CHAPTER 5

MODELING AND OPTIMIZATION OF HYBRID DUAL CHANNEL SEMITRANSPARENT PHOTOVOLTAIC THERMAL MODULE
5.1 HYBRID DUAL CHANNEL SEMITRANSSPARENT PHOTOVOLTAIC THERMAL MODULE

After the study of literature, it has been observed that lots of the work has been done on PVT module, mostly on single channel PVT module. Very little work has been done on a dual channel PVT module. So the effort has been made to model a novel dual channel semitransparent photovoltaic thermal (DCSPVT) hybrid module. Due to the proposed dual channel, additional thermal energy is obtained from the module which will reduce the cell temperature. The reduction in cell temperature causes an improvement in electrical efficiency and also protects the PVT module from structural damage. The life span of the module will also be increased due to the reduction in thermal stress on module. The exergy analysis has been done for Srinagar, Indian climatic condition and results have been compared with the results of single channel semitransparent PVT hybrid module. It is a theoretical model for evaluating the efficiency of the proposed system. The work has been carried out in two steps. (i) Design and thermal modeling of dual channel semitransparent photovoltaic thermal module has been done. (ii) Performance analysis of the proposed hybrid module has been done for Srinagar, India climatic conditions will be called as case-I and obtained results have been compared with single channel semi transparent photovoltaic thermal (SCSPVT) hybrid module and will be called as case-II. Proposed model gives electrical energy as well as thermal energy simultaneously.

5.1.1 System Description

The structure and cross section view of the proposed novel hybrid dual channel semitransparent photovoltaic thermal (DCSPVT) module will be called as case-I, is shown in Figure 5.1. The module has the following two channels; (i) upper channel is between glass touching above solar cell and glass cover (ii) lower channel is between the glass below solar cell and acrylic sheet. The dimensions have been shown in Table 5.1. An upper channel made
with glass is considered above the semitransparent photovoltaic module and lower channel made with acrylic sheet is considered below the module. The blackened plate as an absorber is attached below the lower channel as shown in Figure 5.1. Air as working fluid in the upper and lower channel has been used. When the solar radiation falls on the DCSPVT module, it heats up the working fluid in both the channel.

![Figure 5.1: Side view of dual channel semitransparent PVT module (Case-I)](image1)

Figure 5.1: Side view of dual channel semitransparent PVT module (Case-I)

![Figure 5.2: Side view of single channel semitransparent PVT module (Case-II)](image2)

Figure 5.2: Side view of single channel semitransparent PVT module (Case-II)

Only a small fraction of the absorbed solar radiation is converted into electricity, while the rest is increasing the temperature of the working fluid and absorber plate. The heated air, then flows to the upper channel while the heated air in the lower channel receives additional heating from the absorber plate. The schematic view of single channel semitransparent photovoltaic thermal (SCSPVT) hybrid module is shown in Figure 5.2.

### 5.1.2 Thermal Modeling

The following assumptions have been considered during the thermal modeling of the DCSPVT hybrid module:
• One dimensional heat conduction is a good approximation for the present study.
• There is no temperature gradient along the thickness of solar cell.
• The specific heat of air remains constant.
• The heat capacity of the solar cell is neglected.

### Table 5.1: Design Parameters of DCSPVT Module

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters And Their Value</th>
<th>Parameters And Their Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameters</td>
<td>Value</td>
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<tr>
<td>1.</td>
<td>$\tau_c$</td>
<td>0.95</td>
</tr>
<tr>
<td>2.</td>
<td>$\eta_{TC}$</td>
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<tr>
<td>3.</td>
<td>$\alpha_C$</td>
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<tr>
<td>4.</td>
<td>$\alpha_P$</td>
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<tr>
<td>5.</td>
<td>$\rho$</td>
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<tr>
<td>6.</td>
<td>$\eta_{C,P}$</td>
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<td>7.</td>
<td>$\beta_0$</td>
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<tr>
<td>8.</td>
<td>$\beta_C$</td>
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<tr>
<td>9.</td>
<td>$A_M$</td>
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</tr>
<tr>
<td>10.</td>
<td>B</td>
<td>0.605</td>
</tr>
<tr>
<td>11.</td>
<td>$C_{FU}$</td>
<td>1012</td>
</tr>
<tr>
<td></td>
<td>$C_{FL}$</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>$d_{LU}$, $d_L$</td>
<td>0.05</td>
</tr>
<tr>
<td>13.</td>
<td>$h_o$</td>
<td>5.7+3.8*V_{air}</td>
</tr>
<tr>
<td>14.</td>
<td>$h_{FU}$, $h_{FL}$</td>
<td>2.8+3<em>V_{FU}, 2.8+3</em>V_{FL}</td>
</tr>
</tbody>
</table>

• The system is in quasi-steady state.
• The ohmic losses in the solar cell are negligible.
• There is streamlines flow of air through the channel at small flow rate.
• Since the transmisitivity of non-packing area of glass is nearly 95% and remaining 5% includes absorptivity and reflectivity of the glass. Hence absorption losses which are responsible to raise the temperature of glass in non-packing area are very small (nearly 2 to 2.5%). Therefore, thermal energy received by fluid from non-packing area of glass of
semitransparent module is negligible in comparison to thermal energy received from the back surface of the solar cell and absorbing plate.

- It is assumed that there is no heat transfer between the air flowing in the upper and lower duct in vertical direction.

The energy received by air in the upper duct will raise the temperature of air and some energy will be lost to the ambient through upper glass cover. Hence the energy balance equation for upper duct can be written as:

\[
U_{ic, fu} (T_{SC} - T_{FU}) \times bdx = m_{FU} C_{FU} \frac{dT_{FU}}{dx} + U_{fu, a} (T_{FU} - T_{A}) \times bdx
\]  

(5.1)

Where

\[
U_{ic, fu} = \left[ \frac{I_G}{k_G} + \frac{1}{h_{FU}} \right]^{-1}
\]

\[
U_{fu, a} = \left[ \frac{I_G}{k_G} + \frac{1}{h_0} \right]^{-1}
\]

\[
h_o = 5.7 + 3.8V_{air}
\]

The energy absorbed by the solar cell is responsible for the generation of electrical energy as well as heating of solar cell. The thermal energy absorbed by solar cell will heat the air in the upper duct as well as lower duct. Hence the energy balance equation for solar cell can be written as:

\[
\alpha_{SC} \tau^2_G \beta_c \Gamma_{SL} \times bdx = U_{ic, fu} (T_{SC} - T_{FU}) \times bdx + U_{bcfL} (T_{SC} - T_{FL}) \times bdx + \eta_{TC} \tau^2_G \beta_c \Gamma_{SL} \times bdx
\]

(5.2)

Where

\[
U_{bcfL} = \left[ \frac{I_G}{k_G} + \frac{1}{h_{FL}} \right]^{-1}
\]

\[
\tau_G = 0.95
\]

Air flows in the lower duct will receive thermal energy from the solar cell as well as from the blackened absorbing plate. The input energy will raise the temperature of the air in
lower duct and remaining energy will lost to the ambient through bottom insulation. Hence the energy balance equation for lower duct air:

\[ U_{bc,FL} (T_{SC} - T_{FL}) \times bdx + h_{FL} (T_P - T_{FL}) \times bdx = m_{FL} C_{FL} \frac{dT_{FL}}{dx} + U_{byL.a} (T_{FL} - T_A) \times bdx \]  \hspace{1cm} (5.3)

Where

\[ U_{byL.a} = \left[ \frac{L_p}{k_p} + \frac{L_I}{k_I} + \frac{1}{h_I} \right]^{-1} \]

The energy received from non-packing area of the module will directly absorb by the blackened absorbing plate. The absorbed thermal energy will be distributed in heating the air in lower duct and loss to the ambient through bottom insulation. Hence the energy balance equation for blackened absorbing plate:

\[ \alpha P^3 (1 - \beta_C) I_{SL} \times bdx = h_{FL} (T_P - T_{FL}) \times bdx + U_{tpa} (T_P - T_A) \times bdx \]  \hspace{1cm} (5.4)

Where

\[ U_{tpa} = \left[ \frac{L_I}{k_I} + \frac{1}{h_I} \right]^{-1} \]

\[ h_I = 2.8 + 3V_{air} \]

In steady state condition the thermal energy transformed from upper air duct to lower air duct will be difference of the thermal energy transferred to upper and lower duct respectively from the solar cell. Hence the energy balance equation is:

\[ \frac{k_C}{L_C} (T_{FU} - T_{FL}) \times bdx = U_{ic,fu} (T_{SC} - T_{FU}) \times bdx - U_{bc,FL} (T_{SC} - T_{FL}) \times bdx \]  \hspace{1cm} (5.5)

\[ \frac{k_C}{L_C} T_{FU} + U_{ic,fu} T_{FU} = U_{ic,fu} T_{SC} - U_{bc,FL} T_{SC} + \frac{k_C}{L_C} T_{FL} + U_{bc,FL} T_{FL} \]

\[ \left( \frac{k_C}{L_C} + U_{ic,fu} \right) T_{FU} = \left( U_{ic,fu} - U_{bc,FL} \right) T_{SC} + \left( \frac{k_C}{L_C} + U_{bc,FL} \right) T_{FL} \]  \hspace{1cm} (5.6)
\[
T_{FU} = \left( U_{tc, fu} - U_{bc, fl} \right) T_{SC} + \left( \frac{k_C}{L_C} + U_{bc, fl} \right) T_{FL} \]

(5.7)

Similarly from Equation 5.4, We get:

\[
T_{FL} = \left( \frac{k_C}{L_C} + U_{bc, fl} \right) T_{FU} - \left( U_{tc, fu} - U_{bc, fl} \right) T_{SC} \]

(5.8)

Solving Equation 5.2, we get

\[
\alpha_{SC} \tau^2 G_C \beta_C I_{SL} \times bdx = U_{tc, fu} \left( T_{SC} - T_{FU} \right) \times bdx + U_{bc, fl} \left( T_{SC} - T_{FL} \right) \times bdx + \eta_{TC} \tau^2 G_C \beta_C I_{SL} \times bdx
\]

\[
\alpha_{SC} \tau^2 G_C \beta_C I_{SL} = \left( U_{tc, fu} + U_{bc, fl} \right) T_{SC} - U_{tc, fu} T_{FU} - U_{bc, fl} T_{FL} + \eta_{TC} \tau^2 G_C \beta_C I_{SL} \]

(5.9)

Putting the value of \( T_{FU} \) in Equation 5.9 from Equation 5.7, we get:

\[
\alpha_{SC} \tau^2 G_C \beta_C I_{SL} = \left( U_{tc, fu} + U_{bc, fl} \right) T_{SC} - U_{tc, fu} \left[ \left( U_{tc, fu} - U_{bc, fl} \right) T_{SC} + \left( \frac{k_C}{L_C} + U_{bc, fl} \right) T_{FL} \right] \]

\[
- \left( \frac{k_C}{L_C} + U_{bc, fl} \right) \left( k_C \right) + U_{bc, fl} \right) = \left( U_{tc, fu} + U_{bc, fl} \right) T_{SC} \]

\[
- \left[ \left( \frac{k_C}{L_C} + U_{bc, fl} \right) + U_{bc, fl} \right] T_{FL} + \eta_{TC} \tau^2 G_C \beta_C I_{SL}
\]

\[
\alpha_{SC} \tau^2 G_C \beta_C I_{SL} = \left[ \left( U_{tc, fu} + U_{bc, fl} \right) - U_{tc, fu} \left( U_{tc, fu} - U_{bc, fl} \right) \left( \frac{k_C}{L_C} + U_{bc, fl} \right) \right] T_{SC}
\]

\[
- \left[ \left( \frac{k_C}{L_C} + U_{bc, fl} \right) + U_{bc, fl} \right] T_{FL} + \eta_{TC} \tau^2 G_C \beta_C I_{SL}
\]

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\[
T_{SC} = \frac{U_{tc, fu} + U_{bcfL} - U_{tc, fu} \left( \frac{U_{tc, fu} - U_{bc, fl}}{k_C + U_{tc, fu}} \right)}{U_{tc, fu} + U_{bcfL} - U_{tc, fu} \left( \frac{U_{tc, fu} - U_{bc, fl}}{k_C + U_{tc, fu}} \right)} \left( \alpha_{SC} - \eta_{TC} \right) \beta_C I_{SL} + \left( \frac{k_C + U_{bc, fl}}{L_C} \right) + U_{bcfL} \right] T_{FL}
\]

Equation 5.10a shows average cell temperature. Putting the value of \( T_{FL} \) in Equation 5.9 from Equation 5.8, we get:
\[ \alpha_{SC} \tau_{G}^2 \beta_{C} I_{SL} = (U_{tc, fu} + U_{befL}) T_{SC} - U_{tc, fu} T_{FU} \]

\[ - U_{befL} \left[ \left( \frac{k_{C} + U_{tc, fu}}{L_{C}} \right) T_{FU} - \left( \frac{U_{tc, fu} - U_{bc, fl}}{L_{C}} \right) T_{SC} \right] \]

\[ + \eta_{TC} \tau_{G}^2 \beta_{C} I_{SL} \]

\[ \alpha_{SC} \tau_{G}^2 \beta_{SC} I_{SL} = (U_{tc, fu} + U_{befL}) T_{SC} - U_{tc, fu} T_{FU} \]

\[ - U_{befL} \left( \frac{k_{C} + U_{tc, fu}}{L_{C}} \right) T_{FU} + U_{befL} \left( \frac{U_{tc, fu} - U_{bc, fl}}{L_{C}} \right) T_{C} + \eta_{TC} \tau_{G}^2 \beta_{C} I_{SL} \]

\[ \alpha_{SC} \tau_{G}^2 \beta_{C} I_{SL} = \left[ U_{tc, fu} + U_{befL} + U_{befL} \left( \frac{U_{tc, fu} - U_{bc, fl}}{k_{C} + U_{bc, fl}} \right) \right] T_{SC} \]

\[ - \left[ U_{tc, fu} + U_{befL} \left( \frac{k_{C} + U_{tc, fu}}{L_{C}} \right) \right] T_{FU} + \eta_{TC} \tau_{G}^2 \beta_{C} I_{SL} \]

\[ \left[ U_{tc, fu} + U_{befL} + U_{befL} \left( \frac{U_{tc, fu} - U_{bc, fl}}{k_{C} + U_{bc, fl}} \right) \right] T_{SC} = (\alpha_{SC} - \eta_{TC}) \tau_{G}^2 \beta_{C} I_{SL} \]

\[ + \left[ U_{tc, fu} + U_{befL} \left( \frac{k_{C} + U_{tc, fu}}{L_{C}} \right) \right] T_{FU} \]
\[
T_{SC} = \frac{(\alpha_{SC} - \eta_{TC}) \tau^2 G \beta_C I_{SL} + \left[ U_{tc,fa} + U_{beL} \left( \frac{k_C + U_{tc,fa}}{I_C} \right) \right] T_{FU}}{U_{tc,fa} + U_{beL} + U_{beL} \left( \frac{U_{tc,fa} - U_{be,fl}}{k_C + U_{be,fl}} \right)}
\]  
(5.11)

\[
\overline{T_{SC}} = \frac{(\alpha_{SC} - \eta_{TC}) \tau^2 G \beta_C I_{SL} + \left[ U_{tc,fa} + U_{beL} \left( \frac{k_C + U_{tc,fa}}{I_C} \right) \right] (T_{FUO} + T_{FI})}{2}
\]  
(5.11a)

Equation 5.11a shows an average cell temperature. From Equation 5.11, we know that:

\[
T_{SC} - T_{FU} = \frac{U_{tc,fa} + U_{beL} + U_{beL} \left( \frac{U_{tc,fa} - U_{be,fl}}{k_C + U_{be,fl}} \right)}{U_{tc,fa} + U_{beL} + U_{beL} \left( \frac{k_C + U_{be,fl}}{I_C} \right)} - T_{FU}
\]
\[ T_{SC} - T_{FU} = (\alpha_{SC} - \eta_{TC}) \tau_2^2 G \beta_c I_{SL} + \left[ \begin{array}{c} U_{ic, fu} + U_{befl} \left( \frac{k_c + U_{ic, fu}}{k_c + U_{bc, fl}} \right) \\ U_{ic, fu} + U_{befl} + U_{befl} \left( \frac{U_{ic, fu} - U_{bc, fl}}{k_c + U_{bc, fl}} \right) \end{array} \right] T_{FU} \]

\[ T_{SC} - T_{FU} = \frac{(\alpha_{SC} - \eta_{TC}) \tau_2^2 G \beta_c I_{SL} + U_{befl} (f_1 - f_2 - 1)T_{FU}}{U_{ic, fu} + U_{befl} (1 + f_2)} \]

Where \( f_1 = \left( \frac{k_c + U_{ic, fu}}{k_c + U_{bc, fl}} \right) \) and \( f_2 = \left( \frac{U_{ic, fu} - U_{bc, fl}}{k_c + U_{bc, fl}} \right) \)

\[ T_{SC} - T_{FU} = \frac{(\alpha \tau)_{eff} I_{SL} + U_{befl} (f_1 - f_2 - 1)T_{FU}}{U_{ic, fu} + U_{befl} (1 + f_2)} \]

Where \( (\alpha \tau)_{eff} = (\alpha_{SC} - \eta_{TC}) \tau_2^2 G \beta_c \)

\[ U_{ic, fu} (T_{SC} - T_{FU}) = U_{ic, fu} \frac{(\alpha \tau)_{eff} I_{SL} + U_{befl} (f_1 - f_2 - 1)T_{FU}}{U_{ic, fu} + U_{befl} (1 + f_2)} \]

\[ U_{ic, fu} (T_{SC} - T_{FU}) = \frac{U_{ic, fu} \sqrt{\frac{U_{ic, fu}}{U_{ic, fu} + U_{befl} (1 + f_2)}} (\alpha \tau)_{eff} I_{SL} + \frac{U_{befl} U_{ic, fu} (f_1 - f_2 - 1)}{U_{ic, fu} + U_{befl} (1 + f_2)} T_{FU}} \]
\[ U_{tc, fu} (T_{SC} - T_{FU}) = PF_1 (\alpha \tau)_{1eff} I_{SL} + U_{1eff} T_{FU} \]  

(5.12)

Where \( PF_1 = \frac{U_{tc, fu}}{U_{tc, fu} + U_{bcL} (1 + f_2)} \) and \( U_{1eff} = \frac{U_{bcL} U_{tc, fu} (f_1 - f_2 - 1)}{U_{tc, fu} + U_{bcL} (1 + f_2)} \)

From equation 5.10, we know that

\[ (\alpha_{SC} - \eta_{TC}) \tau^2 G \beta_C I_{SL} + \left[ U_{tc, fu} \frac{k_C + U_{bc, FL}}{L_C} + U_{bcL} \right] T_{FL} \]

\[ T_{SC} - T_{FL} = \frac{U_{tc, fu} + U_{bcL} - U_{tc, fu} \left( \frac{U_{tc, fu} - U_{bc, FL}}{k_C + U_{tc, fu}} \right)}{-T_{FL}} \]

\[ (\alpha_{SC} - \eta_{TC}) \tau^2 G \beta_C I_{SL} + \left[ U_{tc, fu} \frac{k_C + U_{bc, FL}}{L_C} + U_{bcL} \right] T_{FL} = \left[ U_{tc, fu} + U_{bcL} - U_{tc, fu} \frac{U_{tc, fu} - U_{bc, FL}}{k_C + U_{tc, fu}} \right] T_{FL} \]

\[ T_{SC} - T_{FL} = \frac{U_{tc, fu} + U_{bcL} - U_{tc, fu} \left( \frac{U_{tc, fu} - U_{bc, FL}}{k_C + U_{tc, fu}} \right)}{-T_{FL}} \]

\[ T_{SC} - T_{FL} = \frac{(\alpha_{SC} - \eta_{TC}) \tau^2 G \beta_C I_{SL} + U_{tc, fu} (f_3 + f_4 - 1) T_{FL}}{U_{bcL} + (1 - f_4) U_{tc, fu}} \]
Where \( f_3 = \frac{k_F}{L_C} + U_{bc,fl} \) and \( f_4 = \frac{U_{tc,fu} - U_{bc,fl}}{k_F + U_{tc,ru}} \)

\[
T_{SC} - T_{FL} = \frac{(\alpha \tau)_1 I_{SL} + U_{tc,ru} (f_3 + f_4 - 1) T_{FL}}{U_{bc,fl} + (1 - f_4) U_{tc,ru}}
\]

\[
U_{bc,fl} (T_{SC} - T_{FL}) = U_{bc,fl} \frac{(\alpha \tau)_1 I_{SL} + U_{tc,ru} (f_3 + f_4 - 1) T_{FL}}{U_{bc,fl} + (1 - f_4) U_{tc,ru}}
\]

\[
U_{bc,fl} (T_{SC} - T_{FL}) = U_{bc,fl} \frac{U_{bc,fl} (f_3 + f_4 - 1)}{U_{bc,fl} + (1 - f_4) U_{tc,ru}} T_{FL}
\]

\[
U_{bc,fl} (T_{SC} - T_{FL}) = PF_2 (\alpha \tau)_1 I_{SL} - U_{2,eff} T_{FL}
\]

(5.13)

Where \( PF_2 = \frac{U_{bc,fl}}{U_{bc,fl} + (1 - f_4) U_{tc,ru}} \) and \( U_{2,eff} = \frac{U_{tc,ru} U_{bc,fl} (f_3 + f_4 - 1)}{U_{bc,fl} + (1 - f_4) U_{tc,ru}} \)

Solving Equation 5.4, we get

\[
\alpha p^3 \left( 1 - \beta_C \right) I_{SL} \times \text{bdx} = h_{FL} (T_P - T_{FL}) \times \text{bdx} + U_{ipa} (T_P - T_A) \times \text{bdx}
\]

\[
\alpha p^3 \left( 1 - \beta_C \right) I_{SL} = (h_{FL} + U_{ipa}) T_P - h_{FL} T_{FL} - U_{ipa} T_A
\]

\[
(h_{FL} + U_{ipa}) T_P = \alpha p^3 \left( 1 - \beta_C \right) I_{SL} + h_{FL} T_{FL} + U_{ipa} T_A
\]
(h_{FL} + U_{tpa})T_{P} = (\alpha \tau)_{2_{eff}} I_{SL} + h_{FL} T_{FL} + U_{tpa} T_{A}

Where

(\alpha \tau)_{2_{eff}} = \alpha \tau^3 \beta (1 - \beta_C)

Now

T_{P} = \frac{(\alpha \tau)_{2_{eff}} I_{SL} + h_{FL} T_{FL} + U_{tpa} T_{A}}{(h_{FL} + U_{tpa})}

(5.14)

T_{P} - T_{FL} = \frac{(\alpha \tau)_{2_{eff}} I_{SL} + h_{FL} T_{FL} + U_{tpa} T_{A} - h_{FL} T_{FL} - U_{tpa} T_{FL}}{(h_{FL} + U_{tpa})} - T_{FL}

T_{P} - T_{FL} = \frac{(\alpha \tau)_{2_{eff}} I_{SL} + U_{tpa} T_{A} - U_{tpa} T_{FL}}{(h_{FL} + U_{tpa})}

h_{FL} (T_{P} - T_{FL}) = PF_3 (\alpha \tau)_{2_{eff}} I_{SL} - U_{3_{eff}} (T_{FL} - T_{A})

(5.15)

Where

PF_3 = \frac{h_{FL}}{(h_{FL} + U_{tpa})} \quad U_{3_{eff}} = \frac{h_{FL} U_{tpa}}{(h_{FL} + U_{tpa})}

Now putting the value of Equation 5.12 in Equation 5.1 we get:

U_{tc_{fa}} (T_{SC} - T_{FU}) \times bdx = m_{FU} C_{FU} \frac{dT_{FU}}{dx} + U_{ifu,a} (T_{FU} - T_{A}) \times bdx

U_{tc_{fa}} (T_{SC} - T_{FU}) \times b = m_{FU} C_{FU} \frac{dT_{FU}}{dx} + U_{ifu,a} (T_{FU} - T_{A}) \times b

m_{FU} C_{FU} \frac{dT_{FU}}{dx} = b[U_{tc_{fa}} (T_{SC} - T_{FU}) - U_{ifu,a} (T_{FU} - T_{A})]

m_{FU} C_{FU} \frac{dT_{FU}}{dx} = b[PF_1 (\alpha \tau)_{1_{eff}} I_{SL} + U_{1_{eff}} T_{FU} - U_{ifu,a} (T_{FU} - T_{A})]

dT_{FU} \frac{dx}{dx} = \frac{b}{m_{FU} C_{FU}} [PF_1 (\alpha \tau)_{1_{eff}} I_{SL} + U_{1_{eff}} T_{FU} - U_{ifu,a} (T_{FU} - T_{A})]
\[
\frac{dT_{FU}}{dx} = \frac{b}{m_{FU}C_{FU}}PF_1(\alpha \tau)_{1eff} I_{SL} + \frac{b}{m_{FU}C_{FU}} U_{1eff} T_{FU} - \frac{b}{m_{FU}C_{FU}} U_{tfu,a} T_{FU} + \frac{b}{m_{FU}C_{FU}} U_{tfu,a} T_A
\]

\[
\frac{dT_{FU}}{dx} + \left[ \frac{b}{m_{FU}C_{FU}} U_{tfu,a} - \frac{b}{m_{FU}C_{FU}} U_{1eff} \right] T_{FU} = \frac{b}{m_{FU}C_{FU}} PF_1(\alpha \tau)_{1eff} I_{SL} + \frac{b}{m_{FU}C_{FU}} U_{tfu,a} T_A
\]

\[
\frac{dT_{FU}}{dx} + a_1 T_{FU} = f_1(t)
\]

\[\text{(5.16)}\]

Where \[a_1 = \frac{b}{m_{FU}C_{FU}} (U_{tfu,a} - U_{1eff})\]

\[
f_1(t) = \frac{b}{m_{FU}C_{FU}} \left[ PF_1(\alpha \tau)_{1eff} I_{SL} + U_{tfu,a} T_A \right]
\]

Now solving Equation 5.16, we get:

\[
e^{a_1x} \frac{dT_{FU}}{dx} + e^{a_1x} a_1 T_{FU} = e^{a_1x} f_1(t)
\]

\[
\frac{d}{dx} \left( e^{a_1x} T_{FU} \right) = e^{a_1x} f_1(t)
\]

\[\text{(5.17)}\]

Integrating equation 5.17, we get:

\[
e^{a_1x} T_{FU} = \frac{f_1(t)}{a_1} e^{a_1x} + C \quad \text{where C is a constant.}
\]

\[
T_{FU} = \frac{f_1(t)}{a_1} + C e^{-a_1x}
\]

\[\text{(5.18)}\]

Now at \[x = 0, T_{FU} = T_{FU1}\] Hence

\[
T_{FU1} = \frac{f_1(t)}{a_1} + C
\]

\[
C = T_{FU1} - \frac{f_1(t)}{a_1}
\]

and therefore putting the value of C in equation 5.18, we get:

\[
T_{FU} = \frac{f_1(t)}{a_1} + T_{FU1} e^{-a_1x} - \frac{f_1(t)}{a_1} e^{-a_1x}
\]
\[ T_{FU} = \frac{f_1(t)}{a_1} (1 - e^{-a_1 x}) + T_{FUI} \cdot e^{-a_1 x} \quad (5.19) \]

We know that

\[ T_{FUO} = T_{FU} \bigg|_{x=L} \]

\[ T_{FUO} = \frac{f_1(t)}{a_1} (1 - e^{-a_1 L}) + T_{FUI} \cdot e^{-a_1 L} \quad (5.20) \]

Now we know that, the thermal energy obtained from the upper channel is given by:

\[ Q_{U,U} = m_{FU} \cdot C_{FU} \left( T_{FUO} - T_{FUI} \right) \]

\[ Q_{U,U} = m_{FU} \cdot C_{FU} \left\{ \left[ \frac{f_1(t)}{a_1} (1 - e^{-a_1 L}) + T_{FUI} \cdot e^{-a_1 L} \right] - T_{FUI} \right\} \]

\[ Q_{U,U} = m_{FU} \cdot C_{FU} \left\{ \left[ \frac{f_1(t)}{a_1} (1 - e^{-a_1 L}) + T_{FUI} \cdot e^{-a_1 L} \right] - T_{FUI} \right\} \]

\[ Q_{U,U} = m_{FU} \cdot C_{FU} \left[ \frac{f_1(t)}{a_1} (1 - e^{-a_1 L}) + T_{FUI} \cdot e^{-a_1 L} - T_{FUI} \right] \]

\[ Q_{U,U} = m_{FU} \cdot C_{FU} \left[ \frac{f_1(t)}{a_1} (1 - e^{-a_1 L}) - T_{FUI} \cdot (1 - e^{-a_1 L}) \right] \quad (5.21) \]

Now putting the value of Equation 5.13 and 5.15 in Equation 5.3, we get:

\[ U_{bc,FL} (T_{SC} - T_{FL}) \times bdx + h_{FL} (T_P - T_{FL}) \times bdx \]

\[ = m_{FL} C_{FL} \frac{dT_{FL}}{dx} + U_{bfL,a} (T_{FL} - T_A) \times bdx \]

\[ m_{FL} C_{FL} \frac{dT_{FL}}{dx} = b \left[ U_{bc,FL} (T_{SC} - T_{FL}) + h_{FL} (T_P - T_{FL}) - U_{bfL,a} (T_{FL} - T_A) \right] \]

\[ m_{FL} C_{FL} \frac{dT_{FL}}{dx} = b \left[ PF_2 (\alpha \tau)_{1_{eff}} I_{SL} - U_{2_{eff}} T_{FL} + PF_3 (\alpha \tau)_{2_{eff}} I_{SL} - U_{3_{eff}} (T_{FL} - T_A) - U_{bfL,a} (T_{FL} - T_A) \right] \]
\[
\frac{dT_{FL}}{dx} = \frac{b.}{m_{FL} C_{FL}} \left[ (PF_2 (\alpha \tau)_{1eff} + PF_3 (\alpha \tau)_{2eff}) I_{SL} - (U_{2eff} + U_{3eff} + U_{bfl,a}) T_{FL} + (U_{3eff} + U_{bfl,a}) T_A \right]
\]

\[
\frac{dT_{FL}}{dx} + \frac{b.}{m_{FL} C_{FL}} (U_{2eff} + U_{3eff} + U_{bfl,a}) T_{FL} = \frac{b.}{m_{FL} C_{FL}} \left[ (PF_2 (\alpha \tau)_{1eff} + PF_3 (\alpha \tau)_{2eff}) I_{SL} + (U_{3eff} + U_{bfl,a}) T_A \right]
\]

\[
\frac{dT_{FL}}{dx} + a_2 T_{FL} = f_2 (t)
\]  (5.22)

Where
\[
a_2 = \frac{b.}{m_{FL} C_{FL}} (U_{2eff} + U_{3eff} + U_{bfl,a})
\]

\[
f_2 (t) = \frac{b.}{m_{FL} C_{FL}} \left[ (PF_2 (\alpha \tau)_{1eff} + PF_3 (\alpha \tau)_{2eff}) I_{SL} + (U_{3eff} + U_{bfl,a}) T_A \right]
\]

Now solving Equation 5.22, we get:
\[
e^{-a_2x} \frac{dT_{FL}}{dx} + e^{-a_2x} a_2 T_{FL} = e^{-a_2x} f_2 (t)
\]

\[
\frac{d}{dx} (e^{a_2x} T_{FL}) = e^{a_2x} f_2 (t)
\]  (5.23)

Integrating equation 5.23, we get:
\[
e^{a_2x} T_{FL} = \frac{f_2 (t)}{a_2} e^{-a_2x} + C \quad \text{Where C is a constant.}
\]

\[
T_{FL} = \frac{f_2 (t)}{a_2} + C e^{-a_2x}
\]  (5.24)

Now at \( x = 0, T_{FL} = T_{FLI} \) Hence
\[
T_{FLI} = \frac{f_2 (t)}{a_2} + C
\]

\[
C = T_{FLI} - \frac{f_2 (t)}{a_2}
\]

and therefore putting the value of C in Equation 5.24, we get:
\[
T_{FL} = \frac{f_2 (t)}{a_2} + T_{FLI} e^{-a_2x} - \frac{f_2 (t)}{a_2} e^{-a_2x}
\]
\[ T_{FL} = \frac{f_2(t)}{a_2} (1 - e^{-a_2x}) + T_{FLJ} \cdot e^{-a_2x} \]  
\[ (5.25) \]

We know that

\[ T_{FLO} = T_{FL} \mid_{x=L} \]

\[ T_{FLO} = \frac{f_2(t)}{a_2} (1 - e^{-a_2L}) + T_{FLJ} \cdot e^{-a_2L} \]  
\[ (5.26) \]

Now we know that, the thermal energy obtained from the lower channel is given by:

\[ Q_{U,L} = m_{FL} \cdot C_{FL} (T_{FLO} - T_{FLJ}) \]

\[ Q_{U,L} = m_{FL} \cdot C_{FL} \left\{ \left[ \frac{f_2(t)}{a_2} (1 - e^{-a_2L}) + T_{FLJ} \cdot e^{-a_2L} \right] - T_{FLJ} \right\} \]

\[ Q_{U,L} = m_{FL} \cdot C_{FL} \left\{ \left[ \frac{f_2(t)}{a_2} (1 - e^{-a_2L}) + T_{FLJ} \cdot e^{-a_2L} \right] - T_{FLJ} \right\} \]

\[ Q_{U,L} = m_{FL} \cdot C_{FL} \left[ \frac{f_2(t)}{a_2} (1-e^{-a_2L}) + T_{FLJ} \cdot e^{-a_2L} - T_{FLJ} \right] \]

\[ Q_{U,L} = m_{FL} \cdot C_{FL} \left[ \frac{f_2(t)}{a_2} (1-e^{-a_2L}) - T_{FLJ} \cdot (1-e^{-a_2L}) \right] \]  
\[ (5.27) \]

Now the total thermal energy from both the channel is as follows:

\[ Q_{UT} = Q_{U,L} + Q_{U,U} \]  
\[ (5.28) \]

Total thermal energy from both the channel (in kWh) is as follows:

\[ Q_{U,th} = \frac{(Q_{U,L} + Q_{U,U})}{1000} \text{ kWh} \]  
\[ (5.28a) \]
5.1.3 Methodology

The climatic data, namely; solar radiation and ambient temperature have been obtained from the Indian Meteorological Department (IMD), Pune for Srinagar, India as given in Table 5.2 and weather conditions is given in Table 5.3. Same methodology has been adopted for the evaluation of annual performance as given in section 4.1.4.

TABLE 5.2: AVERAGE AMBIENT TEMPERATURE (°C) AND HOURLY GLOBAL RADIATION FOR SRINAGAR

<table>
<thead>
<tr>
<th>Time</th>
<th>08 AM</th>
<th>09 AM</th>
<th>10 AM</th>
<th>11 AM</th>
<th>12 Noon</th>
<th>01 PM</th>
<th>02 PM</th>
<th>03 PM</th>
<th>04 PM</th>
<th>05 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature (T_A)</td>
<td>0.20</td>
<td>-0.50</td>
<td>-0.80</td>
<td>-0.80</td>
<td>-0.90</td>
<td>-0.10</td>
<td>1.60</td>
<td>2.70</td>
<td>4.50</td>
<td>6.40</td>
</tr>
<tr>
<td>Incident Intensity (I_SL)</td>
<td>73.61</td>
<td>252.78</td>
<td>455.56</td>
<td>545.84</td>
<td>577.78</td>
<td>572.22</td>
<td>511.11</td>
<td>418.06</td>
<td>227.78</td>
<td>43.06</td>
</tr>
</tbody>
</table>

5.1.4 Results and Discussion

Firstly the overall exergy efficiency and electrical efficiency as indicated by Equation 1.15 and 1.11, have been evaluated for the Srinagar, India climatic condition. The hourly variations of solar radiation and ambient temperature for the month of January are given in Table 5.2. The variation in electrical efficiency and solar cell temperature with respect to time is shown in Figure 5.3. It is to be noted that, an average improvement in electrical efficiency in case-I is 30.49%, while the average reduction in solar cell temperature for case-I is 43.11 °C as compared to case-II. It is inferred that due to the reduction in solar cell temperature, there is improvement occurs in electrical efficiency. Figure 5.4 shows the variation in outlet fluid temperature at the lower channel in case-I and case-II with respect to time. It is observed that the outlet fluid temperature of the lower channel is less for case-II as compared to case-I. It indicates that some amount of heat is trapped by upper channel so the effect of heat on solar cell is less. Four weather conditions like; clear days, hazy days, hazy and cloudy days and cloudy days have been considered and termed as Set A, Set B, Set C and Set D respectively, have been shown in Table 5.3. The hourly variation of ambient temperature and average hourly global radiation for four different weather condition are
given in Appendix A for Srinagar climatic condition. The annual performance estimation has been done for the Srinagar (India) climatic conditions.

Figure 5.3: Variation in solar cell temperature, electrical efficiency with respect to time for case-I and case-II

Figure 5.4: Variation in outlet fluid temperature at lower channel with respect to time for case-I and Case-II
**Table 5.3: Weather Conditions**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Name</th>
<th>Weather</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Set A</td>
<td>Clear days</td>
<td>The ratio of daily diffuse to daily global radiation $\leq 0.25$ and sunshine hours $\geq 9$ h</td>
</tr>
<tr>
<td>2.</td>
<td>Set B</td>
<td>Hazy days</td>
<td>The ratio of daily diffuse to daily global radiation is between 0.25 and 0.50 and sunshine hours between 7 and 9 h</td>
</tr>
<tr>
<td>3.</td>
<td>Set C</td>
<td>Hazy and cloudy days</td>
<td>The ratio of daily diffuse to daily global radiation is between 0.50 and 0.75 and sunshine hours between 5 and 7 h</td>
</tr>
<tr>
<td>4.</td>
<td>Set D</td>
<td>Cloudy days</td>
<td>The ratio of daily diffuse to daily global radiation $\geq 0.75$ and sunshine hours $\leq 5$ h</td>
</tr>
</tbody>
</table>

The variation in electrical gain, thermal gain, overall thermal gain and overall exergy gain with respect to the months is shown in Figures 5.5 to 5.8 respectively. The average improvements in above parameters are 71.51%, 34.57%, 43.90% and 46.32% respectively in case-I as compared to case-II. It is because of the double channel above and below the solar cell which removes more heat, due to this temperature of solar cell gets down and simultaneously all above discussed gain are improved.

![Electrical gain variation](image)

*Figure 5.5: Variation in Electrical gain with respect to the months of the year for case-I & II.*
Figure 5.6: Variation in thermal gain with respect to the months of the year for case-I & II.

Figure 5.7: Variation in overall thermal gain with respect to the months for case-I & II.
Figure 5.8: Variation in overall exergy gain with respect to the months for case-I & II.

Figure 5.9: Variation in overall exergy efficiency with respect to time for case-I & II
The variation in overall exergy efficiency with respect to time is shown in Figure 5.9. The average improvement in overall exergy efficiency is 3.19% for case-I as compared to case-II. It is reported that due to the dual channel, there is additional thermal energy is tapped by upper channel and simultaneously there is a reduction in solar cell temperature. Figure 5.10 shows annual overall exergy and annual overall thermal gain for case-I and case-II. The improvements in overall exergy gain and overall thermal gain are 46.32% and 43.90% for case-I as compared to case-II respectively.

Figure 5.10: Annual overall exergy and annual overall thermal gain for case-I and case-II

5.2 OPTIMIZATION WITH GA-FS APPROACH

Now a days, it is a demand of the whole world to explore the research in the field of non-conventional energy resources. But we need to improve the efficiency of the solar panels. The work has been carried out in two steps; firstly the parameters of hybrid dual channel semitransparent photovoltaic thermal (DCSPVT) module has been optimized using a genetic algorithm-fuzzy system (GA-FS) approach. During the course of optimization, overall exergy efficiency is the objective function and different design parameters of the proposed module like; the depth of the upper and lower channel, thickness of the glass, solar cell, insulation and blackened plate, velocity of flowing fluid in upper and lower channel and length of the channel have been optimized. Fuzzy controller is used to improve the
performance of genetic algorithms and the approach is called as a genetic algorithm-fuzzy system (GA-FS) approach. In the second step, the performance of the module has been analyzed for four cities of India like Srinagar, Bangalore, Jodhpur and New Delhi. The performance of the module has been done in daytime 08:00 AM to 05:00 PM and annually from January to December. The dimensions of proposed module have been shown in Table 5.4. Air as working fluid in the upper and lower channel has been used. When the solar radiation falls on the DCSPVT module, it heats up the working fluid in both the channel. Only a small fraction of the absorbed solar radiation is converted into electricity, while the rest is increasing the temperature of the working fluid and absorber plate. The heated air, then flows to the upper channel while the heated air in the lower channel receives additional heating from the solar panel. Thermal modeling of the DCSPVT module is already present in section 5.1.2 and the methodology for the evaluation of annual performance is same as given in section 4.1.4 of chapter 4.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters And Their Value</th>
<th>S.No.</th>
<th>Parameters And Their Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameters</td>
<td>Value</td>
<td>Unit</td>
</tr>
<tr>
<td>1.</td>
<td>( \tau_{c_c} )</td>
<td>0.95</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>( \eta_{r_c} )</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>( \alpha_r )</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>5.</td>
<td>( \rho )</td>
<td>1.29</td>
<td>kg/m³</td>
</tr>
<tr>
<td>6.</td>
<td>( \eta_{C, Power} )</td>
<td>0.38</td>
<td>-</td>
</tr>
<tr>
<td>7.</td>
<td>( \beta_0 )</td>
<td>0.0045</td>
<td>1/K</td>
</tr>
<tr>
<td>8.</td>
<td>( \beta_C )</td>
<td>0.89</td>
<td>-</td>
</tr>
<tr>
<td>9.</td>
<td>( C_{FU, FL} )</td>
<td>1012</td>
<td>J/kgK</td>
</tr>
</tbody>
</table>

5.2.1 Genetic Algorithm-Fuzzy System Approach

In this step, the optimization of the parameters has been done with the help of a genetic algorithm-fuzzy system (GA-FS) approach. The improvement in genetic algorithm
has been achieved with the use of fuzzy controller with the simple genetic algorithm. A simple genetic algorithm is a search algorithm which works on the basis of operators like; crossover, mutation and reproduction. In genetic algorithm the parameters like crossover probability ($P_{\text{cross}}$), mutation probability ($P_{\text{mut}}$) and population size is constant during the course of optimization while in genetic algorithm-fuzzy system approach, these parameters are varied dynamically during the program of genetic algorithm with the use of fuzzy knowledge base. The fuzzy knowledge base has been developed from the experience to maximize the efficiency of genetic algorithm. The flow chart of a genetic algorithm is shown in Figure 1.6 and the schematic view of the genetic algorithm-fuzzy system approach is shown in Figure 1.11.

When we optimize the parameter with genetic algorithm, it has been found that the variation between two chromosomes is too much less. In other words, we can say that the fitness value of each chromosome is almost equal. Due to the small difference between the chromosomes, the effect of crossover is meaningless. To overcome this problem of variance between chromosomes, the new characteristics in the existing population can vary the population. The important parameters during the execution of the genetic algorithm-fuzzy system approach have been categorized in three linguistic terms such as low, medium and high and assigned some membership value as shown in Table 5.5. The variation in GA parameters held according to the fitness function as follows logic:

(i.) There is possibility to vary the value of the best fitness (BF) for every generation, but it does not change significantly over a number of generations, i.e. number of generations for unchanged best fitness (U-BF) then there is changes occurs in both $P_{\text{cross}}$ and $P_{\text{mut}}$ due to this information.

(ii.) The search is affected by the diversity of the population. The change in fitness value (VF) of the fitness function (overall exergy efficiency) of a population is the measure of diversity. It is necessary in search of best fitness.
### Table 5.5: Membership Function and Range of Variables

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Name Variables</th>
<th>Linguistic Terms</th>
<th>Membership Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Mutation Probability ($P_{\text{mut}}$)</td>
<td>Low, Medium, High</td>
<td>![Graph 1]</td>
</tr>
<tr>
<td>2.</td>
<td>Crossover Probability ($P_{\text{cross}}$)</td>
<td>Low, Medium, High</td>
<td>![Graph 2]</td>
</tr>
<tr>
<td>3.</td>
<td>Best Fitness (BF)</td>
<td>Low, Medium, High</td>
<td>![Graph 3]</td>
</tr>
<tr>
<td>4.</td>
<td>Variance of Fitness (VF)</td>
<td>Low, Medium, High</td>
<td>![Graph 4]</td>
</tr>
<tr>
<td>5.</td>
<td>Number of generations for unchanged BF (U-BF)</td>
<td>Low, Medium, High</td>
<td>![Graph 5]</td>
</tr>
<tr>
<td>6.</td>
<td>Population Size (Popsize)</td>
<td>Low, Medium, High</td>
<td>![Graph 6]</td>
</tr>
</tbody>
</table>

### 5.2.2 Fuzzy Rule Base for GA-FS Program

The parameters of GA are varied in accordance with the fuzzy knowledge base for the optimization of overall exergy efficiency. The rule base for controlling the GA parameters like; crossover probability, population size and mutation probability are shown in Figure 5.11 (a), Figure 5.11 (b) and Figure 5.11 (c) respectively.
Figure 5.11(a): Flowchart for controlling crossover probability ($P_{\text{cross}}$)

Figure 5.11(b): Flowchart for controlling population size (Popsize)
Figure 5.11(c): Flowchart for controlling mutation probability ($P_{\text{cross}}$)

<table>
<thead>
<tr>
<th>S. No</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 upper channel</td>
<td>$d_u$</td>
<td>0.04</td>
<td>m</td>
</tr>
<tr>
<td>2.</td>
<td>Depth of the lower channel</td>
<td>$d_l$</td>
<td>0.04</td>
<td>m</td>
</tr>
<tr>
<td>3.</td>
<td>Length of the channel</td>
<td>$L$</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>4.</td>
<td>Width of the channel</td>
<td>$B$</td>
<td>0.644</td>
<td>m</td>
</tr>
<tr>
<td>5.</td>
<td>Thickness of insulation</td>
<td>$L_I$</td>
<td>0.001</td>
<td>m</td>
</tr>
<tr>
<td>6.</td>
<td>Thickness of blackened plate</td>
<td>$L_P$</td>
<td>0.001</td>
<td>m</td>
</tr>
<tr>
<td>7.</td>
<td>Thickness of solar cell</td>
<td>$L_C$</td>
<td>0.0003</td>
<td>m</td>
</tr>
<tr>
<td>8.</td>
<td>Thickness of glass</td>
<td>$L_G$</td>
<td>0.003</td>
<td>m</td>
</tr>
<tr>
<td>9.</td>
<td>Velocity of flowing fluid in upper channel</td>
<td>$V_{FU}$</td>
<td>1</td>
<td>m/s</td>
</tr>
<tr>
<td>10.</td>
<td>Velocity of flowing fluid in upper channel</td>
<td>$V_{FL}$</td>
<td>1</td>
<td>m/s</td>
</tr>
<tr>
<td>11.</td>
<td>Crossover Probability</td>
<td>$P_{cross}$</td>
<td>0.7</td>
<td>_</td>
</tr>
<tr>
<td>12.</td>
<td>Mutation Probability</td>
<td>$P_{mut}$</td>
<td>0.0034</td>
<td>_</td>
</tr>
</tbody>
</table>
Initial values of the crossover and mutation probability is given in Table 5.7. The optimized parameters of DCSPVT module are given in Table 5.6. The proposed system is optimized with GA-FS at 11:00AM data for Srinagar, India. The hourly global radiation and ambient temperature is given in Table 5.2.

Table 5.7: Initial value to the GA-FS program

<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>150</td>
</tr>
<tr>
<td>2.</td>
<td>Crossover Probability (P_c)</td>
<td>0.9</td>
</tr>
<tr>
<td>3.</td>
<td>Mutation Probability (P_m)</td>
<td>0.01</td>
</tr>
<tr>
<td>4.</td>
<td>Maximum Generation</td>
<td>500</td>
</tr>
</tbody>
</table>

5.2.3 Encoding

The chromosomes are generated randomly, each chromosome represents value of controllable variables which are binary coded. Basically controllable variables are design parameters of hybrid dual channel semitransparent photovoltaic thermal module like the depth of the upper and lower channel, thickness of insulation, blackened plate, solar cell and glass, length and width of the channel and velocity of flowing fluid in upper and lower channel. Each chromosome is separated out in terms of bits of control variables and these bits of control variables are converted into equivalent decimal values by the following formula:

\[
X_i = X_{i}^{\text{min}} + DV_i (b_1 b_2 b_3 \ldots) \times \frac{X_{i}^{\text{max}} - X_{i}^{\text{min}}}{2^{BR_i i - 1}}
\]  

(5.29)

Where

- \(X_{i}^{\text{max}}\) = maximum generation value of \(i^{th}\) control variable
- \(X_{i}^{\text{min}}\) = maximum generation value of \(i^{th}\) control variable
- BR = total number of bits required to represent \(i^{th}\) control variable
- DV_i = decimal value of bits corresponding to \(i^{th}\) control variable
The program is run for different set of control variables which belongs to each chromosome and the value of overall exergy efficiency (fitness function) is evaluated, if the program converges and fitness function obtained from the program solution is within specified limits then chromosome is included to complete initial population. Otherwise, a new chromosome is generated in the same manner and checked again.

5.2.4 Fitness Function Evaluation

The objective of the genetic algorithm-fuzzy system approach is to maximize the overall exergy efficiency. The equation for overall exergy efficiency for \( i^{th} \) generation is as follows:

\[
\left( \eta_{Ex} \right)_i = \left( \frac{(E_{OUT})_i}{0.933(A_M)_i \times I_{SL}} \right) \times 100
\]

(5.30)

And fitness function is modified to keep the efficiency under the limit as:

\[
FF_i = \left( \frac{(E_{OUT})_i}{0.933(A_M)_i \times I_{SL}} \right) \times 100
\]

(5.30a)

Whereas \( i = 1 \) to \( \text{Popsize} \)

\((E_{OUT})_i = \) exergy out for \( i^{th} \) generation.

\((A_M)_i = \) area of the module for \( i^{th} \) generation.

\( FF_i = \) fitness value of function for \( i^{th} \) chromosomes.

5.2.5 Results and Discussion

Firstly, the optimization of DCSPVT module has been done with a genetic algorithm-fuzzy system approach (GA-FS). The overall exergy efficiency is considered as an objective function during the course of optimization. The optimized parameters are given in Table 5.7. In the second step, the cell temperature, electrical efficiency and overall exergy efficiency as
indicated by Equation 1.9 and 1.11, have been evaluated at optimized parameters as given in Figures 5.12 and 5.13 respectively. The data has been considered for the Srinagar, India climatic condition. The hourly variations of ambient temperature and solar radiation for the month of January are given in Appendix A respectively. In the third step, the monthly electrical gain, thermal gain, overall thermal gain and overall exergy gain are evaluated for different city of India as given in Figures 5.14 to 5.17 respectively. In the fourth step, the annual electrical gain, annual overall exergy gain, annual thermal gain and annual overall thermal gain are evaluated as given in Figure 5.18 to 5.21 respectively.

Figure 5.12: Variation in solar cell temperature, electrical efficiency with respect to time

The variation in electrical efficiency and solar cell temperature with respect to time is shown in Figure 5.12. It is to be noted that, an average improvement in electrical efficiency of the optimized DCSPVT module is 1.13% as compared to un-optimized DCSPVT module. While the average reduction in solar cell temperature of the optimized DCSPVT module is 2.28 °C. It is inferred that due to the reduction in solar cell temperature, there is improvement in electrical efficiency and also makes low-grade heat for specific applications. Due to the reduction in cell temperature the thermal stress reduced on DCSPVT module and protect it from structural damage.
The variation in overall exergy efficiency with respect to time is shown in Figure 5.13. The average improvement in overall exergy efficiency of the optimized DCSPVT module is 12.21\% as compared to un-optimized DCSPVT module. It is reported that due to the dual channel, there is additional thermal energy is tapped by upper channel and simultaneously there is a reduction in solar cell temperature. Four weather conditions have been considered and termed as Set A, Set B, Set C and Set D respectively, have been shown in Table 5.3. The hourly variation of ambient temperature and average hourly global radiation for four different weather condition are given in Appendix A for New Delhi, Jodhpur, Srinagar and Bangalore climatic conditions. The monthly and annual performance estimation has been done for the Srinagar, New Delhi, Jodhpur and Bangalore (India) climatic conditions. The variation in electrical gain, thermal gain, overall thermal gain, overall exergy gain with respect to the months for Srinagar, Bangalore, Jodhpur and New Delhi are shown in Figures 5.14 to 5.17 respectively. It has been observed that the gains are maximum in the months of May while these are minimized in the months of November and December. It is concluded that the performance of DCSPVT module is better in summer and poor in winter when the overall exergy efficiency is considered as an objective function.
5.14: Variation in Electrical gain with respect to the months of the year

5.15: Variation in thermal gain with respect to the months of the year
Figure 5.16: Variation in overall thermal gain with respect to the months of the year

Figure 5.17: Variation in overall exergy gain with respect to the months of the year
The variation in annual electrical gain, annual overall exergy gain, annual thermal gain and annual overall thermal gain for Srinagar, Bangalore, Jodhpur and New Delhi is shown in Figures 5.18 to 5.21 respectively. The annual electrical gain and annual overall exergy gain for Srinagar, Bangalore, Jodhpur and New Delhi are 123, 132, 127, 125 kWh and 154, 165, 158, 152 kWh respectively, while the annual thermal gain and annual overall thermal gain for Srinagar, Bangalore, Jodhpur and New Delhi are 671, 754, 739, 674 kWh and 995, 1102, 1075, 1003 kWh respectively. It is inferred that the annual electrical gain and annual overall exergy gain are maximum for Bangalore and the minimum for Srinagar and New Delhi respectively, while the annual thermal gain and annual overall thermal gain is maximum for Bangalore and minimum for New Delhi.

The electrical and thermal gains are maximum for Bangalore because of more numbers of sunshine hours in Bangalore due to its moderate climate while these are minimum for Srinagar due to the short length of the day due to the cold environmental conditions. The Jodhpur has second highest gains due to the hot environmental conditions while the New Delhi has the gains below the Jodhpur due to the composite climate.

![Bar chart showing annual electrical gain for different cities of India](Image)

Figure 5.18: Annual electrical gain for different cities of India
Figure 5.19: Annual overall exergy gain for different cities of India

Figure 5.20: Annual thermal gain for different cities of India
5.3 SUMMARY

Following summary has been drawn:

- An improvement in annual overall exergy and thermal gain is 49.36% and 45.86% for case-I as compared to case-II respectively.
- An average improvement in electrical and overall exergy efficiency of the optimized DCSPVT module is 1.13% and 12.21% respectively as compared to un-optimized DCSPVT module.
- The performance of DCSPVT module is better in summer and poor in winter conditions considering overall exergy efficiency as an objective function.
- The annual electrical and overall exergy gains are maximum for Bangalore and the minimum for Srinagar city.