CHAPTER 3

BACKGROUND AND MOTIVATION
3.1 BACKGROUND

Lots of the work has been done with hybrid PVT tile, module and array for last three decades and discussed through numerous publications in the literature. The conventional PV module is employed for directly converting solar energy into electricity. The remaining thermal energy available with photovoltaic modules increases its temperature and hence electrical efficiency decreases. If the fluid flows below the PV module/solar cell of Figure 3.1 and 3.2, withdraw the heat from the back surface of cell and improves the efficiency of PV modules/solar cell. The hot air further can be utilized in drying of crops and space heating. The carrier of thermal energy associated with the conventional photovoltaic module can either be air or water. The integrated system (PV module with channel) for utilizing the thermal energy as well as electrical energy with PV module is referred to as the hybrid photovoltaic thermal system as defined earlier too. Energy and exergy analysis can be carried out to monitor the performance of the PVT system. Over the years, a significant research on PVT technology has been carried out by many researchers for conventional PV module of given rated power.

Figure 3.1: Unglazed photovoltaic thermal tile (UGPVTT)
Figure 3.2: Glazed photovoltaic thermal tile (GPVTT)

Air-cooled PVT systems have already been applied in buildings, integrated usually on their inclined roofs or facades. These systems keep the electrical output at a sufficient level, covering building space heating needs during winter and ventilation needs during the summer, avoiding also building overheating.

In IIT Delhi, the work on conventional PVT water and air collector (Figure 3.1 and 3.2) has also been carried out on conventional PVT module of a given rated power. Some of them includes PVT air collectors (Agrawal and Tiwari, 2011a, 2011b, 2011c; Tiwari et al., 2006; Tiwari and Sodha, 2007; Solanki et al., 2012; Rajoria et al., 2015) water collectors (Ahmad et al., 2014; Mishra et al., 2013c; Shyam et al., 2015).

3.2 MOTIVATION

The work related to the design parameters of PVT module has been done conventionally. In order to further increase of thermal and electrical energy of conventional PVT modules, the design parameters of PVT system have been optimized using soft computing techniques. The following new concepts have been proposed and studied in the present thesis.

- The purpose of the research work is to optimize the design parameters of different types of PVT systems to improve the overall efficiency of the system. The performance evaluation of unglazed, glazed PVT module and glazed PVT array is
carried out. The different design parameters of PVT system have been optimized with genetic algorithm and genetic algorithm-fuzzy system approach.

- Novel design of the dual channel semitransparent PVT module has been presented and optimized with genetic algorithm-fuzzy system approach as shown in Figure 3.3. A comparative study has also been presented with the single channel PVT module. The optimum design, configuration followed by assessment of amount of electrical and thermal energy gains is obtained. MATLAB 7.0 is used for developing the program of Genetic Algorithm (GA) approach and Genetic Algorithm-Fuzzy System (GA_FS) approach to optimize the design parameters of a PVT system to improve the efficiency, and to solve mathematical models of the proposed systems.

Figure 3.3: Side view of dual channel semitransparent PV module

- Carbon credit analysis of single channel glazed PVT array and carbon credit and life cycle cost analysis of dual channel semitransparent PVT module have been carried out.
CHAPTER 4

OPTIMIZATION OF SINGLE CHANNEL PHOTOVOLTAIC THERMAL SYSTEMS
CHAPTER 4
OPTIMIZATION OF SINGLE CHANNEL PHOTOVOLTAIC THERMAL SYSTEMS

4.1 UNGLAZED PHOTOVOLTAIC THERMAL MODULE

The group of photovoltaic researcher and photovoltaic industry has a main focus on the new development and enhancement in power efficiency of photovoltaic systems. An effort has been made to design and optimize the parameters of hybrid single channel unglazed photovoltaic thermal (SCUPVT) module. In this work, it has been observed that there are many parameters that influence the electrical efficiency of a hybrid single channel photovoltaic thermal module like the thickness of the glass and tedlar, the temperature at the inlet of channel, solar cell temperature etc. All equations for solar cell and proposed module have been derived. Using genetic algorithm (GA), thermal efficiency and electrical efficiency of the system have been optimized. All the parameters that are used in genetic algorithms are the parameters that could be changed, and the non changeable parameters, like solar radiation and ambient temperature cannot be used in the algorithm.

4.1.1 System Description

A model is proposed with a channel between PV cell and tedlar. A schematic view of a PVT tile is shown in Figure 4.1. The proposed system is called single channel solar cell thermal tile (SCSCTT). A series and parallel combination of single channel photovoltaic thermal tile (Agrawal & Tiwari, 2011c) have been considered which is referred as single channel photovoltaic thermal (SCPVT) module as shown in Figure 4.2.

To get the maximum overall exergy efficiency different parameters of SCPVT module have been optimized using a genetic algorithm. When solar radiation falls on the PV module, the solar energy is converted into electrical energy as well as thermal energy. The electrical energy is stored in a battery, due to the thermal energy the PV module gets heated and reduce electrical efficiency because, the electrical efficiency of a solar cell is negative temperature coefficient of a solar cell temperature.
Figure 4.1: Proposed single channel solar cell tile (SCSCTT)

Figure 4.2: Single channel unglazed photovoltaic thermal (SCUPVT) module

The reason for this, is that a higher temperature increases the conductivity of the semiconductor. This balances out the charge within the material, reducing the magnitude of the electric field at the junction. This in turn inhibits charge separation, which lowers the voltage across the cell. It should be noted that a higher temperature increases the mobility of electrons, which causes the flow of current to increase slightly. This increase is, however minor and insignificant as compared to the decrease in voltage. So for maintaining the
electrical efficiency of PV modules, heat removal is essential. In order to convert heat into 
the thermal energy, model is proposed in which a channel is used below the solar panel and 
air is flown as a flowing fluid by DC fans.

4.1.2 Thermal Modeling

In order to write the energy balance equation of SCSCTT, the following assumptions 
have been made:

1. There is no temperature gradient along the thickness of solar cell.
2. Heat capacity of solar cell is neglected.
3. Specific heat of air remains constant.
4. The system is in quasi-steady state.

The single channel solar cell thermal tile (SCSCTT) is shown in Figure 4.1. The 
small area of SCSCTT is bdx. The energy balance equation also considered by Tiwari and 
Sodha (2006) for solar cell can be written as:

\[
\alpha_{c}I_{SL} \cdot b d \chi = \left[ h_{SCA} (T_{SC} - T_{A}) b d \chi \right] + \left[ h_{SCF} (T_{SC} - T_{F}) b d \chi \right] + \left[ \eta_{TC} I_{SL} \cdot b d \chi \right]
\]

(4.1)

After solving Equation 4.1

\[
\alpha_{SC} I_{SL} \cdot b d \chi = \left[ h_{SCA} T_{SC} - h_{SCA} T_{A} + h_{SCF} T_{SC} - h_{SCF} T_{F} + \eta_{TC} I_{SL} \right] \cdot b d \chi
\]

\[
(h_{SCA} + h_{SCF}) T_{SC} = \alpha_{SC} I_{SL} + h_{SCA} T_{A} + h_{SCF} T_{F} - \eta_{TC} I_{SL}
\]

\[
T_{SC} = \frac{(\alpha_{SC} - \eta_{TC}) I_{SL} + h_{SCA} T_{A} + h_{SCF} T_{F}}{h_{SCA} + h_{SCF}}
\]

Let

\[
\alpha_{eff} = (\alpha_{SC} - \eta_{TC})
\]
The energy balance of air flowing in the channel of SCSCTT for elemental area bdx is given by-

\[
\begin{align*}
\text{Rate of heat transfer} & = \text{Mass flow rate of flowing fluid (air)} + \text{Rate of heat transfer from flowing fluid to ambient} \\
\end{align*}
\]

\[
h_{SCF} (T_{SC} - T_{F}) bdx = m_F C_{air} \frac{dT_F}{dx} dx + h_{FA} (T_F - T_A) bdx
\]

(4.3)

Where \( m_F = \rho \times L \times d \times V_F \)

Putting the value of \( T_{SC} \) in Equation (4.3) we get:

\[
\begin{align*}
h_{SCF} \left[ \alpha_{eff} I_{SL} + h_{SCA} T_A + h_{SCF} T_F \over h_{SCA} + h_{SCF} - T_F \right] bdx &= m_F C_{air} \frac{dT_F}{dx} dx + h_{FA} (T_F - T_A) bdx \\
\end{align*}
\]

(4.3)

Let

\[
h_p = \frac{h_{SCF}}{h_{SCA} + h_{SCF}}
\]

\[
\begin{align*}
\frac{1}{b} m_F C_{air} \frac{dT_F}{dx} + h_{SCF} T_F + h_{FA} (T_F - T_A) - h_{SCF} \left( \frac{\alpha_{eff} I_{SL} + h_{SCA} T_A + h_{SCF} T_F}{h_{SCA} + h_{SCF}} \right) = 0 \\
\frac{1}{b} m_F C_{air} \frac{dT_F}{dx} + h_{SCF} T_F + h_{FA} (T_F - T_A) - h_{SCF} \frac{h_{SCA} h_{SCF} - \alpha_{eff} I_{SL} - h_{SCA} h_{SCF} - T_A - h_{SCF}^2 T_F}{h_{SCA} + h_{SCF}} = 0
\end{align*}
\]

Let

\[
U_{FA} = \frac{h_{SCA} h_{SCF}}{h_{SCA} + h_{SCF}} \text{or} \left( \frac{1}{h_{SCA} + h_{SCF}} \right)^{-1} = U_{FA}
\]
\[
\frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + h_{\text{SCF}} T_F + h_{\text{FA}} (T_F - T_A) - h_p \alpha_{\text{eff}} I_{\text{SL}} - U_{FA} T_A - h_{\text{SCF}} h_p T_F = 0
\]

\[
\frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + h_{\text{SCF}} T_F (1 - h_p) + h_{\text{FA}} (T_F - T_A) - h_p \alpha_{\text{eff}} I_{\text{SL}} - U_{FA} T_A = 0
\]

\[
\frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + h_{\text{SCF}} T_F (1 - \frac{h_{\text{SCF}}}{h_{\text{SCA}} + h_{\text{SCF}}}) + h_{\text{FA}} (T_F - T_A) - h_p \alpha_{\text{eff}} I_{\text{SL}} - U_{FA} T_A = 0
\]

\[
\frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + (\frac{h_{\text{SCF}} h_{\text{SCA}}}{h_{\text{SCA}} + h_{\text{SCF}}}) T_F + h_{\text{FA}} (T_F - T_A) - h_p \alpha_{\text{eff}} I_{\text{SL}} - U_{FA} T_A = 0
\]

\[
U_{FA} = \frac{h_{\text{SCA}} h_{\text{SCF}}}{h_{\text{SCA}} + h_{\text{SCF}}}
\]

\[
\therefore \frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + U_{FA} T_F + h_{\text{FA}} (T_F - T_A) - h_p \alpha_{\text{eff}} I_{\text{SL}} - U_{FA} T_A = 0
\]

\[
\frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + U_{FA} (T_F - T_A) + h_{\text{FA}} (T_F - T_A) - h_p \alpha_{\text{eff}} I_{\text{SL}} = 0
\]

\[
\frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + (T_F - T_A) \left[ h_{\text{FA}} + U_{FA} \right] - h_p \alpha_{\text{eff}} I_{\text{SL}} = 0
\]

Let

\[
U_L = U_{FA} + h_{\text{FA}}
\]

\[
\frac{1}{b} m_F C_{\text{air}} \frac{dT_F}{dx} + U_L (T_F - T_A) - h_p \alpha_{\text{eff}} I_{\text{SL}} = 0
\]

\[
\frac{dT_F}{dx} + \frac{b}{m_F C_{\text{air}}} U_L (T_F - T_A) = \frac{b}{m_F C_{\text{air}}} h_p \alpha_{\text{eff}} I_{\text{SL}}
\]

\[
\frac{dT_F}{dx} + \frac{b U_L}{m_F C_{\text{air}}} T_F = \frac{b}{m_F C_{\text{air}}} \left[ h_p \alpha_{\text{eff}} I_{\text{SL}} + U_L T_A \right]
\]

(4.4)

\[
\frac{dT_F}{dx} + a_1 T_F = f_1 (t)
\]

(4.5)

Where

\[
a_1 = \frac{b U_L}{m_F C_{\text{air}}}
\]

\[
f_1 (t) = \frac{b}{m_F C_{\text{air}}} \left[ h_p \alpha_{\text{eff}} I_{\text{SL}} + U_L T_A \right]
\]
Now solving Equation 4.5, we get:

\[ e^{a_1 x} \cdot \frac{dT_F}{dx} + e^{a_1 x} \cdot a_1 T_F = e^{a_1 x} \cdot f_1(t) \]

\[ \frac{d}{dx} (e^{a_1 x} \cdot T_F) = e^{a_1 x} \cdot f_1(t) \]  \hspace{1cm} (4.6)

Integrating Equation 4.6, we get:

\[ e^{a_1 x} \cdot T_F = \frac{f_1(t)}{a_1} e^{a_1 x} + C \text{ Where } C \text{ is a constant.} \]

\[ T_F = \frac{f_1(t)}{a_1} + C e^{-a_1 x} \]  \hspace{1cm} (4.7)

Now at \( x = 0, T_F = T_{F,i} \) Hence

\[ T_{F,i} = \frac{f_1(t)}{a_1} + C \]

\[ C = T_{F,i} - \frac{f_1(t)}{a_1} \]

Now putting the value of \( C \) in Equation 4.7, we get:

\[ T_L = \frac{f_1(t)}{a_1} + T_{F,i} \cdot e^{-a_1 x} - \frac{f_1(t)}{a_1} \cdot e^{-a_1 x} \]

\[ T_F = \frac{f_1(t)}{a_1} \cdot (1 - e^{-a_1 x}) + T_{F,i} \cdot e^{-a_1 x} \]  \hspace{1cm} (4.8)

We know that

\[ T_{F,\text{out}} = T_F \bigg|_{x=L} \]

\[ T_{F,\text{out}} = \frac{f_1(t)}{a_1} \cdot (1 - e^{-a_1 L}) + T_{F,i} \cdot e^{-a_1 L} \]  \hspace{1cm} (4.9)

Now putting the value of \( f_1(t) \) and \( a_1 \) in Equation 4.9, we gets:

\[ T_{F,\text{out}} = \left[ \frac{h_p \alpha_{\text{eff}}}{U_L} I_{st} + T_A \right] \left[ 1 - \exp \left( \frac{-b U_L L}{m_F C_{air}} \right) \right] + T_{F,i} \cdot \exp \left( \frac{-b U_L L}{m_F C_{air}} \right) \]  \hspace{1cm} (4.10)
The average air temperature over the length of air below SCSCTT is obtained with the help of Equation 4.10 as

\[ T_{F,\text{avg}} = \frac{1}{L} \int_{0}^{L} T_F \, dx \]

or

\[ T_{F,\text{avg}} = \left[ \frac{h_p \alpha_{\text{eff}}}{U_L} I_{SL} + T_A \right] \left[ 1 - \exp \left( -\frac{b U_L L}{m_F C_{\text{air}}} \right) \right] + T_{F,i} \times \frac{1 - \exp \left( -\frac{b U_L L}{m_F C_{\text{air}}} \right)}{b U_L L} \]

(4.11)

The outlet air temperature of N number of SCSCTT connected in series is derived as:

\[ T_{F,\text{outN}} = \left[ \frac{h_p \alpha_{\text{eff}}}{U_L} I_{SL} + T_A \right] \left[ 1 - \exp \left( -\frac{N b U_L L}{m_F C_{\text{air}}} \right) \right] + T_{F,i} \times \exp \left( -\frac{N b U_L L}{m_F C_{\text{air}}} \right) \]

(4.12)

The rate of useful thermal energy obtained for \( n_r \) row of SCUPVT module

\[ Q_{U,N} = n_R m_F C_{\text{air}} (T_{F,\text{outN}} - T_{F,i}) \]

(4.13)

Or

\[ Q_{U,N} = n_R m_F C_{\text{air}} \left[ \frac{h_p \alpha_{\text{eff}}}{U_L} I_{SL} + T_A - T_{F,i} \right] \times \left[ 1 - \exp \left( -\frac{N b U_L L}{m_F C_{\text{air}}} \right) \right] \]

(4.14)

An expression for electrical efficiency of hybrid SCPVT which is a temperature dependent is as follows:
Design parameters of the unglazed PVT module are given in Table 4.1

### TABLE 4.1: DESIGN PARAMETERS OF UNGLAZED PVT MODULE

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$V_F$ (optimised)</td>
<td>4.5</td>
<td>m/s</td>
</tr>
<tr>
<td>2.</td>
<td>$d$ (optimised)</td>
<td>0.00069</td>
<td>m</td>
</tr>
<tr>
<td>3.</td>
<td>$L$ (optimised)</td>
<td>0.2083</td>
<td>m</td>
</tr>
<tr>
<td>4.</td>
<td>$h_{FA}$ (optimised)</td>
<td>1</td>
<td>W/m$^2$k</td>
</tr>
<tr>
<td>5.</td>
<td>$C_{air}$</td>
<td>1012</td>
<td>J/kgK</td>
</tr>
<tr>
<td>6.</td>
<td>$h_{SCA}$</td>
<td>$5.7+3.8V_{air}$</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>7.</td>
<td>$h_{SCF}$</td>
<td>$2.8+3V_F$</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>8.</td>
<td>$\alpha_{SC}$</td>
<td>0.9</td>
<td>--</td>
</tr>
<tr>
<td>9.</td>
<td>$\beta_0$</td>
<td>0.0045</td>
<td>--</td>
</tr>
<tr>
<td>10.</td>
<td>$\eta_0$</td>
<td>0.15</td>
<td>--</td>
</tr>
<tr>
<td>11.</td>
<td>$V_{air}$</td>
<td>1.5</td>
<td>m/s</td>
</tr>
<tr>
<td>12.</td>
<td>$\rho$</td>
<td>1.29</td>
<td>kg/m$^3$</td>
</tr>
</tbody>
</table>

#### 4.1.3 The function to be Maximized in Genetic Algorithm

In this work we have optimized four parameters like the depth of the channel ($d$), length of the channel ($L$), heat transfer coefficient from flowing fluid to ambient ($h_{FA}$) and velocity of the flowing fluid ($V_F$). A genetic algorithm is applied to the present problem to
determine the optimum values of the said parameter by maximizing the overall exergy efficiency as shown in Equation 1.11. The following procedure has been adopted:

- Identify the control parameters on which the overall exergy efficiency depends.
- After that we have defined the upper and lower bound of the parameters those are feasible in designing the module.
- Then we have found the objective function or fitness function.
- Then we have developed a program in MATLAB software for optimizing the parameter based on the flow chart shown in Figure 1.6

The maximization of overall exergy efficiency is concerned with identification of design parameters at its optimum value with respect to an objective function ($\eta_{\text{Ex}}$).

The proposed model of the unglazed PVT module is shown in Figure 4.2. The small area of PVT module is bdx. The cell temperature of $i^{\text{th}}$ generation is as follows:

$$T_{SCi} = \frac{\alpha_{\text{eff}} I_{SL} + h_{SCA} T_A + h_{SCFi} T_F}{h_{SCA} + h_{SCFi}}$$  \hspace{1cm} (4.16)

The useful thermal gain and exergy efficiency can be calculated with the help of Equation 4.14 and 1.11 respectively, for $i^{\text{th}}$ generation as follows:

$$Q_{U,Ni} = n_k m_{Fi} C_{air} \left[ \frac{h_{p} \alpha_{\text{eff}}}{U_{Li}} I_{SL} + T_A - T_{Fi,i} \right] \eta_i \left[ 1 - \exp\left( \frac{-N_b U_{Li} L_a}{m_{Fi} C_{air}} \right) \right]$$ \hspace{1cm} (4.17)

$$\eta_i = \eta_{FC} \left[ 1 - \beta_0 \left\{ \frac{\alpha_{\text{eff}}}{h_{SCA} + h_{SCFi}} I_{SL} - \left( T_{FO} - T_A \right) + \frac{h_{SCFi} h_{p} \alpha_{\text{eff}} I_{SL}}{U_{Li}(h_{SCA} + h_{SCFi})} \right\} \right. \left\{ 1 - \exp\left( \frac{-N_b U_{Li} L_a}{m_{Fi} C_{air}} \right) \right\} \left[ 1 - \frac{N_b U_{Li} L_a}{m_{Fi} C_{air}} \right] \right)$$ \hspace{1cm} (4.18)
4.1.4 Methodology

The climatic data, namely; solar radiation and ambient temperature have been obtained from the Indian Meteorological Department (IMD), Pune for four cities of India as given in appendix A.

Step-1: In this step the design parameters of the unglazed PVT module have been optimized using genetic algorithms and overall exergy efficiency is calculated which is 16.88% at 11:00AM as shown in Figure 4.3.

Step-2: Annual thermal gain is evaluated using the following method

i. The thermal energy for proposed model is evaluated from Equation 4.14 considering N=4 and \( n_R = 9 \) also considered by Agrawal and Tiwari (2011).

ii. Daily thermal gain in kWh is calculated by dividing the thermal energy (which is obtained from Equation 4.14) by 1000.

iii. Monthly thermal gain in kWh is evaluated by multiplying the daily thermal output and number of clear days (which are given in table XI to XIV) in a month for different weather conditions (Set A to Set D).

iv. The annual thermal gain is evaluated by summing the monthly thermal gain of Set A to Set D type of weather.

v. The overall thermal gain has been evaluated by Equation 1.13.

Step-3: Annual electrical gain is evaluated using the following method

i. Electrical efficiency of the proposed model has been evaluated from Equation 1.9 considering N=4 and \( n_R = 9 \) also considered by Agrawal and Tiwari (2011).

ii. Daily electrical gain in kWh is calculated from Equation 1.15b for different weather conditions.

iii. Monthly electrical gain in kWh is evaluated by multiplying the daily electrical output and number of clear days in a month for different weather conditions.

iv. The annual electrical gain is evaluated by summing the monthly electrical gain of Set A to Set D type of weather conditions.

Step-4: In this step exergy equivalent of thermal output has been evaluated by following method

i. The daily exergy equivalent of thermal output is evaluated from Equation 1.15a.
ii. Monthly exergy output in kWh is evaluated by multiplying the daily exergy output and number of clear days in a month for different weather conditions.

iii. Annual exergy output is evaluated by summing the monthly exergy output of Set A to Set D type of weather conditions.

iv. Overall exergy of the glazed PVT module is obtained from Equation 1.15.

**Step-5:** In this step exergy efficiency is evaluated by following method

i. Input exergy is evaluated from Equation 1.12 for different weather conditions.

ii. Monthly input exergy in kWh is evaluated by multiplying the daily input exergy and number of clear days in a month for different weather conditions.

iii. Annual input exergy is evaluated by summing the monthly input exergy of Set A to Set D type of weather conditions.

iv. The daily exergy output of the glazed PVT module for different weather conditions is evaluated from Equation 1.15, 1.15a and 1.15b.

v. Monthly exergy output in kWh is evaluated by multiplying the daily exergy output and number of clear days in a month for different weather conditions.

vi. Annual exergy output is evaluated by summing the monthly exergy output of Set A to Set D type of weather conditions.

vii. An overall exergy efficiency has been evaluated from Equation 1.11.

### 4.1.5 Results And Discussion

Fitting procedure based operation on genetic algorithms (GA) is applied to treat with the overall efficiency curve numerically. Program for GA written in MATLAB software has been used to optimize the efficiency.

Firstly, The analysis has been done at following input data: solar intensity (I_{SL}) is 680.73 kW/m² and ambient temperature (T_A) is 6.6°C at 11:00 AM. The variation in fitness value with respect to the generation has been shown in Figure 4.4(a). It has been observed that, the overall exergy efficiency of SCUPVT module is 16.88%, which is obtained at optimum value of the design parameters as given in Table 4.2. The convergence curve (i.e. Overall exergy efficiency Vs generation curve) is shown in Figure 4.4(b). It is clear that the genetic algorithm is completely converged within 1200 generations.
TABLE 4.2: VALUE OF OPTIMIZED PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of the channel (d)</td>
<td>0.00069 m</td>
</tr>
<tr>
<td>Length of the channel (L)</td>
<td>0.2083 m</td>
</tr>
<tr>
<td>Heat transfer coefficient (h_{FA})</td>
<td>1 W/m²k</td>
</tr>
<tr>
<td>Velocity of flowing fluid (V)</td>
<td>4.5 m/s</td>
</tr>
</tbody>
</table>

Figure 4.3: (a) The variation in fitness value with respect to the generation
(b) The variation in overall exergy efficiency with respect to generation

Figure 4.4: Variation between overall exergy efficiency and depth of the channel
Figure 4.4 shows the variation between overall exergy efficiency and depth of the channel. It has been observed that when the depth of the channel is varying and other parameters are set at its optimized value as shown in Table 4.2, it indicates that the overall exergy efficiency of the module is optimum at \( d = 0.00069 \text{m} \).

![Graph showing the variation between overall exergy efficiency and depth of the channel.](image)

**Figure 4.5:** Variation between overall exergy efficiency and length of the channel

![Graph showing the variation between overall exergy efficiency and heat transfer coefficient.](image)

**Figure 4.6:** Variation between overall exergy efficiency and heat transfer coefficient \( h_{FA} \).
Figure 4.5 shows the variation between overall exergy efficiency and channel length. It has been observed that when the length of the channel is varying and other parameters are set at its optimized value, it indicates that the overall exergy efficiency of the module is optimum at $L = 0.2083$ m.

Variation between overall exergy efficiency and heat transfer coefficient from flowing fluid to ambient has been shown in Figure 4.6. It has been observed that when the value of $h_{FA}$ is varying and other parameters are set at its optimized value, it shows that the overall exergy efficiency of the module is maximum at $h_{FA} = 1$ W/m$^2$k.

Figure 4.7 shows the variation between overall exergy efficiency and velocity of flowing fluid. One can note that when the value of $V_F$ is varying and other parameters are set at its optimized value, it shows that the overall exergy efficiency of the module is optimum at $V_F = 4.5$ m/s. From Figure 4.4 to 4.7, it is concluded that the overall exergy efficiency is optimum, i.e. 16.88% at the optimized value of the parameters. These parameters are optimized using a genetic algorithm. After that, the analysis has been done for a following input data as given in Table 4.3 and obtained results are given in Table 4.4.

The convergence curve of the proposed GA is shown in Figure 4.8. The GA is applied at different instant of time, to analysis the different set of design parameters and
optimum efficiency for a particular set of design parameters. The value of intensity and ambient temperature for different time instant is given in Table 4.3. It is to be noted that the optimum value of overall exergy efficiency are obtained at 12:00 PM, 01:00 PM and 02:00 PM when the intensity and ambient temperature are at high values.

Table 4.3: Input data for a complete day

<table>
<thead>
<tr>
<th>Time / Data</th>
<th>08:00 AM</th>
<th>09:00 AM</th>
<th>10:00 AM</th>
<th>11:00 AM</th>
<th>12:00 Noon</th>
<th>01:00 PM</th>
<th>02:00 PM</th>
<th>03:00 PM</th>
<th>04:00 PM</th>
<th>05:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity of solar Light ($I_{SL}$) in kWh</td>
<td>132.99</td>
<td>355.56</td>
<td>554.69</td>
<td>680.73</td>
<td>726.74</td>
<td>733.85</td>
<td>656.08</td>
<td>500.00</td>
<td>311.46</td>
<td>106.42</td>
</tr>
<tr>
<td>Ambient Temperature ($T_A$) in °C</td>
<td>7.90</td>
<td>7.90</td>
<td>7.90</td>
<td>6.60</td>
<td>6.40</td>
<td>7.70</td>
<td>10.60</td>
<td>13.00</td>
<td>15.00</td>
<td>16.50</td>
</tr>
</tbody>
</table>

Figure 4.8: Variation between overall exergy efficiency and generation at different instant of time, different intensity and ambient temperature
The optimized parameters and optimum values of overall exergy efficiency are given in Table 4.4. From Table 4.4 it is clear that the design parameters are approximately equal. So for better design parameters we can consider the average value of parameters as shown in Table 4.5.

**Table 4.4: Value of Optimized Parameters for a Day Time**

<table>
<thead>
<tr>
<th>Depth, d (m)</th>
<th>Length, L (m)</th>
<th>Heat transfer coefficient, ( h_{FA} )</th>
<th>Velocity of flowing fluid, ( V_F )</th>
<th>% ( \eta_{Ex} )</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00080</td>
<td>0.2325</td>
<td>4.5</td>
<td>16.264</td>
<td>8:00AM</td>
<td></td>
</tr>
<tr>
<td>0.00075</td>
<td>0.2258</td>
<td>4.5</td>
<td>16.551</td>
<td>9:00AM</td>
<td></td>
</tr>
<tr>
<td>0.00077</td>
<td>0.2346</td>
<td>4.5</td>
<td>16.764</td>
<td>10:00AM</td>
<td></td>
</tr>
<tr>
<td>0.00067</td>
<td>0.2031</td>
<td>4.5</td>
<td>16.882</td>
<td>11:00AM</td>
<td></td>
</tr>
<tr>
<td>0.00079</td>
<td>0.2397</td>
<td>4.5</td>
<td>16.921</td>
<td>12:00 NOON</td>
<td></td>
</tr>
<tr>
<td>0.00071</td>
<td>0.2163</td>
<td>4.5</td>
<td>16.922</td>
<td>01:00PM</td>
<td></td>
</tr>
<tr>
<td>0.00075</td>
<td>0.2274</td>
<td>4.5</td>
<td>16.849</td>
<td>02:00PM</td>
<td></td>
</tr>
<tr>
<td>0.00076</td>
<td>0.2301</td>
<td>4.5</td>
<td>16.702</td>
<td>03:00PM</td>
<td></td>
</tr>
<tr>
<td>0.00068</td>
<td>0.2053</td>
<td>4.5</td>
<td>16.502</td>
<td>04:00PM</td>
<td></td>
</tr>
<tr>
<td>0.00082</td>
<td>0.2352</td>
<td>4.5</td>
<td>16.249</td>
<td>05:00PM</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.5: Average Value of Optimum Parameter for a Day**

<table>
<thead>
<tr>
<th>Depth, d (m)</th>
<th>Length, L (m)</th>
<th>Heat transfer coefficient, ( h_{FA} )</th>
<th>Velocity of flowing fluid, ( V_F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00075</td>
<td>0.2250</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.9 shows the variation in overall exergy efficiency with respect to the depth of the channel. It has been observed that when the depth of the channel is varying and other parameters are set at its optimized value as shown in Table 4.2, it shows that the overall exergy efficiency of the module is optimum in the range of \( d = 0.00067 \)m to 0.00082m and can also be seen in Table 4.4.

While the Figure 4.10 shows the variation in overall exergy efficiency with respect to the length of the channel. It has been observed that when the length of the channel is varying and other parameters are set at its optimized value as shown in Table 4.2, it shows that the overall exergy efficiency of the module is optimum in the range of \( L = 0.2031 \)m to 0.2397m and also can be seen in Table 4.4.
Figure 4.9: Plots of overall exergy efficiency Vs depth of the channel at different instant of time at different intensity and ambient temperature

Figure 4.10: Plots of overall exergy efficiency Vs length of the channel at different instant of time at different intensity and ambient temperature
Figure 4.11 shows a variation between overall exergy efficiency and heat transfer coefficient from flowing fluid to ambient $h_{FA}$. It has been observed that when the value of $h_{FA}$ is varying and other parameters are set at its optimized value, it shows that the overall exergy efficiency of the module is optimum at $h_{FA} = 1$ and also can be seen in Table 4.4.

Figure 4.11: Plots of overall exergy efficiency Vs heat transfer coefficient $h_{FA}$ at different instant of time, different intensity and ambient temperature

Figure 4.12 shows a variation between overall exergy efficiency and velocity of flowing fluid. It has been observed that when the velocity of the flowing fluid is varying and other parameters are set at its optimized value, it shows that the overall exergy efficiency of the module is optimum at $V_F = 4.5$ m/s and can also be seen in Table 4.4.

The complete graph of overall exergy efficiency and daytime is shown in Figure 4.13, in which, it is clear that when the intensity is varied, the exergy efficiency varies continuously. It is observed that when the intensity of light is maximum, then the exergy efficiency is maximum. Figure 4.14 shows the variation in cell temperature and electrical efficiency with respect to daytime. It shows that, when a cell temperature is at its maximum value, then the electrical efficiency is at its minimum value and vice versa. It is concluded that the cell temperature is affecting the electrical efficiency.
Figure 4.12: Plots of overall exergy efficiency Vs velocity of flowing fluid at different instant of time, different intensity and ambient temperature

Figure 4.13: Variation in overall exergy efficiency with respect to daytime
Figure 4.14: Variation in electrical efficiency and cell temperature with respect to daytime

Figure 4.15: Variation in overall exergy efficiency and cell temperature with respect to daytime
Figure 4.15 shows the variation between overall exergy efficiency and Cell temperature with respect to daytime. From Figure 4.15, it has been observed that the overall exergy efficiency is optimum when cell temperature is maximum and vice versa. Figure 4.16 shows the variation of electrical efficiency and overall exergy efficiency with respect to daytime. From Figure 4.16, it has been observed that the electrical efficiency is optimized when the overall exergy efficiency is minimum and vice versa due to the dependency of electrical efficiency on cell temperature and it is a negative temperature coefficient of cell temperature while the thermal efficiency is the positive temperature coefficient of cell temperature.

![Figure 4.16: Variation in overall exergy efficiency and electrical efficiency with respect to daytime](image)

Figure 4.17 and Figure 4.18 shows the variation in annual overall exergy gain and annual overall thermal gain respectively, in different cities of India namely; New Delhi, Jodhpur, Srinagar and Bangalore. This evaluation of overall gain has been made for Set A to Set D types of weather conditions are taken as reported in the research by Agrawal and Tiwari (2011).
Figure 4.17: Annual overall exergy gain for four different cities of India by considering set A to set D type weather conditions.

Figure 4.18: Annual overall thermal gain for four different cities of India by considering set A to set D type weather conditions.

An overall annual exergy gain of the proposed SCUPVT system was found to have increased by 14.29%, 16.67%, 14.81% and 8.18% in comparison to the micro channel.
photovoltaic thermal module proposed by Agrawal and Tiwari (2011c) for New Delhi, Jodhpur, Srinagar and Bangalore Indian climatic conditions respectively. The overall annual thermal gain of the proposed SCUPVT system was observed to have improved by 31.58%, 26.83%, 30.67% and 23.86% over the micro channel photovoltaic thermal module proposed by Agrawal and Tiwari (2011c) for New Delhi, Jodhpur, Srinagar and Bangalore for Indian climatic conditions respectively. It is also observed that the overall exergy gain and overall thermal gain are maximum for Bangalore as compared to other cities due to more numbers of sunshine hours. Similarly, it is minimum for Srinagar due to a cold environment and less number of sunshine hours.

4.2 GLAZED PHOTOVOLTAIC THERMAL MODULE

The few works have been done on the PVT module using a Genetic Algorithm. Some related work reported in the literature. The originality of the work presented in this section is to optimize the parameter of the glazed PVT module, of which modeling of such system is reported in literature. Depleting fuel reserves, increasing energy demand, fast rise in the fuel import bill, and compulsions of the Kyoto protocol insisting to minimize Greenhouse-gas (GHG) emissions bring to bear irresistible pressure on India to strap up renewable energy resources as the most suitable alternative to fossil fuels for electricity generation. It is high time for the country to change the country’s energy basket by shifting its focus from conventional fossil fuels (coal and diesel) to renewable energy resources for electricity generation. Lots of theoretical and experimental work on hybrid photovoltaic thermal systems is reported in the literature. These (PVT) systems preliminarily utilize thermal energy from the sun to produce electrical energy. The objective of this effort is to examine an improvement in the efficiency of photovoltaic thermal (PVT) system with the help of genetic algorithm (GA) with multi-objective functions for New Delhi, India climatic condition.

4.2.1 System Description

In this work, the proposed module comprises channel between tedlar and insulation. The glass is considered above the solar cell structure. The schematic view of photovoltaic thermal module is shown in Figure 4.19.
Figure 4.19: Proposed single channel glazed photovoltaic thermal (SCGPVT) module

Figure 4.20: Side view of single channel glazed photovoltaic thermal module

The module is called single channel glazed photovoltaic thermal module (SCGPVTM). The side view of SCPVTM is shown in Figure 4.20. In order to obtain maximum overall exergy efficiency and overall thermal efficiency, different parameters of SCGPVTM are optimized using GA. When solar radiation impinge on PV module, the solar energy is converted into electrical energy and thermal energy. The front surface of a PV module must have a high transmission in the wavelengths which can be used by the solar cells in the PV module. For silicon solar cells, the top surface must have high transmission of light in the wavelength range of 350 nm to 1200 nm. In addition, the reflection from the front
surface should be low. Anti-reflection coating is applied on the top surface of the module in order to reduce the reflection, in practice these coatings are not robust enough to withstand the conditions in which most PV systems are used. Due to thermal energy the PV cell gets heated resulting in reduced electrical efficiency because solar cells in the module are made with semiconductor material. The cooling of PV modules is essential in order to maintain the electrical efficiency. The module assumes solar radiation being absorbed by solar cell and heat energy conducting to the base of the tedlar due to the radiation. Air is flowing into the channel below the tedlar as shown in Figure 4.19.

4.2.2 Thermal Modeling

In order to write the energy balance equation of SCGPVT module, same assumption, consider in section 4.1.2 are considered.

The SCPVT cell is shown in Figure 4.19. The small area of SCPVT cell is bdx. The energy balance equation of the glazed hybrid SCPVT cell as is given by Agrwal and Tiwari (2011), is as follows

$$\left[ \frac{\text{Rate of solar energy available on glazed solar cell}}{\text{Rate of heat loss from top surface of solar cell to ambient through glass cover}} \right] + \left[ \frac{\text{Rate of heat transfer from solar cell to flowing fluid i.e. air through tedlar}}{\text{Rate of electrical energy produced}} \right] = \left[ \frac{\text{Rate of heat gain by flowing fluid i.e. air in channel}}{\text{Rate of heat transfer from flowing fluid (air) through tedlar}} \right]$$

$$\left[ \alpha_c \tau_g I_{SL} \times bdx \right] = \left[ U_{SCAG} (T_{SC} - T_A) bdx \right] + \left[ U_{SCFT} (T_{SC} - T_F) bdx \right] + \left[ \tau_g \eta_{TC} I_{SL} \times bdx \right]$$  \hspace{1cm} (4.19)

The energy balance for air flowing into the channel of SCGPVT for elemental area bdx is given by -

$$U_{SCFT} (T_{SC} - T_F) bdx = m_F C_{air} \frac{dT_F}{dx} dx + U_{FA} (T_F - T_A) bdx$$  \hspace{1cm} (4.20)

Where $m_F = \rho \times L \times d \times V_F$
Solving Equation 4.20, we have

\[
\alpha_c \tau_g I_{SL} \times bdx = \left[ U_{SCAG} (T_{SC} - T_A) bdx \right] + \left[ U_{SCFT} (T_{SC} - T_F) bdx \right] + \left[ \tau_g \eta_IC_{SL} \times bdx \right]
\]

\[
\alpha_c \tau_g I_{SL} = (U_{SCAG} + U_{SCFT}) T_{SC} - U_{SCAG} T_A - T_F U_{SCFT} + \tau_g \eta_{TC} I_{SL}
\]

\[
(U_{SCAG} + U_{SCFT}) T_{SC} = (\alpha_c - \eta_{TC}) \tau_g I_{SL} + U_{SCAG} T_A + T_F U_{SCFT}
\]

\[
T_{SC} = \frac{\alpha_{eff} I_{SL} + U_{SCAG} T_A + U_{SCFT} T_F}{U_{SCAG} + U_{SCFT}}
\]

(4.21)

Where

\[
\alpha_{eff} = \tau_g (\alpha_{SC} - \eta_{TC})
\]

From Equation 4.21 we know that:

\[
T_{SC} - T_F = \frac{\alpha_{eff} I_{SL} + U_{SCAG} T_A + U_{SCFT} T_F}{U_{SCAG} + U_{SCFT}} - T_F
\]

\[
T_{SC} - T_F = \frac{\alpha_{eff} I_{SL} + U_{SCAG} T_A - U_{SCAG} T_F}{U_{SCAG} + U_{SCFT}}
\]

\[
(T_{SC} - T_F) U_{SCFT} = \frac{\alpha_{eff} U_{SCFT} I_{SL} + U_{SCAG} U_{SCFT} T_A - U_{SCAG} U_{SCFT} T_F}{U_{SCAG} + U_{SCFT}}
\]

(4.22)

Now solving Equations 4.22

\[
U_{SCFT} (T_{SC} - T_F) bdx = m_F C_{air} \frac{dT_F}{dx} dx + U_{FA} (T_F - T_A) bdx
\]

\[
m_F C_{air} \frac{dT_F}{dx} = U_{SCFT} (T_{SC} - T_F) b - U_{FA} (T_F - T_A) b
\]

(4.23)

Now putting the value of \((T_{SC} - T_F) U_{SCFT}\) from Equation 4.30 in Equation 4.31, we get:

\[
m_F C_{air} \frac{dT_F}{dx} = b \left[ \alpha_{eff} U_{SCFT} I_{SL} - U_{SCAG} U_{SCFT} (T_F - T_A) - (U_{SCAG} U_{FA} + U_{SCFT} U_{FA}) (T_F - T_A) \right] \]

\[
m_F C_{air} \frac{dT_F}{dx} = b \left[ \alpha_{eff} U_{SCFT} I_{SL} - (U_{SCAG} U_{SCFT} + U_{SCAG} U_{FA} + U_{SCFT} U_{FA}) (T_F - T_A) \right] \]

\[
76
\]
\[
\frac{dT_F}{dx} = \frac{b}{m_F c_{air}} \left[ \alpha_{eff} U_{SCFT} I_{SL} - \frac{(U_{SCAG} U_{SCFT} + U_{SCAG} U_{FA} + U_{SCFT} U_{FA})}{U_{SCAG} + U_{SCFT}} (T_F - T_A) \right]
\]

\[
\frac{dT_F}{dx} = \frac{b}{m_F c_{air}} \left[ h_p \alpha_{eff} I_{SL} - U_{fa} (T_F - T_A) - U_{FA} (T_F - T_A) \right]
\]

\[
\frac{dT_F}{dx} = \frac{b}{m_F c_{air}} \left[ h_p \alpha_{eff} I_{SL} - [U_{fa} + U_{FA}](T_F - T_A) \right]
\]

\[
\frac{dT_F}{dx} = \frac{b}{m_F c_{air}} \left[ h_p \alpha_{eff} I_{SL} - U_L (T_F - T_A) \right]
\]

Where

\[
h_p = \left( \frac{U_{SCFT}}{U_{SCAG} + U_{SCFT}} \right) \quad U_{fa} = \frac{U_{SCAG} U_{SCFT}}{U_{SCAG} + U_{SCFT}}
\]

\[
U_{SCAG} = \left( \frac{L_G}{K_G + \frac{1}{h_{GA}}} \right)^{-1} \quad U_{SCFT} = \left( \frac{L_T}{K_T + \frac{1}{h_{TF}}} \right)^{-1}
\]

\[
U_{FA} = \left( \frac{L_T}{K_T + \frac{1}{h_{TA}}} \right)^{-1} \quad U_L = U_{fa} + U_{fa}
\]

Now

\[
\frac{dT_F}{dx} + \frac{b}{m_F c_{air}} U_L T_F = \frac{b}{m_F c_{air}} \left[ h_p \alpha_{eff} I_{SL} + U_L T_A \right] \quad (4.24)
\]

\[
\frac{dT_F}{dx} + a T_F = f(t) \quad (4.24)
\]

Where

\[
a = \frac{b}{m_F c_{air}} U_L \quad f(t) = \frac{b}{m_F c_{air}} \left[ h_p \alpha_{eff} I_{SL} - U_L T_A \right]
\]

Now solving Equation 4.24, we get:

\[
e^{ax} \frac{dT_F}{dx} + e^{ax} a T_F = e^{ax} f(t)
\]

\[
\frac{d}{dx} \left( e^{ax} T_F \right) = e^{ax} f(t) \quad (4.25)
\]

Integrating equation 4.25, we get:
\[ e^{ax}T_F = \frac{f(t)}{a}e^{ax} + C \] where \( C \) is a constant.

\[ T_F = \frac{f(t)}{a} + C.e^{-ax} \]  \hspace{1cm} (4.26)

Now at \( x = 0, \quad T_F = T_{FI} \)

Hence \[ T_{FI} = \frac{f(t)}{a} + C \]

\[ C = T_{FI} - \frac{f(t)}{a} \]

Now putting the value of \( C \) in equation 4.26, we get:

\[ T_F = \frac{f(t)}{a} + T_{FI}.e^{-ax} - \frac{f(t)}{a}.e^{-ax} \]

\[ T_F = \frac{f(t)}{a} (1 - e^{-ax}) + T_{FI}.e^{-ax} \]  \hspace{1cm} (4.27)

We know that

\[ T_{FO} = T_F \bigg|_{x=L} \]

Hence the output temperature of fluid at cell 1 is:

\[ T_{FO} = \frac{f(t)}{a} (1 - e^{-aL}) + T_{FI}.e^{-aL} \]  \hspace{1cm} (4.28)

\( N \) number of small channel solar cell thermal tiles connected in series, i.e. the thermal output from one cell \( T_{FO} \) is the thermal input \( T_{FI} \) to the second cell and thermal output from the second cell \( T_{FO} \) is the thermal input to the third cell \( T_{FI} \) and so on, as shown in Figure 4.21. The output temperature of cell 2 is:

\[ T'_{FO} = \frac{f(t)}{a} (1 - e^{-aL}) + T_{FO}.e^{-aL} \]  \hspace{1cm} (4.29)
Now putting the value of $T_{FO}$ in Equation 4.28 from Equation 4.27, we get

\[
T'_{FO} = \frac{f(t)}{a} (1 - e^{-at}) + \left[ \frac{f(t)}{a} (1 - e^{-at} + T_{FI} e^{-at}) \right] e^{-at}
\]

\[
T'_{FO} = \frac{f(t)}{a} (1 - e^{-at}) + \frac{f(t)}{a} (1 - e^{-at}) e^{-at} + T_{FI} e^{-at}
\]

\[
T'_{FO} = \frac{f(t)}{a} (1 - e^{-at}) + \frac{f(t)}{a} (e^{-at} + e^{-2at}) + T_{FI} e^{-2at}
\]

\[
T'_{FO} = \frac{f(t)}{a} (1 - e^{-at}) [1 + e^{-at}] + T_{FI} e^{-2at}
\] (4.30)

Similarly the output temperature of fluid at cell 3 is

\[
T''_{FO} = \frac{f(t)}{a} (1 - e^{-at}) [1 + e^{-at}] + \left\{ \frac{f(t)}{a} (1 - e^{-at}) [1 + e^{-at}] + T_{FI} e^{-2at} \right\} e^{-at}
\]

\[
T''_{FO} = \frac{f(t)}{a} (1 - e^{-at}) [1 + e^{-at} + e^{-2at}] + T_{FI} e^{-3at}
\]

Now the output temperature of fluid at $N^{th}$ cell is:

\[
T^N_{FO} = \frac{f(t)}{a} (1 - e^{-at}) \left[ \frac{1 - e^{-Nal}}{1 - e^{-al}} \right] + T_{FI} e^{-(N+1)al}
\]

\[
T^N_{FO} = \frac{f(t)}{a} (1 - e^{-Nal}) + T_{FI} e^{-(N+1)al}
\] (4.31)
Putting the value of 'a' and 'f (t)' in Equation 4.31, we get

\[
T_{NO}^N = \left[ \frac{h_p \alpha_{eff} I_{SL}}{U_L} + T_A \right] \left(1 - e^{-\frac{-N_bU_1L}{m_F C_{air}}} \right) + T_{FT} \cdot e^{-\frac{-(N+1)bU_1L}{m_F C_{air}}}
\]  

(4.32)

The outlet temperature (\(T_{NO}^N\)) at Nth numbers of glazed hybrid single channel solar cell thermal tiles connected in series is given by Equation 4.32. The thermal efficiency also derived by Agrawal and Tiwari (2011) is found as:

\[
\eta_{th} = \frac{m_F C_{air}}{U_L N C \Delta T_{SC}} \left[ 1 - \exp \left( -\frac{-N_bU_1L}{m_F C_{air}} \right) \right] \left[ \frac{h_p \alpha_{eff} - U_L}{I_{SL}} \frac{(T_{FT} - T_A)}{I_{SL}} \right]
\]

(4.33)

The rate of useful thermal energy obtained for the \(N_R\) row of SCGPVT module is calculated as:

\[
Q_{U,N} = N_R m_F C_{air} \left[ \frac{h_p \alpha_{eff} - U_L}{I_{SL}} I_{T_{SL} + T_A - T_{FT}} \right] \cdot \left[ 1 - \exp \left( -\frac{-N_c bU_1L}{m_F C_{air}} \right) \right]
\]

(4.34)

An expression for electrical efficiency of the hybrid SCGPVT module which is a temperature dependent is given by Agrwal and Tiwari (2011) as follows:

\[
\eta = \eta_{EC} \left[ 1 - \beta_0 \left( \frac{\alpha_{eff} I_{SL}}{U_{SCAG} - U_{SCFT} - (T_{FO} - T_A)} + \frac{U_{SCFT} h_p \alpha_{eff} I_{SL}}{U_L U_{SCAG} + U_{SCFT}} \right) \left[ 1 - \exp \left( -\frac{-N_bU_1L}{m_F C_{air}} \right) \right] + \frac{U_{SCFT}}{U_{SCAG} + U_{SCFT}} \left[ 1 - \exp \left( -\frac{-N_c bU_1L}{m_F C_{air}} \right) \right] (T_A - T_{FT}) \right]
\]

(4.35)

4.2.2.1 Design Parameter of SCGPVT module

Design parameters of SCGPVT module are given in Table 4.6.

4.2.3 The function to be maximized in genetic algorithm (GA) and genetic algorithm-fuzzy system (GA-FS)

GA: The aim of this work is to examine an improvement in the efficiency of glazed photovoltaic thermal (PVT) system with the help of genetic algorithm (GA) with multi-objective functions for New Delhi, India climatic conditions. There are a number of parameters effecting the efficiency of PVT system which include the length and depth of the
channel, velocity of air fluid flowing into the channel, thickness of the tedlar and glass, temperature of inlet fluid. All these parameters have been considered to optimize the efficiency of the PVT system. An effort has also been made to design and optimize the parameters of SCGPVT module considering the two objective functions separately like, the overall exergy efficiency and the overall thermal efficiency. Using GA, Both of the above objective functions are separately optimized and analyzed for each of the two cases: namely, Case-I: Improvement in exergy and thermal efficiency when overall exergy efficiency is optimized and Case-II: Improvement in exergy and thermal efficiency when overall thermal efficiency is optimized. The variables used in GA are those that could be varied, keeping parameters like solar radiation, ambient temperature unchanged in the algorithmic calculation.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$V_{\text{air}}$, m/s</td>
<td>1.5</td>
</tr>
<tr>
<td>2.</td>
<td>$T_{\text{FO}}$</td>
<td>25°C</td>
</tr>
<tr>
<td>3.</td>
<td>$K_g$, W/mK</td>
<td>1.1</td>
</tr>
<tr>
<td>4.</td>
<td>$K_T$, W/mK</td>
<td>0.033</td>
</tr>
<tr>
<td>5.</td>
<td>$C_{\text{air}}$, J/kgK</td>
<td>1012</td>
</tr>
<tr>
<td>6.</td>
<td>$h_{\text{GA}}$, W/m²K</td>
<td>$5.7 + 3.8V_{\text{air}}$</td>
</tr>
<tr>
<td>7.</td>
<td>$h_{\text{IA}}$, W/m²K</td>
<td>$2.8 + 3V_F$</td>
</tr>
<tr>
<td>8.</td>
<td>$\beta_0$, 1/K</td>
<td>0.0045</td>
</tr>
<tr>
<td>9.</td>
<td>$\eta_{\text{TC}}$</td>
<td>0.15</td>
</tr>
<tr>
<td>10.</td>
<td>$N_C$</td>
<td>4</td>
</tr>
<tr>
<td>11.</td>
<td>$N_R$</td>
<td>9</td>
</tr>
<tr>
<td>12.</td>
<td>$\rho$, kg/m³</td>
<td>1.29</td>
</tr>
<tr>
<td>13.</td>
<td>$\tau_g$</td>
<td>0.95</td>
</tr>
<tr>
<td>14.</td>
<td>$\alpha_C$</td>
<td>0.9</td>
</tr>
<tr>
<td>15.</td>
<td>$K_{\text{in}}$, W/mK</td>
<td>0.089</td>
</tr>
<tr>
<td>16.</td>
<td>$h_{\text{TF}}$, W/mK</td>
<td>4.3</td>
</tr>
</tbody>
</table>
**GA-FS:** In genetic algorithm-fuzzy system approach the GA parameters like; crossover probability and mutation probability have been divided into three membership functions are named as Small, Average, Large and each function is assigned some membership values as shown in Table 4.7. The values of fitness function are determined by Equation 1.11. The GA parameters vary on the basis of fitness function as for each following logic:

I. The value of optimum fitness (OF) for every generation is likely to modify over a number of generations, but if it does not modify significantly over a number of generations (U-OF) then this information is considered to cause changes in both $P_{cross}$ and $P_{mut}$.

II. In search of true optimum, the diversity of the population is one of the important features which affect the search. The change in fitness values of the objective function (IF) of a population is a measure of its diversity. This is a second feature on which GA parameters may be changed.

The membership functions and membership values for these three variables (OF, U-OF and IF) are selected after several tries to get optimum results. Figure 1.11 shows a diagrammatic representation of GA-FS approach.

**Fuzzy Rule Base for GA-FS Approach**

The GA parameters in GA-FS approach is varied in accordance with fuzzy rule base for the maximization of overall exergy efficiency.

I. Rules for controlling $P_{cross}$

1. If $OF$ is **SMALL** then $P_{cross}$ is **LARGE**.
2. If $OF$ is **AVERAGE** or **LARGE** and $U-OF$ is **SMALL**, then $P_{cross}$ is **LARGE**.
3. If $OF$ is **AVERAGE** or **LARGE** and $U-OF$ is **AVERAGE**, then $P_{cross}$ is **AVERAGE**.
4. If $U-OF$ is **LARGE** and $IF$ is **SMALL** or **AVERAGE**, then $P_{cross}$ is **SMALL**.
   If $U-OF$ is **LARGE** and $IF$ is **LARGE** then $P_{cross}$ is **AVERAGE**.

II. Rules for controlling ($P_{mut}$)

1. If $OF$ is **SMALL** then $P_{mut}$ is **SMALL**.
2. If $OF$ is **AVERAGE** or **LARGE** and $U-OF$ is **SMALL**, then $P_{mut}$ is **SMALL**.
3. If $OF$ is **AVERAGE** or **LARGE** and $U-OF$ is **AVERAGE**, then $P_{mut}$ is **AVERAGE**.
4. If $U-OF$ is **LARGE** and $IF$ is **SMALL** or **AVERAGE**, then $P_{mut}$ is **LARGE**.
5. If $U-OF$ is **LARGE** and $IF$ is **AVERAGE**, then $P_{mut}$ is **SMALL**.
The initial value of the population size, crossover and mutation probability and maximum generation for system optimize with GA and GA-FS is given in Table 4.8 and 4.9 respectively.
Table 4.9: Initial Value to the Genetic Algorithm-Fuzzy System

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Input to GA</th>
<th>Input Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Crossover Probability ((P_c))</td>
<td>Crossover Probability ((P_c))</td>
<td>0.9</td>
</tr>
<tr>
<td>3.</td>
<td>Mutation Probability ((P_m))</td>
<td>Mutation Probability ((P_m))</td>
<td>0.01</td>
</tr>
<tr>
<td>4.</td>
<td>Maximum Generation</td>
<td>Maximum Generation</td>
<td>200</td>
</tr>
</tbody>
</table>

4.2.4 Methodology

- Identify control parameters influencing the overall exergy efficiency of the proposed SCGPVT module.
- Define upper and lower bound of each parameter value feasible for designing the SCGPVT module.
- Decide the objective function also known as fitness function. In this paper there are two objective function one is; overall exergy efficiency and the second is; overall thermal efficiency.
- MATLAB program has been developed for optimizing each parameter as based on the flow chart shown in Figure 1.6.

The same methodology as given in section 4.5 is adopted for the calculation of annual performance analysis of single channel glazed photovoltaic thermal (SCGPVT) module.

4.2.5 Results and Discussion

The optimization has been done with two techniques named as Genetic Algorithm and Genetic Algorithm-Fuzzy System approach.

4.2.5.1 Optimization with Genetic Algorithm

In this work, different parameters like; the depth of the channel \((d)\), length of the channel \((L)\), thickness of the top glass cover \((L_G)\), tedlar \((L_T)\) and insulation \((L_I)\), the velocity of the fluid, i.e. air \((V_F)\) and inlet air temperature \((T_{FI})\) have been optimized for maximizing efficiency of glazed photovoltaic thermal (PVT) system. The genetic algorithm is applied to the problem to optimize value of each parameter in order to maximize overall efficiency. The choice of one hour or single data is used for the optimization of the design parameters of
system as given in Table 4.10 and after optimizing the parameter further analysis has been
done for a complete day and the hourly input data for a complete day is given in Table 4.11.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Name of Input Parameter</th>
<th>Value of Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Intensity of Solar Light ($I_{SL}$)</td>
<td>680.73 W/m²</td>
</tr>
<tr>
<td>2.</td>
<td>Ambient Temperature ($T_A$)</td>
<td>6.6°C</td>
</tr>
</tbody>
</table>

**TABLE 4.11: INPUT DATA FOR A COMPLETE DAY FROM 08:00AM TO 05:00PM**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Time</th>
<th>Intensity of light (W/m²)</th>
<th>Ambient temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>08:00AM</td>
<td>132.99</td>
<td>7.90</td>
</tr>
<tr>
<td>2.</td>
<td>09:00AM</td>
<td>355.56</td>
<td>7.90</td>
</tr>
<tr>
<td>3.</td>
<td>10:00AM</td>
<td>554.69</td>
<td>7.90</td>
</tr>
<tr>
<td>4.</td>
<td>11:00AM</td>
<td>680.73</td>
<td>6.60</td>
</tr>
<tr>
<td>5.</td>
<td>12:00Noon</td>
<td>726.74</td>
<td>6.40</td>
</tr>
<tr>
<td>6.</td>
<td>01:00PM</td>
<td>733.85</td>
<td>7.70</td>
</tr>
<tr>
<td>7.</td>
<td>02:00PM</td>
<td>656.08</td>
<td>10.60</td>
</tr>
<tr>
<td>8.</td>
<td>03:00PM</td>
<td>500.00</td>
<td>13.00</td>
</tr>
<tr>
<td>9.</td>
<td>04:00PM</td>
<td>311.46</td>
<td>15.00</td>
</tr>
<tr>
<td>10.</td>
<td>05:00PM</td>
<td>106.42</td>
<td>16.50</td>
</tr>
</tbody>
</table>

The input data (ambient temperature and solar intensity) considered for analysis have
been obtained from IMD, Pune for a New Delhi, India for a complete year (2009) for four
weather conditions like hazy days, cloudy days, hazy and cloudy days and clear days called
as Set A to Set D respectively as considered by Agrawal and Tiwari (2011) as given in
Appendix A.

**Case-I:** Improvement occurs in exergy and thermal efficiencies when the overall exergy
efficiency is considered as an objective function:

**A. Single data analysis at 11:00AM**

Overall exergy efficiency of single channel glazed PVT module has been optimized
and observations are shown in the Figures 4.23 to 4.28. The input data at 11:00AM is shown
in the Table 4.10. The variation in overall exergy efficiency and fitness value with respect to
generation have been observed shown in Figure 4.22 (a) and (b) respectively, whereby the
optimum value of overall exergy efficiency of SCGPVT module is found to be 14.87%. It is
clear that the value of overall exergy efficiency has been optimized by a genetic algorithm within 1500 generations.

![Graphs showing variation in fitness value and overall exergy efficiency over generations.]

Figure 4.22: (a) Variation in fitness value with respect to generation
(b) Variation in overall exergy efficiency with respect to generation

**TABLE 4.12: OPTIMIZED PARAMETERS WHEN OVERALL EXERGY EFFICIENCY IS OPTIMIZED**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>Optimized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thickness of channel (d)</td>
<td>0.00082 m</td>
</tr>
<tr>
<td>2</td>
<td>Length of channel (L)</td>
<td>0.0341 m</td>
</tr>
<tr>
<td>3</td>
<td>Thickness of back insulation L_{in}</td>
<td>0.1200 m</td>
</tr>
<tr>
<td>4</td>
<td>Velocity of flowing fluid (V_F)</td>
<td>1.0709 m/s</td>
</tr>
<tr>
<td>5</td>
<td>Thickness of tedlar (L_t)</td>
<td>0.0001 m</td>
</tr>
<tr>
<td>6</td>
<td>Thickness of top glass cover (L_g)</td>
<td>0.00016 m</td>
</tr>
<tr>
<td>7</td>
<td>Temperature of fluid at inlet (T_{FI})</td>
<td>15°C</td>
</tr>
</tbody>
</table>

Output observed at 11:00 AM:

The optimum value of overall exergy efficiency of SCGPVT module is 14.87%, which is obtained at optimized parameters. The optimized parameters are given in Table 4.12. The convergence curve is shown in Figure 4.22. The results of the analysis are shown in the Table 4.13.
Figure 4.23: Variation in overall exergy efficiency with respect to daytime.

**TABLE 4.13: RESULTS OBTAINED AT 11:00 AM WHEN OVERALL EXERGY EFFICIENCY IS OPTIMIZED**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Overall exergy efficiency</td>
<td>14.87%</td>
</tr>
<tr>
<td>2</td>
<td>Thermal efficiency</td>
<td>11.88%</td>
</tr>
<tr>
<td>3</td>
<td>Exergy efficiency</td>
<td>14.15%</td>
</tr>
<tr>
<td>4</td>
<td>Overall thermal efficiency</td>
<td>49.11%</td>
</tr>
</tbody>
</table>

**B. Analysis for a Complete Day from 08:00AM to 05:00PM**

The overall exergy efficiency is calculated for a complete day from 08:00AM to 05:00PM at optimized parameters. The optimized parameters are given in Table 4.12. The input data for complete day is shown in the Table 4.11.

Figures 4.23 and 4.24 shows the variation in overall exergy efficiency and Cell temperature with respect to daytime, respectively, and it has been observed that the exergy efficiency is optimum (15.8%) when cell temperature is minimum at 8:00AM while the exergy efficiency is minimum (14.6%) when the cell temperature is maximum at 1:00PM and it is concluded that the exergy efficiency depends on the cell temperature.
From Figure 4.25, it is observed that the trend of exergy efficiency is similar to the trend of overall exergy efficiency. It has been inferred that the effect of thermal efficiency on overall exergy efficiency is less while overall exergy efficiency is an objective function. Figure 4.26 leads to the conclusion that thermal efficiency is regularly increasing during daytime but it is not influencing the overall exergy efficiency in the same way.
Figure 4.26: Variation in thermal efficiency with respect to daytime.

Figure 4.27: Variation between overall thermal efficiency and daytime.
From Figure 4.27, it is to be noted that the trend of overall thermal efficiency is similar to the trend of thermal efficiency. There is a 4.6% improvement in overall exergy efficiency while the overall exergy efficiency is considered as an objective function.

C. Analysis for a Complete Year

Overall exergy efficiency is evaluated for a year from January to December at optimized parameters (Table 4.12). Figure 4.28 shows the variation in overall exergy efficiency with respect to month including all weather conditions and it leads to the conclusion that the overall exergy efficiency is optimum (15.68%) for the month January and minimum (12.71%) for the month of May. Figure 4.29 shows a value of overall thermal gain for different months of the year and it leads to the conclusion that the overall thermal gain is maximum (4.73 kWh) for the month May and it is minimum (2.23 kWh) for the month December. Figure 4.30 shows a value of overall exergy gain for different months of the year and it leads to the conclusion that the overall exergy gain is maximum (1.02 kWh) for the month May and it is minimum (0.61 kWh) for the month November.

Figure 4.28: Variation between overall exergy efficiency and months including all weather conditions of New Delhi
Figure 4.29: Variation in overall thermal gain with respect to month, including all weather conditions of New Delhi.

Figure 4.30: Variation in overall exergy gain with respect to month, including all weather conditions of New Delhi
D. Optimization for a Complete Year from January to December

Optimization has been performed for a complete year. GA tools operate according to the algorithm as shown in Figure 1.6. It operates at the single data at a time and it gives a set of optimized parameters for each month and takes next data after previous execution and it continues until the input data are over. The results obtained during the optimization process are shown in Table 4.14 which indicates distinct value of optimize parameter for each month.

It leads to conclusion that there is very slight variation in one set of optimized parameters to another set for each month. We have considered average values of parameters for optimization of overall exergy efficiency as shown in Table 4.15. The value of overall exergy efficiency has been evaluated on the average value of optimized parameters and it is found 14.86 % as given in Table 4.15 which is similar to the overall exergy efficiency 14.87 %, on single data.

Table 4.14: Results obtained at 11:00 AM for each month when overall exergy efficiency is optimized

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Months</th>
<th>d (m)</th>
<th>L (m)</th>
<th>L_{in} (m)</th>
<th>V_{F} (m/s)</th>
<th>L_{L} (m)</th>
<th>L_{g} (m)</th>
<th>T_{fi} (^{0}C)</th>
<th>Overall exergy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>January</td>
<td>0.0008</td>
<td>0.0291</td>
<td>0.1192</td>
<td>0.97</td>
<td>0.0001</td>
<td>0.0001</td>
<td>14.81</td>
<td>14.862</td>
</tr>
<tr>
<td>2</td>
<td>February</td>
<td>0.0008</td>
<td>0.0475</td>
<td>0.1180</td>
<td>1.41</td>
<td>0.0001</td>
<td>0.0003</td>
<td>15.00</td>
<td>14.861</td>
</tr>
<tr>
<td>3</td>
<td>March</td>
<td>0.0006</td>
<td>0.0289</td>
<td>0.1192</td>
<td>1.42</td>
<td>0.0001</td>
<td>0.0008</td>
<td>14.91</td>
<td>14.857</td>
</tr>
<tr>
<td>4</td>
<td>April</td>
<td>0.0009</td>
<td>0.0289</td>
<td>0.1200</td>
<td>0.85</td>
<td>0.0001</td>
<td>0.0002</td>
<td>14.98</td>
<td>14.863</td>
</tr>
<tr>
<td>5</td>
<td>May</td>
<td>0.0005</td>
<td>0.0228</td>
<td>0.1160</td>
<td>1.24</td>
<td>0.0001</td>
<td>0.0004</td>
<td>14.96</td>
<td>14.859</td>
</tr>
<tr>
<td>6</td>
<td>June</td>
<td>0.0007</td>
<td>0.0278</td>
<td>0.1200</td>
<td>0.90</td>
<td>0.0001</td>
<td>0.0006</td>
<td>14.94</td>
<td>14.860</td>
</tr>
<tr>
<td>7</td>
<td>July</td>
<td>0.0008</td>
<td>0.0190</td>
<td>0.1175</td>
<td>0.54</td>
<td>0.0001</td>
<td>0.0007</td>
<td>14.89</td>
<td>14.860</td>
</tr>
<tr>
<td>8</td>
<td>August</td>
<td>0.0007</td>
<td>0.0420</td>
<td>0.1193</td>
<td>1.43</td>
<td>0.0001</td>
<td>0.0001</td>
<td>14.94</td>
<td>14.862</td>
</tr>
<tr>
<td>9</td>
<td>September</td>
<td>0.0008</td>
<td>0.0260</td>
<td>0.1186</td>
<td>0.70</td>
<td>0.0001</td>
<td>0.0001</td>
<td>14.45</td>
<td>14.861</td>
</tr>
<tr>
<td>10</td>
<td>October</td>
<td>0.0008</td>
<td>0.0356</td>
<td>0.1161</td>
<td>1.21</td>
<td>0.0001</td>
<td>0.0006</td>
<td>14.94</td>
<td>14.855</td>
</tr>
<tr>
<td>11</td>
<td>November</td>
<td>0.0008</td>
<td>0.0266</td>
<td>0.1125</td>
<td>0.76</td>
<td>0.0002</td>
<td>0.0001</td>
<td>14.96</td>
<td>14.853</td>
</tr>
<tr>
<td>12</td>
<td>December</td>
<td>0.0008</td>
<td>0.0395</td>
<td>0.1199</td>
<td>1.35</td>
<td>0.0001</td>
<td>0.0005</td>
<td>14.99</td>
<td>14.861</td>
</tr>
</tbody>
</table>

Table 4.15: Average parameters obtained at 11:00 AM for each month when overall exergy efficiency is optimized

<table>
<thead>
<tr>
<th>S.No.</th>
<th>D (m)</th>
<th>L (m)</th>
<th>L_{in} (m)</th>
<th>V_{F} (m/s)</th>
<th>L_{L} (m)</th>
<th>L_{g} (m)</th>
<th>T_{fi} (^{0}C)</th>
<th>Overall exergy efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0008</td>
<td>0.0311</td>
<td>0.1180</td>
<td>0.91</td>
<td>0.0001</td>
<td>0.0004</td>
<td>14.89</td>
<td>14.86</td>
</tr>
</tbody>
</table>

Case-II: Improvement occurs in exergy and thermal efficiencies when overall thermal efficiency is considered as an objective function.
A. Single data analysis at 11:00AM

Overall thermal efficiency of single channel glazed photovoltaic thermal module has been optimized and observations are shown in Figures 4.31 to 4.36. The input data at 11:00AM is shown in Table 4.10. The variation in fitness function and overall thermal efficiency with respect to generation is shown in Figure 4.31 whereby, the maximum overall thermal efficiency of SCGPVT module is found to be 56.54% and it is clear that the value of overall thermal efficiency has been optimized by a genetic algorithm within 1000 generations. The numeric values of optimized parameters are given in Table 4.12 and Table 4.16 respectively, when overall exergy and overall thermal efficiencies are considered as objective function. The value of input parameters is given in Table 4.10 and 4.11.

Output observed at 11:00AM:

The maximum overall thermal efficiency of SCGPVT module is 56.54 %, which is obtained at optimum value of the parameters. The optimized parameters are given in Table 4.16. The convergence curve is shown in Figure 4.31. The results of the analysis are shown in the Table 4.17.
TABLE 4.16: OPTIMIZED PARAMETERS WHEN OVERALL THERMAL EFFICIENCY IS OPTIMIZED

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of channel (d)</td>
<td>0.00089 m</td>
</tr>
<tr>
<td>Length of channel (L)</td>
<td>0.0100 m</td>
</tr>
<tr>
<td>Thickness of back insulation $L_{in}$</td>
<td>0.00919 m</td>
</tr>
<tr>
<td>Velocity of flowing fluid $V_f$</td>
<td>1.4990 m/s</td>
</tr>
<tr>
<td>Thickness of tedlar ($L_t$)</td>
<td>0.0001 m</td>
</tr>
<tr>
<td>Thickness of top glass cover $L_g$</td>
<td>0.00085 m</td>
</tr>
<tr>
<td>Temperature of fluid at inlet $T_{in}$</td>
<td>5.0089°C</td>
</tr>
</tbody>
</table>

TABLE 4.17: RESULTS OBTAINED AT 11:00 AM WHEN OVERALL THERMAL EFFICIENCY IS OPTIMIZED

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Overall exergy efficiency</td>
<td>14.18 %</td>
</tr>
<tr>
<td>2.</td>
<td>Thermal efficiency</td>
<td>19.48 %</td>
</tr>
<tr>
<td>3.</td>
<td>Exergy efficiency</td>
<td>14.08 %</td>
</tr>
<tr>
<td>4.</td>
<td>Overall thermal efficiency</td>
<td>56.54%</td>
</tr>
</tbody>
</table>

B. Analysis for a complete day from 08:00AM to 05:00PM

Overall thermal efficiency is calculated for a complete day at optimum value of the parameters. The optimized parameters are given in Table 4.16. The input data for complete day is shown in the Table 4.11.

Figure 4.32: Variation between overall thermal efficiency and daytime.
Figure 4.32 and Figure 4.33 show the variation in overall thermal efficiency and ambient temperature with respect to time, respectively, and it has been observed that the overall thermal efficiency depends on the ambient temperature. When ambient temperature is maximum then the overall thermal efficiency is maximum at 5:00PM while the overall thermal efficiency is minimum at 12:00 Noon when the ambient temperature is minimum.

Figure 4.33: Variation between ambient temperature and daytime.

From Figure 4.34 it has been observed that the trend of thermal efficiency is similar to the trend of overall thermal efficiency. This leads us to conclude that the effect of exergy efficiency on overall thermal efficiency is less, while overall thermal efficiency is considered as an objective function.

Figure 4.35 shows that the overall exergy efficiency is regularly decreasing during daytime without much influence on overall thermal efficiency. Similarly, from Figure 4.36, it is observed that the variation in exergy efficiency is not similar to the variation of overall exergy efficiency as was the case for thermal efficiency.

There is a 13.14% improvement in overall thermal efficiency while the overall thermal efficiency is considered as an objective function. The optimized parameters have been obtained with the help of GA tool. Now this is challenging to industry how can they
manufactured such proposed hybrid SCGPVT module to get better electrical efficiency and the same time we are able to get thermal energy which can be useful.

Figure 4.34: Variation between thermal efficiency and daytime.

Figure 4.35: Variation between the overall exergy efficiency and daytime.
4.2.5.2 Optimization with Genetic Algorithm-Fuzzy System (GA-FS) Approach

The optimized parameters of the SCGPVT module, optimized with GA and GA-FS approach is given in Table 4.18 and Table 4.19 respectively. There are six parameters like; length and depth of the channel, velocity of flowing fluid, overall heat transfer coefficient from solar cell to ambient and flowing fluid and overall back loss heat transfer coefficient from flowing fluid to the ambient, have been considered for optimization during the maximizing process of overall exergy efficiency.

The comparative study has been presented here for three types of system like; (i) Glazed PVT module without GA as proposed by Agarwal & Tiwari (2011) (ii) Glazed PVT module optimized with GA. (iii) Glazed PVT module optimized with GA-FS Approach. Firstly the overall exergy efficiency as indicated by Equation 1.11 is evaluated at 11:00 AM for the month of January 2009. Further the annual overall exergy and thermal gains have been evaluated for New Delhi climatic conditions. The same methodology has been adopted as considered by Agarwal & Tiwari (2011c) for the evaluation of annual thermal gain, annual exergy gain and overall exergy efficiency. The design parameters for the system without GA

Figure 4.36: Variation between the exergy efficiency and daytime.
are given in Table 4.20. Figure 4.37 shows a variation between the overall exergy efficiency and the generation for glazed PVT system optimized with GA-FS approach.

Figure 4.37: Variation in overall exergy efficiency with respect to generation for system optimized with GA-FS approach

<table>
<thead>
<tr>
<th>S. No</th>
<th>Optimize Parameters</th>
<th>Name of Parameter</th>
<th>Symbol</th>
<th>Optimize value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Depth of the channel</td>
<td>D</td>
<td>0.0008</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Length of the channel</td>
<td>L</td>
<td>0.0840</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Velocity of flowing fluid</td>
<td>V_F</td>
<td>3.24</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Overall heat transfer coefficient from cell to ambient through glass</td>
<td>U_SCAG</td>
<td>11.97</td>
<td>W/m^2</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Overall heat transfer coefficient from cell to fluid through tedlar</td>
<td>U_SCFT</td>
<td>4.99</td>
<td>W/m^2</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Overall back loss heat transfer coefficient from fluid to ambient</td>
<td>U_FA</td>
<td>5.01</td>
<td>W/m^2</td>
<td></td>
</tr>
</tbody>
</table>

From Figure 4.37, it has been observed that the overall exergy efficiency at 11:00 AM for the month of January is 15.82% and 15.69 % when optimized with GA-FS and GA respectively. The obtained overall exergy efficiency is optimum at 186 and 2995 generations when optimized with GA-FS approach and GA respectively. It indicates that the GA-FS
approach has faster convergence as compare to GA. The value of optimized parameters is given in Table 4.18 and Table 4.19 for glazed PVT system optimized with GA and GA-FS respectively.

**Table 4.19: Parameters optimized with GA-FS approach**

<table>
<thead>
<tr>
<th>S. No</th>
<th>Optimized Parameters</th>
<th>Name of Parameter</th>
<th>Symbol</th>
<th>Optimize value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Depth of the channel</td>
<td>D</td>
<td>0.00037</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Length of the channel</td>
<td>L</td>
<td>0.0601</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Velocity of flowing fluid</td>
<td>V_f</td>
<td>2.45</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Overall heat transfer coefficient from cell to ambient through glass</td>
<td>U_{SCAG}</td>
<td>11.64</td>
<td>W/m²</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Overall heat transfer coefficient from cell to fluid through tedlar</td>
<td>U_{SCFT}</td>
<td>4.95</td>
<td>W/m²</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Overall back loss heat transfer coefficient from fluid to ambient</td>
<td>U_{FA}</td>
<td>2.13</td>
<td>W/m²</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Crossover Probability</td>
<td>P_{cross}</td>
<td>0.6352</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Mutation Probability</td>
<td>P_{mut}</td>
<td>0.0034</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.38: Variation in crossover probability (P_{cross}) with respect to generation for system optimized with GA-FS approach
Figure 4.38 shows a variation in $P_{\text{cross}}$ with respect to generation for system optimized with GA-FS approach in which $P_{\text{cross}}$ converges within 10 generations. Similarly, Figure 4.39 shows a variation in $P_{\text{mut}}$ with respect to generation for system optimized with GA-FS approach in which $P_{\text{mut}}$ converges within 10 generations. The crossover probability and mutation probability are found to be 0.6352 and 0.0034 respectively as shown in Table 4.19. The design parameters of the system without GA is given in Table 4.20. The Output obtained from the glazed PVT system optimized with GA is given in Table 4.21 and Table 4.22.

The variables used in GA-FS approach and their membership value and linguistic terms are given in Table 4.7. The output obtained from the glazed PVT system optimized with GA-FS approach is given in Table 4.23 and Table 4.24. From Table 4.21 to 4.23, it has been observed that the overall exergy efficiency obtained from the system optimized with GA-FS approach is 15.82 %, which is 1.27 % and 5.40% more than the efficiency of the system optimized with genetic algorithm and system without GA respectively.
**TABLE 4.20: DESIGN PARAMETERS OF SYSTEM WITHOUT GA**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters And Their Value</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\tau_g$</td>
<td>0.95</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>$\eta_{TC}$</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>3.</td>
<td>$\alpha_C$</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>4.</td>
<td>$\beta_0$</td>
<td>0.0045</td>
<td>-</td>
</tr>
<tr>
<td>5.</td>
<td>$C_{air}$</td>
<td>1012</td>
<td>J/kg K</td>
</tr>
<tr>
<td>6.</td>
<td>$T_{FO}$</td>
<td>25</td>
<td>°C</td>
</tr>
<tr>
<td>7.</td>
<td>$V_{air}$</td>
<td>1.5</td>
<td>m/s</td>
</tr>
<tr>
<td>8.</td>
<td>$V_F$</td>
<td>0.9</td>
<td>m/s</td>
</tr>
<tr>
<td>9.</td>
<td>$m_F$</td>
<td>0.000108</td>
<td>Kg/s</td>
</tr>
<tr>
<td>10.</td>
<td>$K_g$</td>
<td>1.1</td>
<td>W/mK</td>
</tr>
<tr>
<td>11.</td>
<td>$L_g$</td>
<td>0.003</td>
<td>m</td>
</tr>
<tr>
<td>12.</td>
<td>$A_c$</td>
<td>0.0144</td>
<td>m$^2$</td>
</tr>
<tr>
<td>13.</td>
<td>$h_{GA}$</td>
<td>11.4</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>14.</td>
<td>$h_{TF}$</td>
<td>4.3</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>15.</td>
<td>$N, n_R$</td>
<td>4.9</td>
<td>-</td>
</tr>
<tr>
<td>16.</td>
<td>$\eta_{C, Power}$</td>
<td>0.38</td>
<td>-</td>
</tr>
<tr>
<td>17.</td>
<td>$h_{IA}$</td>
<td>7.3</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>18.</td>
<td>$U_{SCAG}$</td>
<td>11.1</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>19.</td>
<td>$U_{SCFT}$</td>
<td>4.03</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>20.</td>
<td>$U_{FA}$</td>
<td>6.89</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>21.</td>
<td>$U_{fa}$</td>
<td>2.94</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>22.</td>
<td>$U_{L}$</td>
<td>9.83</td>
<td>W/m$^2$K</td>
</tr>
</tbody>
</table>

**TABLE 4.21: OUTPUT OBTAINED FROM GLAZED PVT SYSTEM OPTIMIZED WITH GA**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>At 11:00 AM for New Delhi</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Overall exergy efficiency</td>
<td>15.69</td>
<td>%</td>
</tr>
<tr>
<td>2.</td>
<td>Annual overall exergy gain</td>
<td>124.59</td>
<td>kWh</td>
</tr>
<tr>
<td>3.</td>
<td>Annual overall thermal gain</td>
<td>388.47</td>
<td>kWh</td>
</tr>
<tr>
<td>4.</td>
<td>Elapsed time in optimization</td>
<td>123.14</td>
<td>Sec</td>
</tr>
<tr>
<td>5.</td>
<td>Number of generations at which optimization done</td>
<td>2995</td>
<td>Gen.</td>
</tr>
</tbody>
</table>

101
TABLE 4.22: MONTHLY OUTPUT OBTAINED FROM GLAZED PVT SYSTEM OPTIMIZE WITH GA

<table>
<thead>
<tr>
<th>S.No</th>
<th>OUTPUT</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JULY</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
</table>

TABLE 4.23: OUTPUT OBTAINED FROM THE GLAZED PVT SYSTEM OPTIMIZED WITH GA-FS

<table>
<thead>
<tr>
<th>S.No.</th>
<th>At 11:00 AM for New Delhi</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Overall exergy efficiency</td>
<td>15.82</td>
<td>%</td>
</tr>
<tr>
<td>2.</td>
<td>Annual overall exergy gain</td>
<td>125.23</td>
<td>kWh</td>
</tr>
<tr>
<td>3.</td>
<td>Annual overall thermal gain</td>
<td>422.46</td>
<td>kWh</td>
</tr>
<tr>
<td>4.</td>
<td>Elapsed time in optimization</td>
<td>15.70</td>
<td>Sec</td>
</tr>
<tr>
<td>5.</td>
<td>Number of generations at which optimization done</td>
<td>186</td>
<td>Gen.</td>
</tr>
</tbody>
</table>

TABLE 4.24: OUTPUT OBTAINED FROM GLAZED PVT SYSTEM OPTIMIZE WITH GA-FS APPROACH

<table>
<thead>
<tr>
<th>S.No</th>
<th>OUTPUT</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JULY</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
</table>

The improvements in annual overall exergy gain and annual overall thermal gain are quite small as obtained by GA-FS as compared to GA. It has been observed that the optimization process with GA-FS approach takes 15.7 seconds for optimization of parameters and converges within 186 generations and there is a 684.3 % reduction in the time elapsed for optimization than the GA. Figure 4.40 shows the variation in overall exergy efficiency with respect to month inclusive all weather conditions of New Delhi for Glazed PVT system with different optimization tools. From Figure 4.40, it has been observed that there is improvements occurring in every month overall exergy efficiency as compared to the system without GA and with GA.
4.3 GLAZED PHOTOVOLTAIC THERMAL ARRAY

In this section, work is carried out in three steps. In the first step, optimization of single channel glazed photovoltaic thermal (SCGPVT) array has been done with genetic algorithm (GA) considering the overall exergy gain is an objective function of the SCGPVT array. For maximization of overall exergy gain, total seven design variables have been optimized such as length of the channel (L), mass flow rate of flowing fluid (m_F), velocity of flowing fluid (V_F), convective heat transfer coefficient through the tedlar (U_T), overall heat transfer coefficient between solar cell to ambient through glass cover (U_SCAG), overall back loss heat transfer coefficient from flowing fluid to ambient (U_FA) and convective heat transfer coefficient of tedlar (h_T).
Figure 4.41: Proposed single channel glazed photovoltaic thermal (SCGPVT) array
4.3.1 System Description

The proposed model for single channel glazed photovoltaic thermal array is shown in Figure 4.41. The main objective of this work is to study the annual performance of single channel glazed PVT array having channel below the tedlar and air is flowing as a fluid through the channel. The insulation layer is considered below the channel. Whenever solar radiation falls on SCGPVT array, the solar energy is converted into the electrical and thermal energies. In the first step work is carried out and seven parameters are optimized using genetic algorithms and maximum overall exergy gain is evaluated. After that overall annual gain in the form of exergy (electrical energy), energy (thermal energy) and overall exergy efficiency of SCGPVT array has been evaluated. Four types of weather conditions of New Delhi (India) have been considered during the course of the evaluation. The configuration of Rajoria et al. (2013) has been considered. The hourly rate of useful thermal energy gain is computed using Equation 4.58 considering $N_T = 36$, $N_{RM} = 18$, $N_M = 1$ and $N_{RT} = 2$ i.e. the PVT array has two columns of 18 modules and each module has 36 numbers of PVT tiles as shown in Figure 4.43 (a). The PVT module is shown in Figure 4.43 (b) and PVT tile is shown in Figure 4.43 (c). The area of each optimized tile is 0.15 m x 0.15 m. The design parameters are given in Table 4.37.

4.3.2 Thermal Modeling

In order to write the energy balance equation of SCGPVT module, the same assumption and methodology have been considered as in section 4.2. In order to write energy balance equations of PV modules, the same assumption and methodology have been considered as in Rajoria et al. (2012). The energy balance equation for PVT tile can be written as:

$$
\tau_G \left[ \alpha_{SC} \beta_c + \alpha_T (1 - \beta_c) \right] I_{SL} bdx = \left[ U_{SCAG} (T_{SC} - T_A) + U_T (T_{SC} - T_{BS}) \right] bdx + \eta_{TC} \alpha_{SC} \tau_G \beta_c I_{SL} bdx
$$

(4.36)
Where \( b \) is the width of the PVT tile and \( dx \) is the elemental length in the direction of flow of air. From Equation 4.36, we get:

\[
\tau_G \left[ \alpha_{SC} \beta_C + \alpha_T (1-\beta_C) \right] I_{SL} - \eta_{TC} \alpha_{SC} \tau_G \beta_C I_{SL} = U_{SCAG} \left( T_{SC} - U_T T_{SC} - U_T T_{BS} \right)
\]

\[
\tau_G \left[ \alpha_{SC} \beta_C + \alpha_T (1-\beta_C) - \eta_{TC} \beta_C \alpha_{SC} \right] I_{SL} = (U_{SCAG} + U_T) T_{SC} - U_{SCAG} T_A - U_T T_{BS}
\]

\[
(U_{SCAG} + U_T) T_{SC} = \tau_G \left[ \alpha_{SC} \beta_C + \alpha_T (1-\beta_C) - \eta_{TC} \beta_C \alpha_{SC} \right] I_{SL} + U_{SCAG} T_A + U_T T_{BS}
\]

\[
T_{SC} = \frac{\alpha_{eff} I_{SL} + U_{SCAG} T_A + U_T T_{BS}}{U_{SCAG} + U_T}
\]

(4.37)

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters And Their Value</th>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( \tau_S )</td>
<td></td>
<td>0.95</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>( \eta_{TC} )</td>
<td></td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>3.</td>
<td>( \alpha_C )</td>
<td></td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>4.</td>
<td>( \alpha_T )</td>
<td></td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>5.</td>
<td>( \beta_C )</td>
<td></td>
<td>0.83</td>
<td>-</td>
</tr>
<tr>
<td>6.</td>
<td>( \beta_0 )</td>
<td></td>
<td>0.0045</td>
<td>-</td>
</tr>
<tr>
<td>7.</td>
<td>( C_{air} )</td>
<td></td>
<td>1012</td>
<td>J/kgK</td>
</tr>
<tr>
<td>8.</td>
<td>( T_{Fi} )</td>
<td>( T_A + 1)</td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>9.</td>
<td>( V_{air} )</td>
<td></td>
<td>1.5</td>
<td>m/s</td>
</tr>
<tr>
<td>10.</td>
<td>( N_{RM}, N_T, N_M, N_RA )</td>
<td></td>
<td>18, 36, 1, 2</td>
<td>-</td>
</tr>
<tr>
<td>11.</td>
<td>( \eta_{C,Power} )</td>
<td></td>
<td>0.38</td>
<td>-</td>
</tr>
<tr>
<td>12.</td>
<td>( h_{PF} )</td>
<td></td>
<td>0.375</td>
<td>-</td>
</tr>
<tr>
<td>13.</td>
<td>( K_p )</td>
<td></td>
<td>1.1</td>
<td>W/mK</td>
</tr>
<tr>
<td>14.</td>
<td>( K_T )</td>
<td></td>
<td>0.033</td>
<td>W/mK</td>
</tr>
<tr>
<td>15.</td>
<td>( L_T )</td>
<td></td>
<td>0.003</td>
<td>m</td>
</tr>
<tr>
<td>16.</td>
<td>( L_g )</td>
<td></td>
<td>0.003</td>
<td>m</td>
</tr>
<tr>
<td>17.</td>
<td>( T_{Sun} )</td>
<td></td>
<td>5778</td>
<td>K</td>
</tr>
</tbody>
</table>

Where

\[
\alpha_{eff} = \tau_G \left[ \alpha_{SC} \beta_C + \alpha_T (1-\beta_C) - \eta_{TC} \beta_C \alpha_{SC} \right]
\]

The energy balance equation for the back surface of the tedlar can be written as:
Rate of overall heat transfer from PVT tile to back surface of tedlar = Rate of heat transfer from back surface of tedlar to flowing fluid

\[ U_T (T_{SC} - T_{BS}) dx = h_r (T_{BS} - T_F) dx \]  

(4.38)

From Equation 4.38, we get:

\[ (U_T + h_r) T_{BS} = U_T T_{SC} + h_r T_F \]  

(4.39)

Substituting the value of \( T_{SC} \) in Equation 4.39 from Equation 4.37, we get

\[ (U_T + h_r) T_{BS} = \frac{U_T \alpha_{eff} I_{SL} + U_{SCAG} T_A + U_T T_{BS}}{U_{SCAG} + U_T} + h_r T_F \]

\[ T_{BS} = \frac{\frac{U_T \alpha_{eff} I_{SL}}{U_{SCAG} + U_T} + \frac{U_T U_{SCAG} T_A}{U_{SCAG} + U_T} + h_r T_F}{\left( U_T + h_r - \frac{U_T^2}{U_{SCAG} + U_T} \right)} \]

\[ T_{BS} = \frac{PF_{TS} \alpha_{eff} I_{SL} + U_{iT} T_A + h_r T_F}{\left( U_T + h_r - \frac{U_T^2}{U_{SCAG} + U_T} \right)} \]

\[ T_{BS} = \frac{PF_{TS} \alpha_{eff} I_{SL} + U_{iT} T_A + h_r T_F}{U_T \left[ 1 - \frac{U_T}{U_{SCAG} + U_T} \right] + h_r} \]

\[ T_{BS} = \frac{PF_{TS} \alpha_{eff} I_{SL} + U_{iT} T_A + h_r T_F}{U_{iT} + h_r} \]  

(4.40)

Where \( PF_{TS} = \frac{U_T}{U_{SCAG} + U_T} \) and \( U_{iT} = \frac{U_T U_{SCAG}}{U_{SCAG} + U_T} \)
The energy balance equation for the air flowing below the tedlar can be written as:

\[
\text{Rate of heat transfer to the flowing fluid} + \text{Overall heat transfer from flowing fluid to ambient} = \text{Rate of heat transfer from back surface of tedlar to flowing fluid}
\]

\[
m_F C_{air} \frac{dT_F}{dx} + U_{FA} (T_F - T_A) b dx = h_r (T_{BS} - T_F) b dx
\]

(4.41)

From Equation 4.40, we know that:

\[
T_{BS} - T_F = \frac{PF_{TS} \alpha_{eff} I_{SL} + U_{iT} T_A + h_r T_F}{U_{iT} + h_r} - T_F
\]

\[
T_{BS} - T_F = \frac{PF_{TS} \alpha_{eff} I_{SL} + U_{iT} T_A + h_r T_F - U_{iT} T_F - h_r T_F}{U_{iT} + h_r}
\]

\[
T_{BS} - T_F = \frac{PF_{TS} \alpha_{eff} I_{SL} + U_{iT} T_A - U_{iT} T_F}{U_{iT} + h_r}
\]

\[
h_r (T_{BS} - T_F) = h_r \left[ \frac{PF_{TS} \alpha_{eff} I_{SL} + U_{iT} T_A - U_{iT} T_F}{U_{iT} + h_r} \right]
\]

(4.42)

Now substituting the value of \( h_r (T_{BS} - T_F) \) from Equation 4.42 into Equation 4.41, we obtained:

\[
m_F C_{air} \frac{dT_F}{dx} + U_{FA} (T_F - T_A) b = b \left[ \frac{h_T PF_{TS} \alpha_{eff} I_{SL}}{U_{iT} + h_r} + \frac{h_r U_{iT} T_A}{U_{iT} + h_r} - \frac{h_r U_{iT} T_F}{U_{iT} + h_r} \right]
\]

\[
m_F C_{air} \frac{dT_F}{dx} + \frac{bh_r U_{iT} T_F}{U_{iT} + h_r} + b U_{FA} T_F = \frac{h_T h_f U_{iT} T_A}{U_{iT} + h_T} + \frac{h_r U_{iT} T_A}{U_{iT} + h_T} + U_{FA} T_A
\]

\[
m_F C_{air} \frac{dT_F}{dx} + b(U_{fa} + U_{FA}) T_F = \frac{PF_{BS} PF_{TS} \alpha_{eff} I_{SL}}{U_{iT} + h_f} + \frac{(U_{fa} + U_{FA}) T_A}{U_{iT} + h_T}
\]
\[ m_F C_{air} \frac{dT_F}{dx} + b U_L T_F = b \left[ P_{FS} P_{TS} \alpha_{eff} I_{SL} + U_L T_A \right] \]

Where \[ U_{fa} = \frac{h_F U_i T}{U_{iT} + h_T} \]
\[ P_{FS} = \frac{h_T}{U_{iT} + h_T} \]

\[ U_L = (U_{fa} + U_{FA}) \]

Now
\[ \frac{dT_F}{dx} + b U_L \frac{T_F}{m_F C_{air}} = \frac{b}{m_F C_{air}} \left[ P_{FS} P_{TS} \alpha_{eff} I_{SL} + U_L T_A \right] \]

\[ \frac{dT_F}{dx} + a T_F = f_1(x) \] (4.43)

Where \[ a = \frac{b U_L}{m_F C_{air}} \]

\[ f(t) = \frac{b}{m_F C_{air}} \left[ P_{FS} P_{TS} \alpha_{eff} I_{SL} + U_L T_A \right] \]

Now solving Equation 4.43, we get:

\[ e^{ax} \frac{dT_F}{dx} + e^{ax} a T_F = e^{ax} f(t) \]
\[ \frac{d}{dx} \left( e^{ax} T_F \right) = e^{ax} f(t) \] (4.44)

Integrating Equation 4.44, we get:

\[ e^{ax} T_F = \frac{f(t)}{a} e^{ax} + C \]
Where C is a constant.

\[ T_F = \frac{f(t)}{a} + C e^{-ax} \] (4.45)

Now at \[ x = 0, T_F = T_{F,i} \] Hence
\[ T_{F,i} = \frac{f(t)}{a} + C \]

\[ C = T_{F,i} - \frac{f(t)}{a} \]

and therefore putting the value of \( C \) in Equation 4.44, we get:

\[ T_F = \frac{f(t)}{a} + T_{F,i} \cdot e^{-ax} - \frac{f(t)}{a} \cdot e^{-ax} \]

\[ T_F = \frac{f(t)}{a} \cdot (1 - e^{-ax}) + T_{F,i} \cdot e^{-ax} \]

(4.46)

We know that;

\[ T_{F, out} = T_F \bigg|_{x=L} \]

\[ T_{F, out} = \frac{f(t)}{a} \cdot (1 - e^{-al}) + T_{F,i} \cdot e^{-al} \]

(4.47)

From Equation 4.47, the outlet air temperature from \( n^{th} \) PVT tile and \( N^{th} \) PVT module connected in series is derived as:

\[ T_{FON} = \left[ \frac{PF_{BS}PF_{TS} \alpha_{eff} I_{SL}}{U_L} + T_A \right] \left[ 1 - \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \right] + T_{F,i} \cdot \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \]

(4.48)

If all set of hybrid PVT tiles and PVT modules are identical, then the expression for useful heat gain for \( N_{RM} \) row of PVT module and \( N_{RA} \) row of the hybrid PVT array is given as:

\[ Q_U (N_{RT}, N_{RA}) = N_{RT} N_{RA} m_F C_{air} (T_{FON} - T_{F,i}) \]

(4.49)

Substituting the value of \( T_{FON} \) in Equation 4.49, we get:

\[ Q_U (N_{RT}, N_{RA}) = N_{RT} N_{RA} m_F C_{air} \left[ \left( \frac{PF_{BS}PF_{TS} \alpha_{eff} I_{SL}}{U_L} + T_A \right) \left[ 1 - \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \right] + T_{F,i} \cdot \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) - T_{F,i} \right] \]

\[ Q_U (N_{RT}, N_{RA}) = N_{RT} N_{RA} m_F C_{air} \left[ \left( \frac{PF_{BS}PF_{TS} \alpha_{eff} I_{SL}}{U_L} + T_A \right) \left[ 1 - \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \right] - T_{F,i} \right] \]

\[ Q_U (N_{RT}, N_{RA}) = N_{RT} N_{RA} m_F C_{air} \left[ \left( \frac{PF_{BS}PF_{TS} \alpha_{eff} I_{SL}}{U_L} + T_A \right) \left[ 1 - \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \right] - T_{F,i} \right] \]

\[ Q_U (N_{RT}, N_{RA}) = N_{RT} N_{RA} m_F C_{air} \left[ \left( \frac{PF_{BS}PF_{TS} \alpha_{eff} I_{SL}}{U_L} + T_A \right) \left[ 1 - \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \right] - T_{F,i} \right] \]

\[ Q_U (N_{RT}, N_{RA}) = N_{RT} N_{RA} m_F C_{air} \left[ \left( \frac{PF_{BS}PF_{TS} \alpha_{eff} I_{SL}}{U_L} + T_A \right) \left[ 1 - \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \right] - T_{F,i} \right] \]

\[ Q_U (N_{RT}, N_{RA}) = N_{RT} N_{RA} m_F C_{air} \left[ \left( \frac{PF_{BS}PF_{TS} \alpha_{eff} I_{SL}}{U_L} + T_A \right) \left[ 1 - \exp \left( -\frac{N_T N_M b L U_L}{m_F C_{air}} \right) \right] - T_{F,i} \right] \]
\[
Q_{U} (N_{RT} \cdot N_{RA}) = N_{RT} N_{RA} m_{F} C_{air} \left[ \frac{P F_{IS} P F_{JS} \alpha_{eff} I_{SL}}{U_{L}} + T_{a} - T_{f,j} \right] \left[ 1 - \exp \left( - \frac{N_{T} N_{M} b L U_{L}}{m_{F} C_{air}} \right) \right]
\] (4.50)

### 4.3.2.1 Exergy Analysis

The electrical gain (kWh) of the hybrid PVT array is given as:

\[
E_{x_{electrical}} = \left[ \frac{\eta N_{T} N_{M} A_{SC} I_{SL}}{1000} \right]
\] (4.51)

### 4.3.3 Results and Discussion

The comparative study has been presented here for two types of system like; (i) Un-optimized SCGPVT array, (ii) SCGPVT array optimized by a genetic algorithm. Firstly the overall exergy gain is evaluated using Equation 1.15 at 11:00 AM for the month of January 2009 and the input parameters are given in Table 4.26. Further the analysis has been performed for the New Delhi climatic conditions considering four weather conditions as; clear days, hazy days, hazy and cloudy days and cloudy days. The ambient temperature, hourly variation of solar radiation and clear days in New Delhi are given in Appendix A. Following analysis has been done, which are as follows:

#### 4.3.3.1 Exergy Analysis of Un-optimized System

The constant design parameters of a un-optimized array are given in Table 4.25 as considered by Rajoria et al. (2012) in the literature. The results obtained from un-optimized SCGPVT array is shown in Table 4.29. The variation in exergy gain, thermal gain, overall exergy gain and overall thermal gain with respect to the month for un-optimized array is shown in Figures 4.44 to Figure 4.47 respectively for New Delhi climatic conditions.

#### Table 4.26: Input Parameters for Optimization

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Solar Intensity, In</td>
<td>680.73</td>
<td>kWh</td>
</tr>
<tr>
<td>2.</td>
<td>Ambient Temperature, T_A</td>
<td>6.6</td>
<td>°C</td>
</tr>
</tbody>
</table>

#### 4.3.3.2 Exergy Analysis of the System Optimized with Genetic Algorithm (GA)

A basically genetic algorithm is a search algorithm based on the technicalities of natural selection. The real function can be maximized or minimized with the help of genetic
algorithm by choosing input values systematically within an allowed boundary and computing the value of the function. A search algorithm is used to search the optimum solution which terminate in a finite number of steps or iterative methods that converge to a solution and the fitness function (FF) is calculated to allocate a quality value to every solution formed. Three primary operations are used for the movement algorithm named as: Parent reproduction, Crossover and Mutation. The details of important operations during the solution of maximum overall exergy gain are given in sub-section 1.10.1 and the flow chart is given in Figure 1.6.

i. Encoding

The binary coded chromosomes are randomly generated. Each chromosome represents set of controllable variables so-called parameters having values within allowed boundary like; length of the channel (L), mass flow rate of flowing fluid (m_F), velocity of flowing fluid (V_F), convective heat transfer coefficient through the tedlar (U_T), overall heat transfer coefficient between solar cell to ambient through glass cover (U_SCA_G), overall back loss heat transfer coefficient from flowing fluid to ambient (U_F_A) and convective heat transfer coefficient of tedlar (h_T). The following formula is used to convert the number of bits of each chromosome for different control variables into decimal values.

\[ x_i = x_i^{(\text{min})} + \frac{x_i^{(\text{max})} - x_i^{(\text{min})}}{2^i - 1} (\text{dec}(s_i)) \]  

Where

- \( x_i^{(\text{min})} \) = minimum generation value of \( i \)th control variable
- \( x_i^{(\text{max})} \) = maximum generation value of \( i \)th control variable

\( \text{dec}(s_i) \) = decoded value of a binary substring \( s_i \) which is calculated as \( \sum_{i=0}^{i=0} 2^i s_i \)

Where \( s_i \in (0,1) \)

The program executes for a set of the parameter's value belonging to each chromosome for maximization of overall exergy gain. If maximization converges and obtained an overall exergy gain within specified limits, then chromosome is included to complete initial population. Otherwise, a new chromosome is generated according to the same procedure and tested again.
ii. **Fitness Function Evaluation**

The objective of the maximization problem is to maximize the overall exergy gain. In GA based optimization of proposed systems, overall exergy gain for each generated chromosome is calculated, based on the respective equation as follows:

$$ \sum E_{x\text{overall}}^i = \sum E_{x\text{electrical}}^i + \sum E_{x\text{thermal}}^i $$ (4.53)

And fitness function is modified to keep overall exergy gain under limits as:

$$ FF_i = E_{x\text{overall}} $$ (4.54)

Whereas $i = 1$ to population size

$E_{x\text{overall}} = \text{overall exergy gain}$

$FF_i = \text{fitness value of function for } i^{th} \text{ chromosome.}$

The initial value of the population size, crossover and mutation probability and maximum generation are given in Table 4.27. The optimized parameters of SCGPVT system, optimized with genetic algorithm are given in Table 4.28.

**TABLE 4.27: INITIAL VALUE TO THE GENETIC ALGORITHM**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Input Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Population Size</td>
<td>350</td>
</tr>
<tr>
<td>2.</td>
<td>Crossover Probability ($P_c$)</td>
<td>0.82</td>
</tr>
<tr>
<td>3.</td>
<td>Mutation Probability ($P_m$)</td>
<td>0.0026</td>
</tr>
<tr>
<td>4.</td>
<td>Maximum Generation</td>
<td>1500</td>
</tr>
</tbody>
</table>

**TABLE 4.28: OPTIMIZED PARAMETERS OF GLAZED PVT ARRAY**

<table>
<thead>
<tr>
<th>S. No</th>
<th>Optimized Parameters</th>
<th>Symbol</th>
<th>Optimize value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Length of the channel</td>
<td>L</td>
<td>0.15</td>
<td>m</td>
</tr>
<tr>
<td>2.</td>
<td>Mass flow rate</td>
<td>$m_f$</td>
<td>0.0225</td>
<td>kg/s</td>
</tr>
<tr>
<td>3.</td>
<td>Velocity of flowing fluid</td>
<td>$V_f$</td>
<td>0.5830</td>
<td>m/s</td>
</tr>
<tr>
<td>4.</td>
<td>Convective heat transfer coefficient through the tedlar</td>
<td>$U_T$</td>
<td>67.41</td>
<td>W/m$^2$K</td>
</tr>
<tr>
<td>S. No</td>
<td>Optimized Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>--------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Overall heat transfer coefficient from cell to ambient through glass cover</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$U_{SCAG}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>W/m$^2$K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Overall back loss heat transfer coefficient from fluid to ambient</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$U_{FA}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>W/m$^2$K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Heat transfer coefficient of tedlar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$h_{T}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>W/m$^2$K</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.42: (a) Variation in fitness value with respect to generation  
(b) Variation in overall exergy gain with respect to generation

Figure 4.42 (a) and (b) shows a variation in fitness value and overall exergy gain with respect to generation respectively. From Figure 4.42, it has been observed that the overall exergy gain at 11:00 AM for the month of January is 1.42 kWh. The results obtained from the optimized SCGPVT array are shown in Table 4.29. From Table 4.29, it is observed that the overall exergy gain obtained from optimized system is 1.42 kWh, which is 87.86% more than the overall exergy gain of a un-optimized array given in literature. There are 69.52% and 88.05% improvement occurs in annual overall exergy gain and annual overall thermal gain respectively, then the un-optimized system for the same input irradiance and ambient
temperature. Figures 4.43 to Figure 4.46 shows a variation in exergy gain, thermal gain, overall exergy gain and overall thermal gain with respect to the month respectively, for optimized and un-optimized SCGPVT system for New Delhi climatic conditions.

**TABLE 4.29: COMPARATIVE RESULTS OF UN-OPTIMIZED AND OPTIMIZED GLAZED PVT ARRAY**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Type of Outputs</th>
<th>Un-optimized Outputs</th>
<th>Optimized Outputs</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Exergy Gain</td>
<td>0.6600</td>
<td>0.6741</td>
<td>kWh</td>
</tr>
<tr>
<td>2.</td>
<td>Thermal Gain</td>
<td>0.8161</td>
<td>2.33</td>
<td>kWh</td>
</tr>
<tr>
<td>3.</td>
<td>Overall Exergy Gain</td>
<td>0.7559</td>
<td>1.42</td>
<td>kWh</td>
</tr>
<tr>
<td>4.</td>
<td>Overall Thermal Gain</td>
<td>2.55</td>
<td>4.10</td>
<td>kWh</td>
</tr>
<tr>
<td>5.</td>
<td>Exergy Efficiency</td>
<td>10.39</td>
<td>10.60</td>
<td>%</td>
</tr>
<tr>
<td>6.</td>
<td>Annual Exergy Gain</td>
<td>1793.9</td>
<td>2606.3</td>
<td>kWh</td>
</tr>
<tr>
<td>7.</td>
<td>Annual Thermal Gain</td>
<td>2122.7</td>
<td>6010.7</td>
<td>kWh</td>
</tr>
<tr>
<td>8.</td>
<td>Annual Overall Exergy Gain</td>
<td>2002.2</td>
<td>3394.1</td>
<td>kWh</td>
</tr>
<tr>
<td>9.</td>
<td>Annual Overall Thermal Gain</td>
<td>6843.5</td>
<td>12869</td>
<td>kWh</td>
</tr>
</tbody>
</table>

Figure 4.43: Variation in exergy gain with respect to months
Figure 4.44: Variation in thermal gain with respect to months

Figure 4.45: Variation in overall exergy gain with respect to months
From Figures 4.43 to Figure 4.46, it has been observed that there are improvements occurring in every month's exergy gain, thermal gain, overall exergy gain and overall thermal gain respectively as compared to un-optimized system given in literature. The climatic data, namely; ambient temperature, solar radiation and clear days have been obtained from the Indian Meteorological Department (IMD), Pune for New Delhi of India as given in Appendix A.

4.4 SUMMARY

- The overall exergy efficiency of SCUPVT system is optimized, i.e. 16.88% at the optimized value of the parameters. The parameters have been optimized using a genetic algorithm.
- An overall annual electrical gain of the proposed SCUPVT system has been increased by 14.29%, 16.67%, 14.81% and 8.18% in comparison to the MCPVT module proposed by
Agrawal and Tiwari (2011c) for New Delhi, Jodhpur, Srinagar and Bangalore Indian climatic conditions respectively.

- The overall annual thermal gain of the proposed SCUPVT system has been improved by 31.58%, 26.83%, 30.67% and 23.86% over the MCPVT module proposed by Agrawal and Tiwari (2011) for New Delhi, Jodhpur, Srinagar and Bangalore for Indian climatic conditions respectively.

- It has been observed that the overall exergy efficiency of SCGPVT module optimized with GA-FS approach is improved.

- GA-FS approach has faster convergence as compare to GA.

- The overall exergy efficiency obtained from the system optimized with GA-FS approach is 15.82 %, which is 1.27 % and 5.40% more than the efficiency of the system optimized with GA and un-optimized system respectively.

- The optimization process with GA-FS approach takes 15.7 Sec for optimization of parameters and converges within 186 generations. There is a 684.3 % reduction in the time elapsed for optimization than the GA.

- There are 69.52% and 88.05% improvement in annual overall exergy and thermal gain respectively, than the un-optimized system for the same input irradiance and ambient temperature.