**Research Article**

# Mathematical modeling of semitransparent photovoltaicthermal (SPVT) system with different packing factors: An experimental validation

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**ABSTRACT**

Solar energy is guided by mix mode photovoltaic cell (PV)having thermal effect not only take a part of electricity generation, besides other fundamental approach is to control the rise in temperature of the cell. Our main priority of this type of configuration of cell is for electricity generation. Other aspect of controlling temperature of the cell, fluid is used which carries away excessive gain in temperature. In this paper air as fluid is used that pull out undue amount of heat from the cell module. As the temperature regulated there is very favourable chance of efficiency (electrical) shoots up.

In this article, four different experimental set up of mix mode has taken in which a duct made of wood having dimensions 0.86 m × 0.63 m × 0.05 m fixed along with the module in which 10 W capacity DC fan is also incorporated for the circulation of air. Various observations deduce from this paper that case-III has the highest efficiency am on g ot he r ca se s. On comparing efficiencies with different cases. Case-III gain of 0.7% more as compared to Case-II where as it is 1.7% more gain than case-I.

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## INTRODUCTION

A Photovoltaic (PV) module which is basically a device which directly converts sun light in the form of radiations into electrical energy. This effect is called photovoltaic effect. In Solar cells amazing facts are that around 80% radiations falling into it does not totally convert into electrical energy. There are two effects of these radiations, few are just get reflected and other escalates the thermal effect

of the PV module that depicts lessen of efficiency which is from the electrical perspective. For the maximum advantage of the module, we need to increase the efficiency. The best way to escalates the efficiency of solar PV assembly is to use blended mode PV assembly, which not only regulate the electrical energy but also thermal one. In this perspective Kern et al. [1] analysed and indicated the effect of blended system, which reduces the backup energy requirements in low rise buildings that are having substantially high heating loads. In the hybrid system Hendrie [2] indicated the unique effect of the electric production on the flow of air and liquid through solar collectors. The quality and efficacy of blended mode in terms of efficiencies that regulate the thermal effect reduces from 45.2% to 40.4% in liquid flow and 40% to 32.9% during air flow. The computer simulation on already exist Hotell-whiller Model has been done between the separate thermal and photovoltaic collector with that of blended or hybrid one Florchuetz [3]. For escalating the combined efficiency of thermal and electrical of hybrid PV assembly and makes it viable Raghuraman[4] author has analysed and predicted there from the design recommendations for flat plate photovoltaic thermal is to increase the net energy taken from the hybrid system. Wilshaw et al. [5] Solar cells operating temperature a vital role in efficiency of hybrid system. Authors depict the final resulting expression for the operating temperature, which is nonlinear to the convective and radiative terms. Schott [6] Author analysed the placing of the solar panel at $60^0$ tilted plane south direction orientated than any other plane configuration. The climatic parameters effect the modelling of any hybrid PV system. The effect of irradiance is very less under clear and overcast sky. Author suggested to a dynamic model is required to study the variation of irradiance. Thermal energy sweeping through aluminium absorber and copper tubes photovoltaic collector was discussed by Chow [7]. Author analysed sudden change in energy which flows across various parameters of collectors and deduce every instant of energy output under the condition that water flows at 0.005Kg/s per tube. Hybrid Solar panel uses water or air to sweep thermal energy and increase electrical energy. This can be achieved also solar heat collector (SHC) which is placed above the solar panel and designed area is higher than solar panel, that makes an increase in 10% of energy Zakharchenko et al. [8]. To detect the parameters of PV assembly like temperature which is affected by flowing of water through i-*şt, has been communicated by Tiwari, [9]. Author made a prototype of ophotovoltaic solar panel in associated with thermal system, from here daily thermal efficiency found 58% very precise to experimental work efficiency of 61.3%. Solar energy conversion at low temperature and high temperature was analysed by Vorobiev[10]. In these two options were discussed that includes concentrator, photovoltaic cell, high temperature stage and solar tracking system. Author analysed result and depicts novice thermo electric devices which escalates the efficiency of

photovoltaic module. Photovoltaic Thermal module from onset to till date many steps have been taken from development of standards for high degree of accuracy and capability measurements to non-technical issues like certification, subsidiary, awareness and trainings etc, which are reviewed by Zondag [11] also advancements in various applications of hybrid PVT modules as heating through solar assemblies, pure and fresh water after removing salt content from it, green house through solar assemblies, purification of water through evaporating the impurities and power co – generation through solar assemblies are reviewed Tiwari et al [12], Tyagi et al.[13] Several researches are trying to improve the efficiency of PVT module with different configurations and materials used in module. The competitive factor depends upon how the heat transfer occurs, its practical usability, it's importance in day-to-day applications and also the future prospects. Michael et al. [14]. Dubey et al. [15] The application of thermal photovoltaic system or hybrid module in rural areas is significant, sustainable and economical also. Author communicated that in hybrid system, at every instant efficiency increase from 33% to 64% as per changed in glazed area. The important role is type of assembly whether it is semitransparent (Glass – Glass) or opaque (Glass-Tedlar). Joshi et al. [16]. Author studied and computed the capability of Semitransparent (Glass- Glass) assembly and opaque (Glass to Tedlar) assembly, under which overall thermal efficiency of I$^{st}$ assembly given above is more than II$^{nd}$ assembly with air flow duct incorporated. Solar photovoltaic (Glass-Glass) module encourages its applicability in dwellings with integrated modules Park et al. [17]. The efficacy of this application is discussed and analysed the experimental results such that per1$^0$C increase in ambient temperature of room power decrease by 0.48% under STC. and under outdoor conditions it is decreased by 0.52%. Wei et al. [18] Novice module of mono crystalline silicon photovoltaic plate compares with monocrystalline silicon PVT solar collector. On the performance evaluation, the result depicted that thermal efficiency calculated on 24Hrs basis is 40% and that consists 75% 0f conventional solar module. Agrawal et al. [19], Temperature and Electrical efficiency relation also affect the overall energy savings in a covering of transparent material of the mixed mode PVT assembly with air collector. Author communicated total yearly rise of thermal energy is 1252KWh and rise in gross exergy is 289.5KWh in case of hybrid PVT module air collector. In PVT thermal array Rajoria et al. [20], author introduced prototype model in which computation done on the basis of total useful energy or exergy and thermal energy on yearly basis. The assemblies are in series consists of two attached columns of 18PV and in parallel connection. They have highest overall exergy gain which is 12.9% higher than other configurations. PV module physical parameters that depend upon temperature and solar radiations are evaluated with the simulation of equivalent circuit of module. Salmi et al. [21], Vats et al. [22] Authors

experimentally found that application of PVT module attached with roof of the room is analysed and performance of opaque and semi-transparent (Glass-Glass) assemblies are computed and their performance are analysed under room temperature of Semi-transparent (Glass –Glass) photovoltaic thermal (SPVT) facade, opaque photovoltaic thermal (OPVT) facade and SPVT roof and OPVT roof with air duct is $1.46^0$C and $1.13^0$C respectively. Whereas without air duct is $9.80^0$C and $9.55^0$C respectively. The most effective is building integrated semi-transparent (Glass-Glass) photovoltaic thermal (BISPVT) roof with absence of any air flow system in the chilly climatic conditions. Mishra et al. [23]. Author analysed the performance on the basis of exergy and output of thermal energy for different kinds like Crystalline silicon(c-Si), Multicrytalline or Polycrystalline silicon(poly- Si), Amorphous silicon(a-Si), Cadmium telluride (CdTe) and Copper indium gallium selenide (CIGS) combined PVT duct assembly where water as fluid is used to carry the excessive thermal energy. Zhang et al. [24] For different types of modules, temperature is the key factor which affects the efficiency of the PVT hybrid assembly. On the basis of calculation of important physical parameters based on heat transfer coefficient of convection polycrystalline(poly-Si) thin film photovoltaic cell is best hybrid system. Shyam et al. [25]. Solar PVT hybrid module is not only emphasized on electrical efficiency or total exergy of the module but also on important factor that is payback time, carbon credits and energy matrices. Author analysed two cases (i) entering part from where air gets inside is covered with semi-transparent PV module and case (II) exit part from where air gets out is covered with semi-transparent PV module. Out of these cases, Case (i) is highly advantageous as if the air flow rate is less and few number of series connected collectors. On the other hand if air large number of collectors are connected in series and air flow rate is higher than both cases are equally weightage. Saini et al. [26], The effect of green house solar dryer has an important part in determining the effect of regulation thermal energy under different weather conditions.The results depicted that total thermal energy for Crystalline silicon(c-Si), Multicrystalline or Polycrystalline silicon(poly-Si), Amorphous silicon(a-Si), Cadmium telluride (CdTe) and Copper indium gallium selenide (CIGS) PV with parching phenomenon are 1838.16,1740.98,1351.22,1472.22 and 1527.86 KWh respectively. Dimri et al. [27], Thermoelectric cooler is also another way of sweeping thermal energy and increase the electrical energy .It is based on temperature difference which rise to extra electrical energy. Shahsavar et al. [28], Saadon et al. [29], The use of exhaust air and supply air for bot out the thermal energy in semitransparent building incorporated system. The total exergy of 19.97kWh is saved . Where net thermal energy of 3038.83kWh and electrical energy of 2259.64kWh.To enhance the efficiency of PVT module a new design proposed by Abakam et al. [30] in which two semi transparent PV modules used, in which

electrical efficiency 20.76%, thermal efficiency 65.7% and overall efficiency 86.5%.Multilayer PV modules has a positive edge with respect to energy harvesting to the refrence unit area than to conventional one. Ali Heydari et al. [31] have studied the thermal performance investigation of a hybrid solar air heater applied in a solar dryer using thermodynamic modeling. They found an increase in the efficiency of air heater in hybrid system.

In this paper experimental based system analysed for different ratings of 80Wp, 50Wp &25Wp (Case –I, II and III) Glass-to-Glass(semi-transparent) PV cell systems of different packing factors. The important variables on which efficiency (electrical) depends and also effects it are solar irradiance and atmospheric average temperature. The prototype has been developed which is practically authenticated for outdoor climate of New Delhi. In India, Ghaziabad (U.P) situated, HIET institute of engineering and technology, practical model is set up and has been evaluated on the various variables. Photovoltaic modules are prepared in Central Electronics Ltd., Sahibabad, U.P. India that has been used in this experiment.

## SYSTEM DESCRIPTION

The cut view of mix mode semitransparent module with an enclosure for circulating of air is very much clear from the Figure 1. In the below diagram solar irradiance strikes on the module of area $0.5332m^2(A_m)$ and for different packing factor. From Figure 2 enclosure dimensions are 0.86m × 0.63m × 0.05m. The enclosure arrangement is such a way so that the flow of air by force mode is achieved by 10WDC fan which is energized with the same PVT module. The DC fan is used to for the cooling purpose of mix mode PV module.
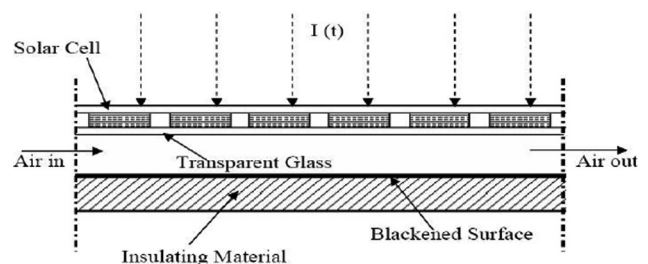


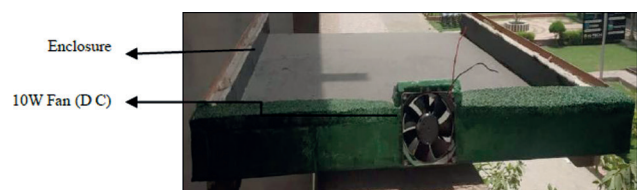**Figure 1.** Cross section of semi-transparent PV module with enclosure(duct).



**Figure 2.** 10WDC fan with Enclosure.

**Table 1.** Design sheet of various parameters

| S. No. | Nomenclature | Specifications |
|---|---|---|
| 1. | Area of Module ($A_m$) | 0.5332 m² |
| 2. | Absorptivity Solar cell ($a_c$) | 0.9 |
| 3. | Packing factor Solar cell ($b_c$) (80Wp) | 0.81 |
| 4. | Packing factor Solar cell ($b_c$) (50Wp) | 0.523 |
| 5. | Packing factor Solar cell ($b_c$) (25Wp) | 0.3139 |
| 6. | Absorptivity blackened plate ($a_b$) | 0.85 |
| 7. | Transmissivity of Glass ($t_g$) | 0.95 |
| 8. | Efficiency module ($h_m$) | 12% |
| 9. | Solar module efficiency under standard test condition(STC) ($h_o$) | 14% |
| 10. | Fluid mass flow rate ($\dot{m}_f$) | 0.006513 (Kg/sec) |
| 11. | Specific heat of Fluid used($C_f$) | 1012 (J/(Kg.K)) |
| 12. | Material temperature coefficient ($b_0$) | 0.0045 |
| 13. | Air velocity ($v$) | 1m/sec |
| 14. | Heat loss Coefficient from bottom to fluid ($h_{if}$) | 2.8 + 3v; v = 1m/sec |
| 15. | Heat loss coefficient from top ($h_0$) | 5.7 + 3.8v; v = 1m/sec |
| 16. | Length of Glass ($L_g$) | 0.003m |
| 17. | Glass Thermal Conductivity ($K_g$) | 0.816 (W/(m.K)) |
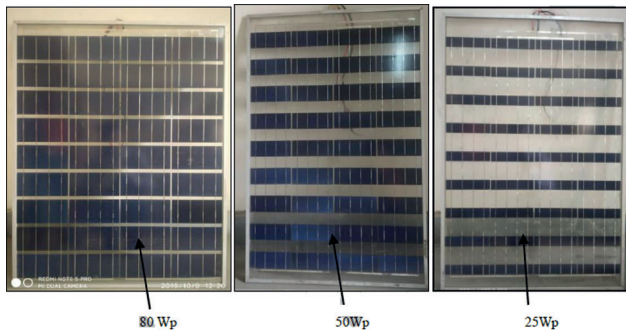


**Figure 3.** Mix Mode Photovoltaic Modules of different packing factors.

Three different cases I, II, III has shown in Figures 3(a), 3(b) and 3(c) respectively. The various parameters design sheet is shown in Table1.

## MATHEMATICAL MODELLING

The following postulates have to be taken for the equation of energy balance.

- For present research, one-dimensional conduction of heat tobe considered for approximation.
- The cover of glass is to be considered at uniform temperature.
- rough the duct, the air should be considered as a streamlined. The equation of energy balance of PVT modules can be written as:

(i) For solar cells PV systems Mishra et al. [23]:
The energy balance equation for solar cell of PV module can be written:

$$\alpha_c \beta_c r_g I(t) bdx = U_{tca}\left(T_c - T_a\right)bdx + U_{bcf}\left(T_c - T_f\right)bdx \\ + \left(h_m\right)\beta_c I(t) bdx \tag{1}$$

{PV cells receive Rate of solar energy} = {Through top surface of system Rate of heat energy loss from PV cells to ambient} + {From bottom surface of system Rate of heat energy loss from PV cells to fluid} + {From PV cells system Rate of electrical energy produced}.

Now $U_{tca}$ and $U_{bcf}$ are explained as

$$U_{tca} = \left[\frac{L_g}{K_g} + \frac{1}{h_0}\right]^{-1},$$

$$U_{bcf} = \left[\frac{L_g}{K_g} + \frac{1}{h_{if}}\right]^{-1}.$$

Cell temperature is evaluated from equation no:1

$$T_c = \frac{T_f U_{bcf} + T_a U_{tca} + I(t)\alpha_c\beta_c c_g - I(t)\,_m\beta_c}{U_{bcf} + U_{tca}} \tag{2}$$

Efficiency (electrical) of mix mode module from Schott et al. [6]

$$c = 0\big(1 - \beta_0\big(T_c - T_a\big)\big) \qquad (3)$$

(ii) For blackened absorber plate:

$$\alpha_b\big(1 - \beta_c\big)r_g r_g I(t)bdx = U_{bpa}\big(T_p - T_a\big)bdx$$
$$+ h_{pf}\big(T_p - T_f\big)bdx \qquad (4)$$

Bottom plate heat is evaluated from Eq. (4) is shown below.

$$T_p = \frac{I(t)\,\alpha_b\big(1 - \beta_c\big)c_g{}^2 + T_a U_{bpa} + T_f h_{pf}}{h_{pf} + U_{bpa}} \qquad (5)$$

(iii) Movement of air through enclosure on that basis balance equation of energy is shown below.

$$\dot{m}fcf\,\frac{dTf}{dx} = h_{pf}\big(T_p - T_f\big)b + U_{bcf}\big(T_c - T_f\big) \qquad (6)$$

Initial conditions in analysis of Eq. (6) given by:

$T_f$ at $x = L$, $T_f = T_{fo}$ and when $Tf$ at $x = 0$, $T_f = T_{fi}$

On solving Eq. (6) by Eqs. (5) and (2) given by:

$$\qquad (7)$$

Where,
Where,
For the entire length of enclosure, the average heat through it is evaluated as shown below.

$$\qquad (8)$$

If two cases are considered Case a)$T_{fi} = T_a$ and Case b) $T_f = T_{cf}$, place these case values in Equations (3,7 and 8)

On temperature depend efficiency (electrical) evaluated as shown below.

$$c = 0\big(1 - \beta_0 Um\big) \qquad (9)$$

$$\text{Where, } Um = \frac{\begin{array}{c}\left(\dfrac{f(t)}{a}\right)\big[1 - (Ux)\big]\big(1 - e^{-U_t}\big) \\[4pt] +T_a\big[Ux\big]\big(1 - e^{-1/Ux}\big)\big[U_{bcf} - U_{bcf}\big] \\[4pt] +1(t)\alpha_c\beta_c c_g - I(t)_m\beta_c\end{array}}{U_{bcf} + U_{tca}}$$

$$\text{Where, } Ut = A_m\left\{\begin{array}{l}\left(\dfrac{-hpf}{\big(h_{pf} + U_{bpa}\big)}\right) + h_{pf} \\[10pt] +\left(\dfrac{\big(U_{bcf}\big)}{\big(U_{tca} + U_{bcf}\big)}\right)U_{tca}\end{array}\right\}$$

Where $U_x = (\dot{m}_f c_f)/(U_t)$

## METHODOLOGY

Atmospheric effects of National Capital Region (NCR), India defines the solar irradiance I(t) as well as atmospheric heat as (Ta) also heat content of mix mode PV system (Tm). Different postulates are adopted to determine the efficiency(electrical), efficiency(thermal) of different packing factors. It also diagnoses the impact of solar cell temperature on different efficiencies of mix mode system.

First Step: Analysis of Mathematical equations of the mix mode system is done by the use of MATLAB version R2018a.
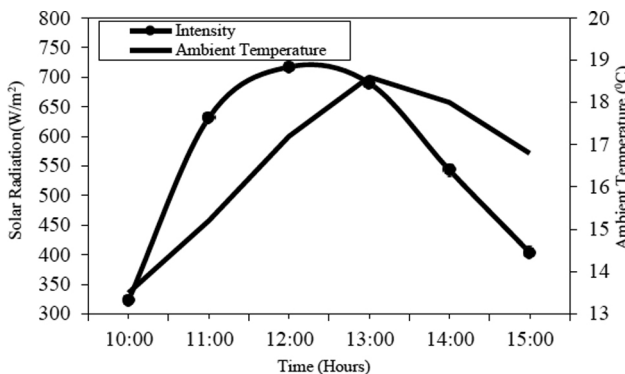
**Figure 4.** For a Hazy day of Feburary 2020 Rate of change of atmospheric temperature with respect to solar irradiance.
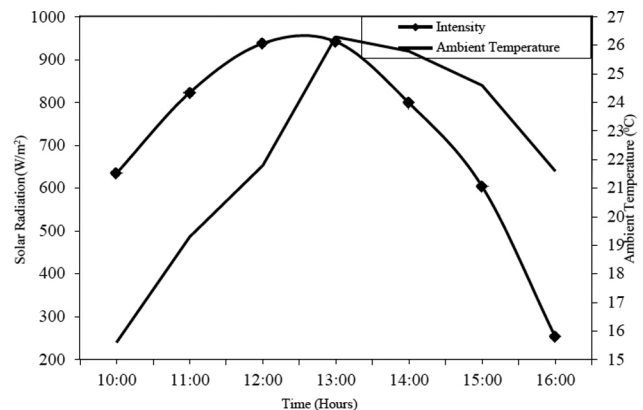
**Figure 5.** For a Cloudy day of Feburary 2020 Rate of change of atmospheric temperature with respect to solar irradiance.

Second Step: Different mathematical computations are done on the basis of designed sheets of various parameters as shown in Table 1.

Third Step: Mix mode PV system temperature and its effect on efficiency(electrical) from

Equations (2 & 9). These are computed on the atmospheric conditions and designed sheets of various parameters.

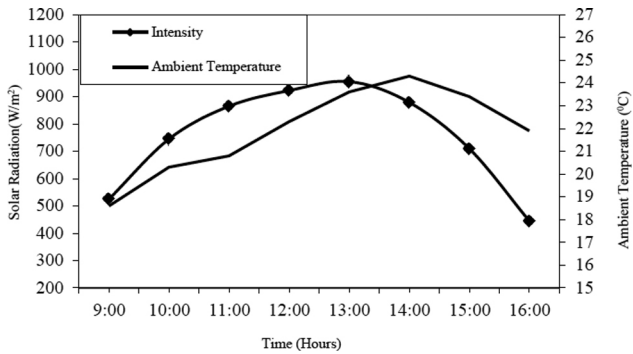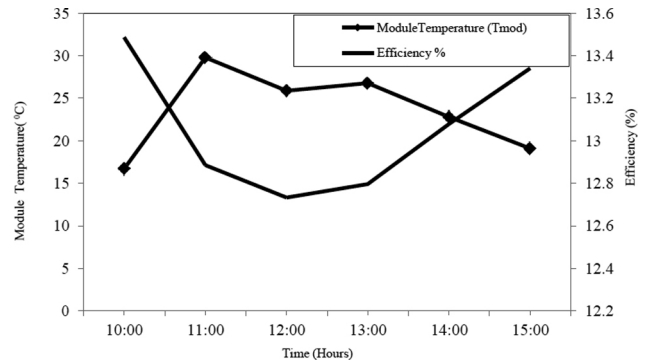Fourth Step: Data Using MATLAB as mathematical modelling and practical data are clubbed



**Figure 6.** For a Clear day of Feburary 2020 Rate of change of atmospheric temperature with respect to solar irradiance.



**Figure 7(a)** In Case-I of a Hazy day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
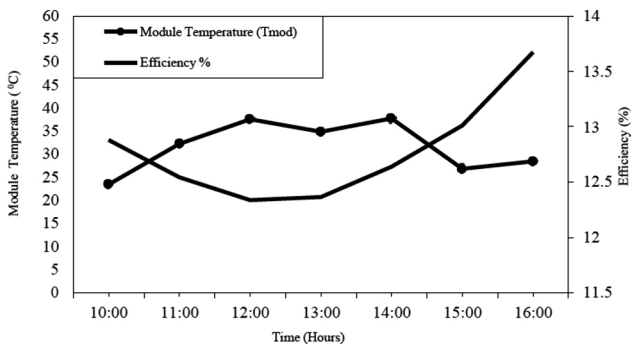


**Figure 7(b).** In Case-I of a cloudy day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
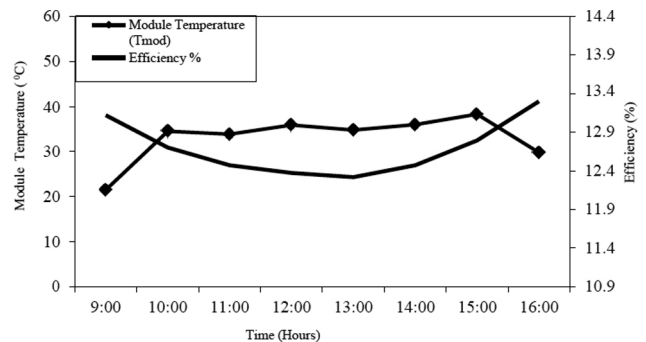


**Figure 7(c).** In Case-I of a Clear day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
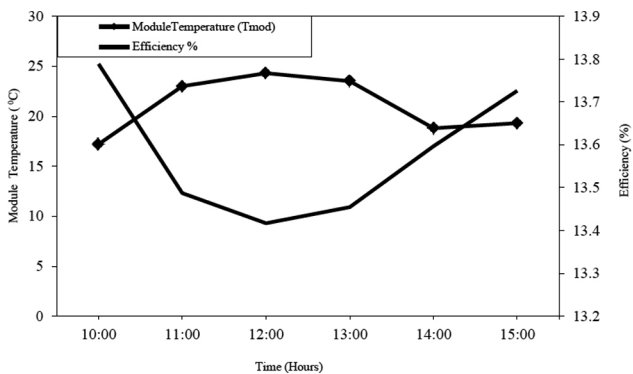


**Figure 8(a).** In Case-II of a Hazy day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
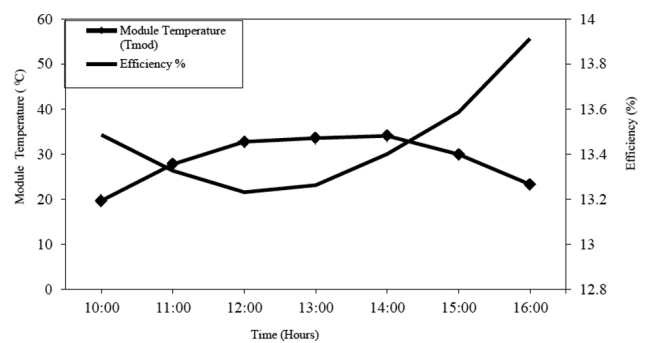


**Figure 8(b).** In Case-II of a Clody day Rate of change of atmospheric temperature with respect to Efficiency(electrical).

and various inferences are deduced as shown in Figures 11(a to c). These practical data are computed on the basis of atmospheric conditions of HIET engineering college, Ghaziabad (U.P) India.

## RESULTS AND DISCUSSION

For different types of atmospheric conditions like clear day, cloudy and hazy day, the change in atmospheric temperature and solar irradiance for all Cases (I, II, III) on hour-to-hour basis is shown in different figures (4,5&6). Various graphs of different cases (I, II & III) interpret the rate of change of efficiency with respect to heat produced at mix mode PV system. From the graph of Case-I in the figure 7(a to c) a unique relationship deduced between the efficiency (electrical) and temperature rise of mix mode PV module. It inferences the inversely proportional relationship between efficiency (electrical) and atmospheric temperature. The same effect occurs in Cases- II and III respectively which are shown in Figures 8(a to c) and Figures 9(a to c) respectively.

Combined graphs of different cases with the representation of rate ocf change of atmospheric temperature and efficiency h (electrical) is shown in Fiures(10a to 10c). After interospection of all graphs of all the cases , it is deduced that Case-III has the highest efficiency(electrical) which is also proved from temperature of the mix mode PV system that is least among all other cases.

## VALIDATION OF OUTDOOR SIMULATION EXPERIMENT

Experimental and theoretical rate of change of temperature of Case-I under all climatic conditions are compared and shown in Figures (11a to 11c). Experiment is conducted on mix mode PV system enclosed with flow of air through it and tilted at an angle of $30^0$ which is approximately latitude of Delhi and National Capital region.

## ERROR ANALYSIS

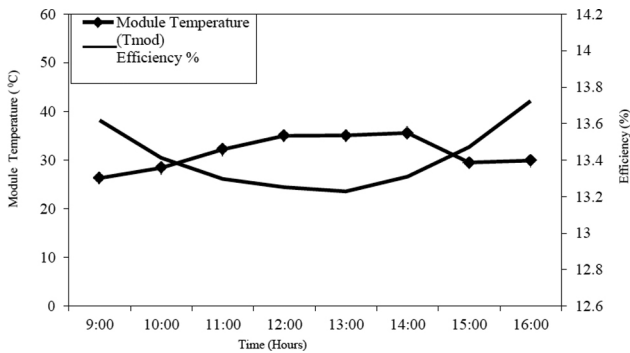The expression of correlation coefficient (r) is given by Chapre et al. [32].



**Figure 8(c).** In Case-II of a Clear day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
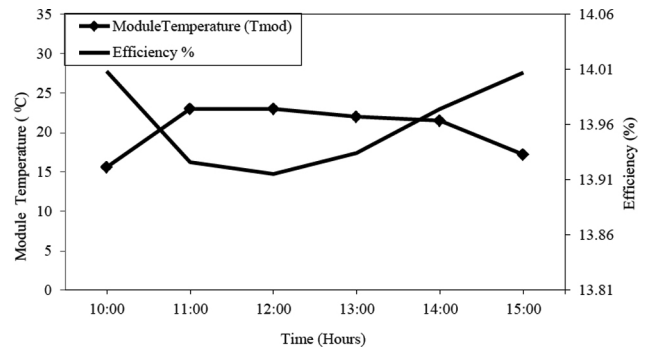


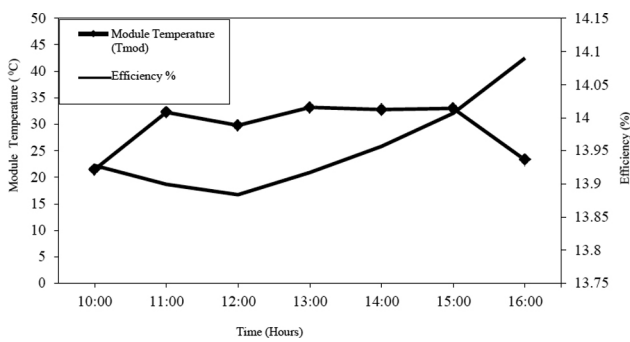**Figure 9(a).** In Case-III of a Hazy day Rate of change of atmospheric temperature with respect to Efficiency(electrical).



**Figure 9(b).** In Case-III of a Cloudy day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
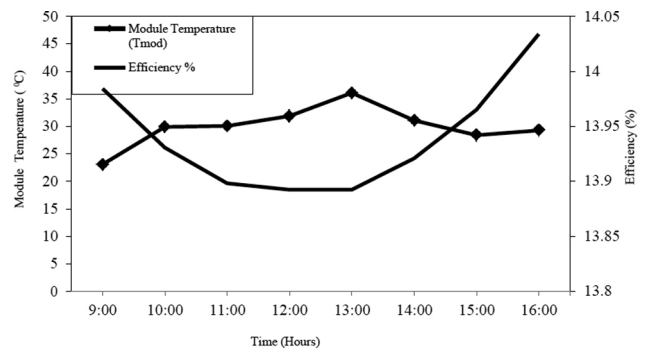


**Figure 9(c).** In Case-III of a Clear day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
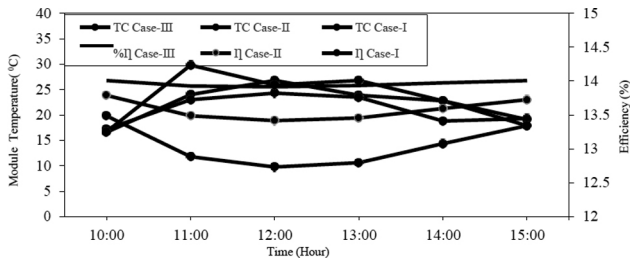
**Figure 10 (a).** For all Cases of a Hazy day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
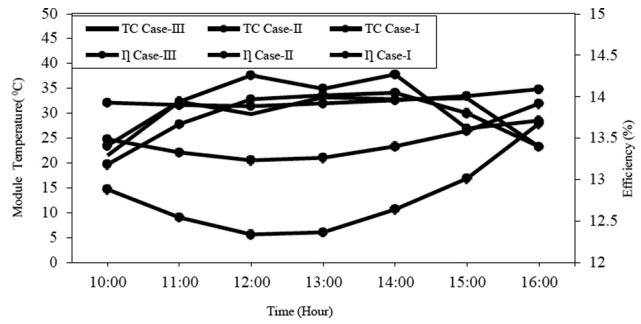


**Figure 10(c).** For all Cases of a Clear day Rate of change of atmospheric temperature with respect to Efficiency(electrical).
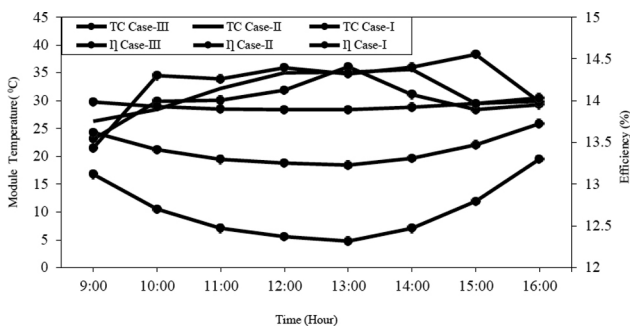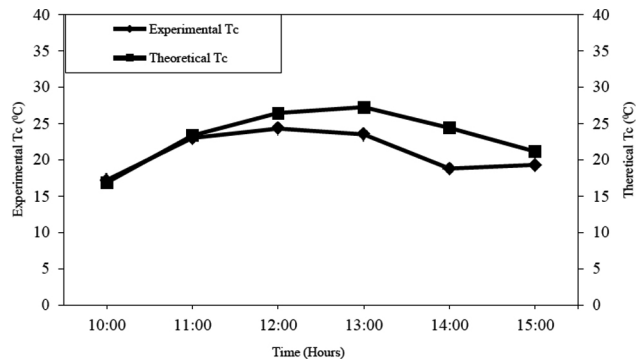


**Figure 10(c).** For all Cases of a Clear day Rate of change of atmospheric temperature with respect to Efficiency(electrical).



**Figure 11(a).** Case-I :Differentiation between practical and theoretical values of rate of change of temperature of Hazy day.
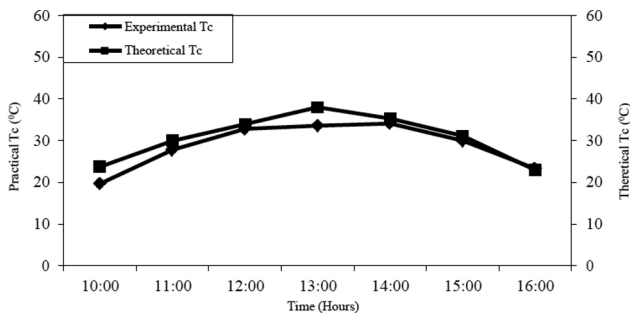


**Figure 11(b).** Case-I :Differentiation between practical and theoretical values of rate of change of temperature of Cloudy day.
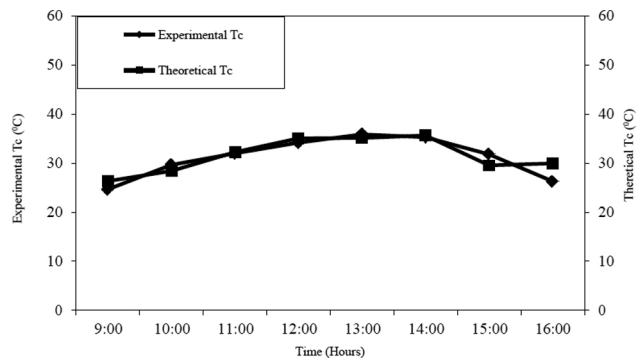


**Figure 11(c).** Case-I :Differentiation between practical and theoretical values of rate of change of temperature of Clear day.

$$\text{Correlation coefficient } (r) \frac{n \; XY}{\sqrt{n \; X_i^2 X_i^2}} \frac{X_i Y_{ii}}{\sqrt{n \; Y_i^2 Y_i^2}} \quad (10)$$

Where *Yi and Xi* are practical and theoretical values respectively and n defines the number of observed records.

Expression of root mean square percent deviation (e) is given by:

$$\text{Root mean square percent deviation } (e) \sqrt{\frac{(e_i)^2}{n}} \quad (11)$$

$$e_i \frac{X_i Y_i}{X_i} \, 100$$

Different conditions for r given by:

if $r > 0$ a positive linear relationship exists.

$r = 0$ implies no linear relationship between theoretical and experimental results.

$r < 0$ a negative linear relationship exists.

The Correlation coefficient (r) is 0.838, 0.776 and 0.766 for hazy, cloudy and clear day respectfully whereas deviation percentage of actual and theoretical values (e) is 26.40,25.60 and 23.649 for hazy, cloudy and clear days conditions. From the above data it is very clear that deviation is well under limits and a handy harmony between theoretical and practical values.

## CONCLUSIONS

In this article, the condensed scenarios are as follows:

1) Among all the cases (I, II & III) are experimentally evaluated based on intensity, ambient temperature and module temperature.

2) Case–I is validated based on module temperature, which is experimentally conducted in the month of February2020.

3) The above three cases were compared based on efficiency and module temperature.

4) From the Figures10(a) to 10(c), it has been observed that among all cases, III$^{rd}$ Case module has 0.38% higher efficiency in average as compared to II$^{nd}$ Case and also Case-III has 0.907% more average efficiency than Case-I for hazy day conditions, whereas for cloudy day Case-III has 0.495% more average efficiency than Case-II also Case-III has 1.17% average higher efficiency than Case-I. For clear day conditions Case-III has 0.525% more average efficiency than Case –II also Case-III has 1.24% average higher efficiency than Case-I.

5) Since Case-III has the highest electrical efficiency, so instead of using single case-I module two Case-III modules may be used.

## ACKNOWLEDGEMENTS

## NOMENCLATURE

| | |
|---|---|
| $A_m$ | Area of the module in (m$^2$) |
| $L$ | Length of the module in (m) |
| b | Breadth of module in (m) |
| lg | Length of glass in (m) |
| dx | Length elemental in (m) |
| $\dot{m}_f$ | Mass flow rate of fluid in (kg/s) |
| $C_f$ | Specific heat of fluid in (J/(kg. K)) |
| I(t) | Irradiance of Sun in (W/m$^2$) |
| h | Loss coefficient of Heat in (W/m$^2$) |
| K | Conductivity thermal in (W/(m.K)) |
| $h_0$ | Loss coefficient heat from top in (W/m$^2$) |
| T | Temperature in (˚C) |
| $h_i$ | Loss coefficient heat from bottom in (W/m$^2$) |
| $U_{tca}$ | Loss heat transfer coefficient which is overall (total) from solar cells to atmosphere (W/(m$^2$. K)) |
| v | Velocity of air in (m/s) |
| $U_{bcf}$ | Bottom heat loss transfer coefficient which is overall(total) from solar cells to fluid (W/(m$^2$. K)) |
| Wp | System power (Watt –Peak) |

*Subscripts*

| | |
|---|---|
| c | Solar cell |
| m | Module |
| p | Plate |
| f | Fluid |
| a | Ambient |
| fi | Inlet fluid |
| g | Glass |
| $f_0$ | Outlet fluid |

*Greek Letters*

| | |
|---|---|
| α | Absorptivity |
| $β_o$ | Material temperature coefficient |
| $α_b$ | Absorptivity blackened plate |
| β | Packing factor |
| $η_0$ | Efficiency of solar cell at standard test condition (STC) |
| τ | Transmissivity |
| η | Efficiency |

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

## ETHICS

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