):253-69.

[16] Dubey S, Tiwari GN, "Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater," *Solar Energy* 2008;82:602-12.

[17] Erdil E, Ilkan M, Egelioglu F, "An experimental study on energy generation with a photovoltaic (PV)-solar thermal hybrid system," *Energy* 2008;33:1241-5.

[18] Chow TT, Chan ALS, Fong KF, Lin Z, He W, Ji J, "Energy and exergy analysis of photovoltaic-thermal collector with and without glass cover," *Applied Energy* 2009;86(3):310-6.

[19] Eicker U, "Solar Technologies of Buildings," New York, John Wiley & Sons, Inc; 2003.

[20] Moshfegh B, Sandberg M, "Flow and heat transfer in the air gap behind photovoltaic panels," *Renewable and Sustainable Energy Reviews* 1998;2:287-301.

[21] Sandberg M, Moshfegh B, "Buoyancy-induced air flow in photovoltaic facades: effect of geometry of the air gap and location of solar cell modules," *Building and Environment* 2002;37:211-8.

[22] Naphon P, "On the performance and entropy generation of the double-pass solar air heater with longitudinal fins," *Renewable Energy* 2005;30:1345-57.

[23] Garg HP, Agarwal RK, Joshi JC, "Experimental study on a hybrid photovoltaic thermal solar water heater and its performance prediction," *Energy Conversion and Management* 1994;35:621-33.

[24] Tripanagnostopoulos Y, Souliotis M, Battisti R, Corrado A, "Performance, cost and Life-cycle assessment study of hybrid PVT/AIR solar systems," *Progress in Photovoltaics: Research and Applications* 2006;14:65-76.

[25] Brinkworth BJ, Sandberg M, "Design procedure for cooling ducts to minimize efficiency loss due to temperature rise in PV arrays," *Solar Energy* 2006;80:89-103.

[26] Benemann J, Chehab O, Schaar-Gabriel E, "Building-integrated PV modules," *Solar Energy Materials and Solar Cells* 2001;67:345-54.

[27] Hodge E, Gibbons C, "Convective cooling of photovoltaics," *In: ISES Euro sun*, Freiburg, 2004.

[28] Pottler K, Sippel CM, Beck A, Fricke J, "Optimized finned absorber geometries for solar air heating collectors," *Solar Energy* 1999;67:35-52.

[29] Tiggelbeck St, Mitra NK, Fiebig M, "Experimental Investigations of Heat Transfer Enhancement and Flow Losses in a Channel with Double Rows of Longitudinal Vortex Generators," *Int. Journal of Heat and Mass Transfer* 1993;26(9):2327-37.

[30] Tonui JK, Tripanagnostopoulos Y, "Improved PV/T solar collectors with heat extraction by forced or natural air circulation," *Renewable Energy* 2007;32:623-37.

[31] Tripanagnostopoulos Y, "Aspects and improvements of hybrid photovoltaic/thermal solar energy systems," *Solar Energy* 2007;81:1117-31.

[32] Hastings SR, Morck O, Solar air systems, a design handbook, James & James, London 2000.

[33] Kern EC, Russell MC, "Combined photovoltaic and thermal hybrid collector systems," In: *13th IEEE Photovoltaic Specialists*, Washington DC, USA; 1978. p.1153-7.

[34] Hendrie SD, "Evaluation of combined photovoltaic/thermal collectors," *ISES International Congress and Silver Jubilee*, Atlanta, GA, 28 May-1 June 1979;3:1865-9.

[35] Florschuetz LW, "Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors," *Solar Energy* 1979;22:361-6.

[36] Raghuraman P, "Analytical prediction of liquid and air photovoltaic/thermal flat-plate collectors performance," *Transactions of the ASME Journal of Solar Energy Engineering* 1981;103:291-8.

[37] Cox CH, Raghuraman P, "Design considerations for flat-plate photovoltaic/thermal collectors," *Solar Energy* 1985;35:227-41.

[38] Bhargava AK, Garg HP, Agarwal RK, "Study of a hybrid solar system- solar air heater combined with solar cell," *Energy Conversion and Management* 1991;31(5):471-9.

[39] Sopian K, Yigit KS, Liu HT, Kakac S, Veziroglu TN, "Performance analysis of photovoltaic thermal air heaters," *Energy Conversion and Management* 1996;37:1657-70.

[40] Ricaud A, Roubeau P, "Capthel, a 66% efficient hybrid solar module and the Ecothel co-generation solar system," *Proceedings of IEEE First World Conference on Photovoltaic Energy Conversion*, Waikoloa, Hawaii; 1994. p. 1012-5.

[41] Yang HX, Marshall GH, Brinkworth BJ, "An experimental study of the thermal regulation of a PV-clad building roof," *Proceedings of 12th European Photovoltaic solar energy conference,* Amsterdam, The Netherlands; 11-15 April 1994. p. 1115-8.

[42] Posnansky M, Gnos S, Coonen S, "The importance of hybrid PV Building integration," *Proceedings of first world conference on Photovoltaic energy conversion*, Hawaii; 5-9 December 1994. p. 998-1003.

[43] Ossenbrink HA, Rigolini Chehab O, Olaf van der Vebbe, "Building integration of an amorphous silicon photovoltaic façade," *Proceedings of IEEE 1st World Conference on PV energy conversion*, Hawaii; 5-9 December 1994. p. 770-3.

[44] Moshfegh B, Sandberg M, Bloem JJ, Ossenbrink H, "Analysis of fluid flow and heat transfer within the photovoltaic facade on the ELSA building," *Proceedings of JRC ISPRA 13th European PV Solar Energy Conference* Nice; 23-27 October 1995.

[45] Brinkworth BJ, Cross BM, Marshall RH, Hongxing Yang, "Thermal regulation of photovoltaic cladding," *Solar Energy* 1997;61:169-78.

[46] Brinkworth BJ, "Estimation of flow and heat transfer for the design of PV cooling ducts," *Solar Energy* 2000;69:320-413.

[47] Brinkworth BJ, Marshall RH, Ibarahim Z, "A validated model of naturally ventilated PV cladding," *Solar Energy* 2000;69:67–81.

[48] Krauter S, Arauja RG, Schroer S, Hanitsh R, Salhi MJ, Triebel C, et al, "Combined photovoltaic and solar thermal systems for facade integration and building insulation," *Solar Energy* 1999;67: 239-48.

[49] Eicker U, Fux V, Infield D, Mei Li, "Heating and cooling of combined PV-solar air collectors facades," *Proceedings of International Conference of 16th European PV solar energy,* Glasgow, UK; 1-5 May 2000. p. 1836-9.

[50] Bazilian M, Leeders F, van der Ree BGC, Prasad D, "Photovoltaic cogeneration in the built environment," *Solar Energy* 2001;71:57-69.

[51] Hegazy AA, "Comparative study of the performance of four photovoltaic/thermal solar air collectors," *Energy Conversion and Management* 2000;41:861-81.

[52] Lee WM, Infield DG, Gottschalg R, "Thermal modeling of building integrated PV systems," *Proceedings of 17th PV Solar Energy Conference*. Munich; 22-26 October 2001. p. 2754-7.

[53] Chow TT, Hand JW, Strachan PA, "Building-integrated photovoltaic and thermal applications in a subtropical hotel building," *Applied Thermal Engineering* 2003;23: 2035-49.

[54] Ito S, Miura N, "Usage of a DC fan together with photovoltaic modules in a solar air heating system," *Proceedings of (CD-ROM) ISES World Congress*, 14-19 June 2003, Goteborg, Sweden.

[55] Cartmell BP, Shankland NJ, Fiala D, Hanby V, "A multioperational ventilated photovoltaic and solar air collector: Application, simulation and initial monitoring feedback," *Solar Energy* 2004;76:45-53.

[56] Infield D, Mei Li, Eicker U, "Thermal performance estimation for ventilated PV facades," *Solar Energy* 2004;76:93-8.

[57] Guiavarch A, Peuportier B, "Photovoltaic collectors efficiency according to their integration in buildings," *Solar Energy* 2006;80:65-77.

[58] Charron R, Athienitis AK, "Optimization of the performance of double-facades with integrated photovoltaic panels and motorized blinds," *Solar Energy* 2006;80:482-91.

[59] Elazari A, "Multi Solar System-Solar multimodule for electrical and hot water supply for residentially building," *Proceedings of 2nd World Conference on Photovoltaic Solar Energy Conversion*, Vienna, Austria; 6-10 July 1998. p. 2430-3.

[60] Charalambous PG, Maidment GG, Kalogirou SA, Yiakoumetti K, "Photovoltaic thermal (PV/T) collectors: a review," *Applied Thermal Engineering* 2007;27: 275-86.

[61] Battisti R, Corrado A, "Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology," *Energy* 2005;30:952-67.

[62] Butera F, Aste N, Adhikari RS and Bracco R, "Ecomensa project at CRF: Performance of solar façade," *Proceedings 600 Congresso Nazionale ATI*, Rome 2005.

[63] Jones AD, Underwood CP, "A thermal model for photovoltaic systems," *Solar Energy* 2001;70(4):349-59.

[64] Schott T, "Operational temperatures of PV modules," *In 6th PV Solar Energy Conference* 1985. p. 392-6.

[65] Bergene T, Lovvik OM, "Model calculations on a flat plate solar heat collector with integrated solar cells," *Solar Energy* 1995:55(6):453-62.

[66] Othman MYH, Yatim B, Sopian K, Bakar MNA, "Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector with CPC and fins," *Renewable Energy* 2005;30:2005-17.

[67] Sandnes B, Rekstad J, "A photovoltaic/thermal (PV/T) collector with a polymer absorber plate," Experimental study and analytical model. *Solar Energy* 2002;72(1):63-73.

[68] Joshi AS, Tiwari A, "Energy and exergy efficiencies of a hybrid photovoltaic thermal (PV/T) air collector," *Renewable Energy* 2007;32(13):2223-41.

[69] Bosanac M, Sorensen B, Ivan K, Sorensen H, Bruno N, Jamal B, "Photovoltaic/thermal solar collectors and their potential in Denmark," *Final Report, EFP Project*, 2003;1713/00-0014. Link: www.solenergi.dk/rapporter/pvtpotentialindenmark.pdf.

[70] Dubey S, Sandhu GS, Tiwari GN, "Analytical expression for electrical efficiency of PV/T hybrid air collector," *Applied Energy* 2009;86:697-705.

[71] Dubey S, Tiwari GN, "Analysis of PV/T flat plate water collectors connected in series," *Solar energy* 2009;83:1485-98.

[72] Joshi AS, Dincer I, Reddy BV, "Thermodynamic assessment of photovoltaic systems," *Solar Energy* 2009;83(8):1139-49.

[73] Garg HP, Adhikari RS, "Conventional hybrid photovoltaic/thermal (PV/T) air heating collector: steady-state simulation," *Renewable Energy* 1997;11:363-85.

[74] Ji J, Chow TT, Pei G, He W, He H, "Performance analysis of a photovoltaic heat pump," *Applied Energy* 2008;85:680-93.

[75] Kalogirou SA, Tripanagnostopoulos Y, "Hybrid PV/T solar systems for domestic hot water and electricity production," *Energy Conversion and Management* 2006;47:3368-82.

[76] He W, Chow TT, Lu J, Pei G, Chan L, "Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water," *Applied Energy* 2006;83: 199-210.

[77] Robles-Ocampo B, Ruiz-Vasquez E, Canseco-Sanchez H, Cornejo-Meza RC, Trapaga-Martınez G, Garcia-Rodriguez FJ, et al, "Photovoltaic/thermal solar hybrid system with bifacial PV module and transparent plane collector," *Solar Energy Materials and Solar Cells* 2007;91(20):1966-71.

[78] Tripanagnostopoulos Y, Nousia TH, Souliotis M, "Low cost improvements to building integrated air cooled hybrid PV-Thermal systems," *Proceedings of 16th European PV Solar Energy Conference*, Glasgow, UK, 1-5 May 2000;2:1874-99.

[79] Tripanagnostopoulos Y, Tzavellas D, Zoulia I, Chortatou M, "Hybrid PV/T systems with dual heat extraction operation," *Proceedings of the 17th PV solar energy conference*, Munich; 22-26 October 2001. p. 2515-8.

[80] Tripanagnostopoulos Y, Nousia TH, Souliotis M, "Test results of air cooled modified PV modules," *Proceedings 17th PV Solar Energy Conference* Munich, Germany; 22-26 October 2001. p. 2519-22.

[81] Choudhury C, Garg HP, "Performance of air-heating collector with packed airflow passage," *Solar Energy* 1993;50:205-21.

[82] Tiwari A, Sodha MS, "Parametric study of various configurations of hybrid PV/thermal air collector: Experimental validation of theoretical model," *Solar Energy Materials & Solar Cells* 2007;91:17-28.

[83] Bakker M, Zondag HA, van Helden WGJ, "Design of a dual flow photovoltaic/ thermal panel," *Proceedings of PV* in Europe, Rome 2002. p. 349-59.

[84] Soteris K, "The potential of solar industrial process heat applications," *Applied Energy* 2003;76(4):337–61.

[85] Joshi AS, Tiwari A, Tiwari GN, Dincer I, Reddy BV, "Performance evaluation of a hybrid photovoltaic thermal (PV/T) (glass-to-glass) system," *International Journal of Thermal Sciences* 2009;48:154-64.

[86] Tonui JK, Tripanagnostopoulos Y, "Air cooled PV/T solar collectors with low cost performance improvements," *Solar Energy* 2007;81:498-511.

[87] van Helden WGJ, van Zolingen RJC, Zondag HA, "PV Thermal Systems: PV Panels Supplying Renewable Electricity and Heat," *Progress in Photovoltaics: Research and Application* 2004;12:415-26.

[88] Tonui JK, Tripanagnostopoulos Y, "Air cooled PV/T solar collectors with low cost performance improvements," *Solar Energy* 2007;81:498-511.

[89] Tonui JK, Tripanagnostopoulos Y, "Performance improvement of PV/T solar collectors with natural air flow operation," *Solar Energy* 2008;82:1-12.

[90] Evans DL. "Simplified method for predicting PV array output." *Solar Energy* 1981;27:555-60.

[91] Buchberg H, Catton I, Edwards DK, "Natural convention in enclosed Space: A Review of Application to Solar Energy Collection," *ASME J. of Heat Transfer* 1976; 98(2): 182-8.

[92] Solar Energy: Fundamentals, Design, Modeling and Applications, G.N. Tiwari, CRC Press Inc, 2002, India.

[93] Heaton HS, Reynolds WC, Kays WM, "Heat transfer in annular passage. Simultaneous development of velocity and temperature fields in laminar flow," *Int J Heat Mass Transfer* 1964; 7: 763-81.

[94] Tan HM, Charters WWS, "Effect of thermal entrance region on turbulent forced-convective heat transfer for an asymmetrically rectangular duct with uniform heat flux," *Solar Energy* 1969; 12: 513-6.

[95] Duffie JA, Beckman WA, Solar Engineering of Thermal Processes, 3rd ed. John Wiley & Sons, Inc; 2006, p. 747-75.

[96] Smithberg E, Landies F, "Friction and forced convection heat transfer characteristics in tubes with twisted tape swirl generators," *Journal of Heat Transfer, Transactions of ASME* 1964; 86: 39-49.

[97] Date AS, Singham JR, "Numerical prediction of friction and heat transfer characteristics of fully developed laminar flow in tubes containing twisted tapes," *Transactions of ASME*, 1972.

PUBLICATIONS

1. M. Arif Hasan, K. Sumathy, "Photovoltaic Thermal Module Concepts and their Performance Analysis: A Review," *J. of Renewable and Sustainable Energy Reviews*, 2010. (In press)

2. M. Arif Hasan, K. Sumathy, "Performance Analysis of a Modified Air Cooled PV Module: Experimental Validation of Theoretical model," *Int. J. of Green Energy*, 2010 (submitted on March 23rd).

3. M. Arif Hasan, K. Sumathy, "Effect of Seasonal Variation on the Performance of a PV/T Solar Collector with Helical Inserts," *Proc. of Int. Conference on Emerging Trends in Energy and Environment (ICETEE)*, Chennai, India, Jan 7-8, 2010.

4. M. Arif Hasan, K. Sumathy, "Performance Improvement of Photovoltaic Thermal Solar Collectors with Helical Tape Inserts," *Proc. of Photovoltaics World Conference 2010*, Austin, Texas, USA, February 23-25, 2010. (Orally presented).