

Performance of Partially Covered N Number of Photovoltaic Thermal (PVT) - Compound Parabolic Concentrator (CPC) Series Connected Water Heating System

Rohit Tripathi, Sumit Tiwari, G. N. Tiwari

Abstract—In present study, an approach is adopted where photovoltaic thermal flat plate collector is integrated with compound parabolic concentrator. Analytical expression of temperature dependent electrical efficiency of N number of partially covered Photovoltaic Thermal (PVT) - Compound Parabolic Concentrator (CPC) water collector connected in series has been derived with the help of basic thermal energy balance equations. Analysis has been carried for winter weather condition at Delhi location, India. Energy and exergy performance of N - partially covered Photovoltaic Thermal (PVT) - Compound Parabolic Concentrator (CPC) Water collector system has been compared for two cases: (i) 25% area of water collector covered by PV module, (ii) 75% area of water collector covered by PV module. It is observed that case (i) has been best suited for thermal performance and case (ii) for electrical energy as well as overall exergy.

Keywords—Compound parabolic concentrator, Energy, Photovoltaic thermal, Temperature dependent electrical efficiency.

I. INTRODUCTION

MANY researches towards the solar energy occur all over the world due to the concern of global crisis on oil and gas prices. According to some energy experts, oil has reached on peak price. Gas and coal are reserved bigger than oil. This process will push energy prices higher, until sustainable sources replace dependency on fossil fuels as major source of energy. The sustainable green energy such as solar energy has been recognized as one of the auspicious source of energy to replace the need of fossil fuels. The challenge is accepted to reduce CO₂ and other gas emissions by solar energy. Solar energy is a green energy which has the capability to meet a significant proportion of the international energy demands. Parametric study of various configurations of hybrid PV/thermal air collector: experimental validation of theoretical model has been presented in [1]. The vital component in solar energy system is the PVT collector. The concept of PVT collector presented in [9] for the first time. A theoretical model of PVT using techniques of convectional thermal plane collector presented in [15]. The theoretical

model for partially covered N-PVT water collectors connected in series has been experimentally validated in [12].

A compound parabolic concentrator (CPC) is a non-imaging concentrator that is essentially two half parabolas. A CPC has advantage of the fact that for a tilted parabolic reflector, the parabola's half that is closer to the sun will focus the sun's rays below the parabola's focus. As such, by truncating the parabola's half that is now further from the sun and then reflecting the resulting half parabola about an axis of symmetry, a CPC curvature is created. Performance of a concentrating photovoltaic/thermal solar collector has been presented in [8]. Thermal behaviour of solar air heater and water collector with/without compound parabolic concentrator has been discussed in [10]-[13]. Two types of PVT water heating namely tube-in-plate configuration and parallel plate configuration. Tube-in-plate configuration has been presented and parallel plate configuration has evaluated in [2]. A review of solar collectors and thermal energy storage in solar thermal applications has discussed in [16]. Design of flat-plate photovoltaic/thermal collectors has been presented in [3].

The analytical expression of outlet temperature and useful energy and exergy for N-series connected PVT flat plate water collectors partially covered by the photovoltaic module at lower portion have been developed in [6]. Analytical equation for partially covered photovoltaic thermal (PVT) – compound parabolic concentrator (CPC) for a single unit of collector has been derived in [4]. It was found that overall efficiency of 25% of receiver is covered by PV portion, is highest to other configurations. Analytical expression of temperature dependent electrical efficiency of N-PVT water collector connected in series has been developed in [14]. It is observed two cases are discussed: one is PV module at lower portion and second is PV module at upper portion in the receiver. Further, any number of collectors are connected in series with photovoltaic thermal – compound parabolic concentrator (PVT-CPC) water collector system to increase the degree of outlet collection temperature. Thermal modelling of N partially covered photovoltaic thermal (PVT)-compound parabolic concentrator (CPC) collector connected in series has been presented in [11].

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II. SYSTEM DESCRIPTION

In the proposed system, a number (N) of PVT-CPC water collectors have been connected in series. The proposed collector design has been shown in Figs. 1 (a) and (b). The PVT-CPC water collectors have been inclined at 28.5° , equal to latitude of New Delhi, India to receive the annual maximum solar radiation. In this case, the outlet of first partial PV covered PVT-CPC collector (T_{fo1}) has been connected to the inlet of second PVT-CPC collector and again the outlet of second PVT-CPC collector (T_{fo2}) has been connected to the inlet of third PVT-CPC collector and so on up to N^{th} collector. The final outlet water temperature of proposed system is considered as T_{foN} . Numerical computations have been carried out for a typical day of winter condition for December, 2014.

III. THERMAL MODELLING

Following assumptions have been taken to write the basic energy balance equations for proposed number of PVT-CPC collectors connected in series:

1. The PVT-CPC system is in quasi steady state.
2. Ohmic losses in PV modules are neglected.
3. Heat capacity of glass cover, insulation, absorber and3. Heat capacity of glass cover, insulation, absorber and solar cell materials etc. are neglected.
4. There is no temperature gradient across thickness of PV module, insulation and glass materials, as [5]-[7].

Energy balance equations:

- A. Energy balance equation for solar cell of semitransparent PV module (Figs. 1 (a), (b))

$$\rho\alpha_c\tau_g\beta_cI_bA_{am} = [U_{tc,a}(T_c - T_a) + U_{tc,p}(T_c - T_p)]A_{rm} + \rho\eta_m I_b A_{am} \quad (1)$$

- B. Energy balance for absorber plate below the Photovoltaic module

$$\rho\alpha_c\tau_g(1-\beta_c)I_bA_{am} + U_{tc,p}(T_c - T_p)A_{rm} = F'h_{pf}(T_p - T_f)A_{rm} + U_{tp,a}(T_p - T_f) \quad (2)$$

- C. Energy balance for flowing water as fluid below the absorber plate

$$\dot{m}_f c_f \frac{dT_f}{dx} dx = F'h_{pf}(T_p - T_f)A_{rm} b dx \quad (3)$$

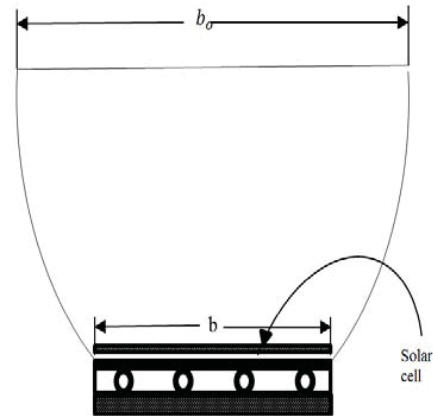
The solution of the above equation can be obtained by using initial condition i.e. ($T_f|_{x=0} = T_{fi}$) as

$$T_f = \left[\frac{PF_2(\alpha\tau)_{m,eff} I_b}{U_{L,m}} + T_a \right] \left[1 - \exp\left\{ \frac{-bF'U_{L,m}x}{\dot{m}_f c_f} \right\} \right] + T_{fi} \exp\left[\frac{-bF'U_{L,m}x}{\dot{m}_f c_f} \right] \quad (4)$$

$$T_{fo1} = T_f|_{x=L_m} = \left[\frac{PF_2(\alpha\tau)_{m,eff} I_b}{U_{L,m}} + T_a \right] \left[1 - \exp\left\{ \frac{-F'U_{L,m}A_{rm}}{\dot{m}_f c_f} \right\} \right] + T_{fi} \exp\left[\frac{-F'U_{L,m}A_{rm}}{\dot{m}_f c_f} \right] \quad (5)$$

TABLE I
VALUES OF DESIGN PARAMETERS OF PROPOSED SYSTEM

$A_r = 1 \text{ m}^2$	$U_{tc,p} = 5.58 \text{ W/m}^2 \text{ }^\circ\text{C}$
$A_{rm} = 0.25 \text{ m}^2$	$U_{tp,a} = 4.8 \text{ W/m}^2 \text{ }^\circ\text{C}$
$A_{rm} = 0.75 \text{ m}^2$	$PF_1 = 0.3782$
$A_{rc} = 0.75 \text{ m}^2$	$PF_2 = 0.9512$
$A_{rc} = 0.25 \text{ m}^2$	$PF_c = 0.9842$
$A_a = 2 \text{ m}^2$	$h_{pf} = 100 \text{ W/m}^2$
$A_{am} = 0.5 \text{ m}^2$	$h_i = 5.7 \text{ W/m}^2$
$A_{am} = 1.5 \text{ m}^2$	$h'_i = 5.8 \text{ W/m}^2$
$A_{ac} = 1.5 \text{ m}^2$	$h_o = 9.5 \text{ W/m}^2$
$A_{ac} = 0.5 \text{ m}^2$	$\rho = 0.84$
$c_f = 4179 \text{ J/kg K}$	$\tau_g = 0.95$
$\dot{m}_f = 0.012 \text{ kg/s}$	$\alpha_c = 0.9$
$F_{rm} = 0.8110 \text{ m}^2$	$\beta_c = 0.89$
$K_g = 0.816 \text{ W/m }^\circ\text{C}$	$\alpha_p = 0.8$
$L_g = 0.003 \text{ m}$	$F' = 0.9680$
$K_i = 0.166 \text{ W/m }^\circ\text{C}$	$F_{rc} = 0.8693 \text{ m}^2$
$L_i = 0.100 \text{ m}$	$FF = 0.8$
$K_p = 6 \text{ W/m }^\circ\text{C}$	$\eta_o = 0.15$
$L_p = 0.002 \text{ m}$	Tube diameter = 0.0125 m
$U_{L1} = 3.47 \text{ W/m}^2 \text{ }^\circ\text{C}$	
$U_{L,m} = 7.87 \text{ W/m}^2 \text{ }^\circ\text{C}$	
$U_{tc,a} = 9.17 \text{ W/m}^2 \text{ }^\circ\text{C}$	
$U_{LC} = 4.7 \text{ W/m}^2 \text{ }^\circ\text{C}$	



(a)

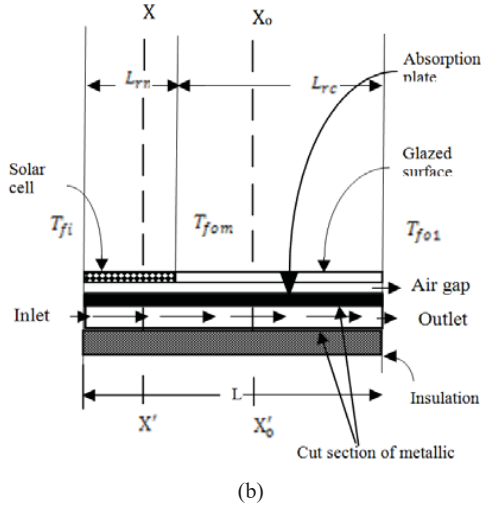


Fig. 1 (a), (b) Cross section of side view and cut section of front view of partially covered First of N-PVT-CPC collector where $A_a = 2 \text{ m}^2$, $A_r = 1 \text{ m}^2$, $A_{rm} = 1 \text{ m}^2$, $A_{rc} = 0$

The outlet water temperature of first PVT-CPC collector T_{fo1} is given by

$$T_{fo1} = \frac{I_b (AF_R (\alpha\tau))_1 (1 - K_p^N)}{\dot{m}_f c_f (1 - K_p)} + \frac{T_a (AF_R U_L)_1 (1 - K_p^N)}{\dot{m}_f c_f (1 - K_p)} + T_{fi} \left(1 - \frac{(AF_R U_L)_1}{\dot{m}_f c_f} \right) \quad (6)$$

The expression for T_{foN} in the present case has been derived. One can get the following

$$T_{foN} = \frac{I_b (AF_R (\alpha\tau))_1 (1 - K_p^N)}{\dot{m}_f c_f (1 - K_p)} + \frac{T_a (AF_R U_L)_1 (1 - K_p^N)}{\dot{m}_f c_f (1 - K_p)} + K_p^N T_{fi} \quad (7)$$

With help of (7), the rate of useful thermal energy gain from partially covered N-PVT-CPC water collector has been calculated by

$$\dot{Q}_{uthe,N} = \dot{m}_f c_f (T_{foN} - T_{fi}) \quad (8)$$

And the rate of useful thermal exergy gain from partially covered N-PVT-CPC water collector has been evaluated by

$$\dot{Q}_{sth} = \dot{m}_f c_f (T_{foN} - T_{fi}) - \dot{m}_f c_f (T_a + 273) \ln \left(\frac{T_{foN} + 273}{T_{fi} + 273} \right) \quad (9)$$

The analytical expression for the temperature dependent electrical efficiency of solar cells of number (N) of PVT-CPC water collectors has been evaluated by

$$\eta_{cN} = \eta_0 \left[1 - \beta_0 (\bar{T}_c - T_0) \right] \quad (10)$$

where, $\bar{T}_{cN}$ is average solar cell temperature of Nth PVT-CPC water collectors. Now,

$$\eta_{cN} = \frac{\eta_0 \left[1 - \frac{\beta_0}{(U_{tc,p} + U_{tc,a})} \{ (X I_b + Y T_a + Z T_{fi}) - T_0 \} \right]}{\left[1 - \frac{\eta_0 \beta_0 I_b}{(U_{tc,p} + U_{tc,a})} (\alpha + \beta \gamma) \right]} \quad (11)$$

where X, Y, Z, α , β , and γ are defined in Appendix.

The temperature dependent electrical efficiency of PV modules of N PVT-CPC water collector is

$$\eta_{mN} = \tau_g \beta_c \eta_{cN} \quad (12)$$

The rate of usable electrical energy gain or exergy from N-identical PVT-CPC water collector has been solved by

$$\dot{Q}_{xel,N} = A_{rm} I_b \sum_{i=1}^N \eta_{mN} \quad (13)$$

The overall exergy is obtained from proposed system can be calculated to add electrical and thermal exergy by

$$\dot{Q}_{ux,overall} = \dot{Q}_{xel,N} + \dot{Q}_{sth,N} \quad (14)$$

IV. RESULTS AND DISCUSSIONS

In present analysis, the input data has been collected from IMD Pune, India. Direct radiation has been calculated on 30° angle as latitude for New Delhi, India by MATLAB 2010a. Here eight number of collectors are connected in series in partially covered N-PVT-CPC water collectors. The mass flow rate of water has been fixed at 0.012 kg/s which is constant for both cases.

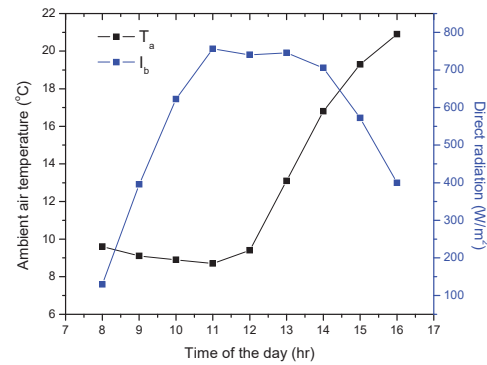


Fig. 2 Hourly variation of input parameters as beam radiation (I_b) to ambient air temperature (T_a)

The hourly variation of ambient air temperature and beam radiation from the sun have been shown in Figs. 2, 3 show hourly variation of average solar cell temperature, plate temperature and flowing water temperature for both cases.

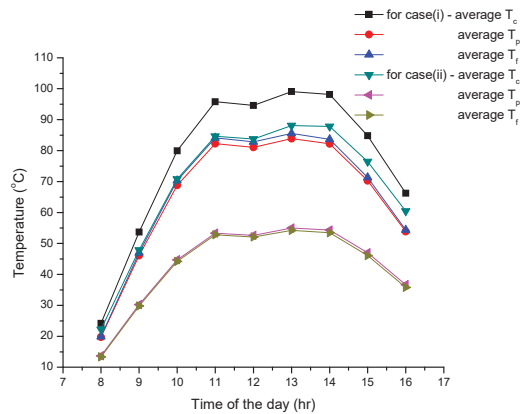


Fig. 3 Hourly variation of average solar cell temperature (T_c), average plate temperature (T_p) and average fluid as water temperature (T_f)

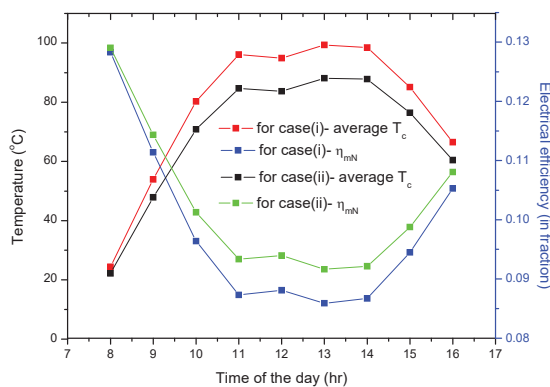


Fig. 4 Hourly variation of average solar cell temperature (T_c) to electrical efficiency of PV modules (η_{mN})

It is observed that average solar cell temperature has been found maximum as compared to plate temperature and flowing water temperature, whereas average flowing water temperature has been found minimum temperature for both cases, as expected. The temperature ranges are higher in case (i) than case (ii). Fig. 4 shows average solar cell temperature to electrical efficiency of PV module for both cases. It is clear to see that electrical efficiency of PV module decreases with increase in average solar cell temperature for both cases, as expected. The electrical efficiency has been found higher in case (ii) and average solar cell temperature has been higher in case (i). Fig. 5 shows hourly variation of outlet water temperature for both cases whereas outlet temperature has been found higher in case (i), due to larger glazed area. The maximum outlet temperature in an hour has been found 98.47°C.

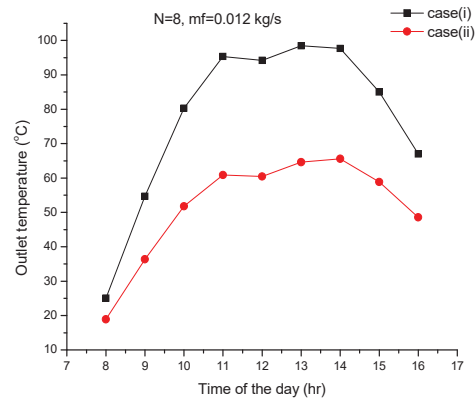


Fig. 5 Hourly variation of outlet water temperature (T_{foN}) of N-PVT-CPC water collector for $N=8$, with mass flow rate 0.012 kg/s, for a clear day

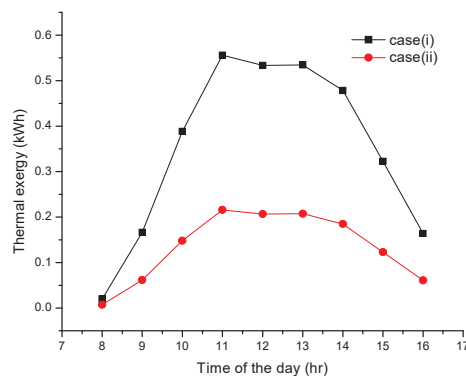


Fig. 6 Hourly variation of thermal exergy of proposed system with number of eight collectors for a typical day in December month

Fig. 6 shows hourly variation of thermal exergy of N PVT-CPC water collector connected in series for both cases. It is clear to observe that the thermal exergy has been found maximum in case (i). Total thermal exergy has been found 3.16 kWh per day for case (i) whereas 1.21 kWh per day for case (ii) for clear day condition in month of December in 2014. The hourly variation of electrical energy /exergy per day has been shown in Fig. 7. It is seen that the electrical energy/exergy has been found maximum in case (ii) due to larger PV module area. The total maximum electrical output has been achieved 2.99 kWh per day for clear sky condition. The hourly variation of overall exergy has been shown in Fig. 8. It is seen that total overall exergy has been found maximum 4.21 kWh per day for case (ii) due to maximum electrical output whereas 4.11 kWh per day for case (i). It is also seen that for few certain hours the overall exergy is higher in case (i), due to maximum solar radiation where thermal output has been found higher.

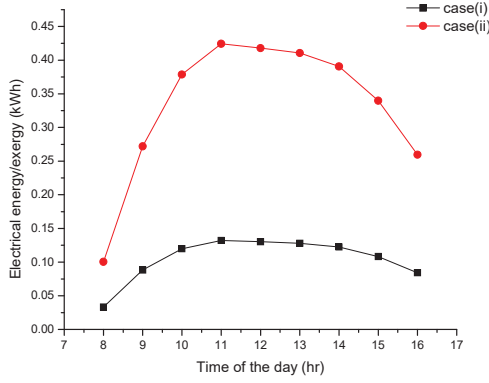


Fig. 7 Hourly variation of electrical energy/exergy of proposed system with number of eight collectors for a typical day in December month

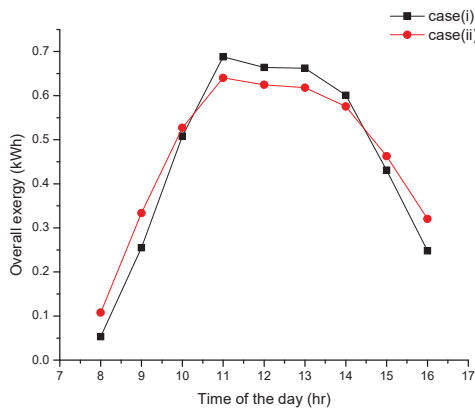


Fig. 8 Hourly variation of overall exergy of proposed system with number of eight collectors for a typical day in December month

V. CONCLUSIONS

- The electrical efficiency of PV module of partially covered N-PVT-CPC water collector connected in series decreases with increase in average solar cell temperature.
- The outlet temperature of partially covered N-PVT-CPC water collector connected in series is maximum in case (i) due to larger glazed area on receiver.
- For use of thermal point of view, case (i) is best suited configuration of partially covered N-PVT-CPC water collector connected in series.
- For use of electrical point of view, case (ii) is best suited configuration of partially covered N-PVT-CPC water collector connected in series.

NOMENCLATURE

α_c	Absorptivity of the solar cell
$\dot{m}_f$	Mass flow rate of water (kg/m ²)
τ_g	Transmissivity of the glass
C_f	Specific heat of water (J/kg K)

β_0	Temperature coefficient of efficiency (K ⁻¹)
L_r	Total length of receiver area (m)
L_a	Total length of aperture area (m)
L_{rc}, L_{rm}	Length of receiver covered by glass or PV module (m)
L_{ac}, L_{am}	Length of aperture covered by glass or PV module (m)
η_c	Solar cell efficiency
η_m	PV module efficiency
b	Breath of receiver (m)
b_o	Breath of aperture (m)
A_{rm}	Area of receiver covered by PV module (m ²)
A_{rc}	Area of receiver covered by glass (m ²)
A_{am}	Area of aperture covered by PV module (m ²)
A_{ac}	Area of aperture covered by glass (m ²)
L_g	Thickness of glass cover (m)
K_g	Thermal conductivity of glass (W/m K)
$I_b(t)$	Beam radiation (W/m ²)
T_a	Ambient temperature (°C)
L_i	Thickness of insulation (m)
K_i	Thermal conductivity of insulation (W/m K)
$(\alpha\tau)_{eff}$	Product of effective absorptivity and transmittivity
F'	Collector efficiency factor
T_{fi}	Inlet water temperature (°C)
T_f	Water temperature (°C)
η_o	Efficiency at standard test condition
$U_{tc,a}$	Overall heat transfer coefficient from cell to ambient (W/m ² K)
$U_{tc,p}$	Overall heat transfer coefficient from cell to plate (W/m ² K)
h_{pf}	Heat transfer coefficient from blackened plate to water (W/m ² K)
β	Packing factor of the module

APPENDIX

Following terms are used in thermal modelling and numerical computation for N-PVT-CPC water collectors system:

$$U_{tc,a} = \left[\frac{1}{h_o} + \frac{L_g}{K_g} \right]^{-1}; h_i' = 2.8 + 3v'$$

$$h_o = 5.7 + 3.8v; v = 1m/s; v' = 1m/s$$

$$U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g} \right]^{-1}; h_i = 5.7;$$

$$U_{tp,a} = \left[\frac{1}{U_{tc,a}} + \frac{1}{U_{tc,p}} \right]^{-1} + \left[\frac{1}{h_i'} + \frac{1}{h_{pf}} + \frac{L_i}{K_i} \right]^{-1}$$

$$\begin{aligned}
U_{L1} &= \frac{U_{tc,p} U_{tc,a}}{U_{tc,p} + U_{tc,p}}; U_{L2} = U_{L1} + U_{tp,a}; \\
U_{L,m} &= \frac{h_{pf} U_{L2}}{F' h_{pf} + U_{L2}}; PF_2 = \frac{h_{pf}}{F' h_{pf} + U_{L2}}; \\
PF_c &= \frac{h_{pf}}{F' h_{pf} + U_{tp,a}}; \\
(\alpha\tau)_{1,eff} &= (\alpha_c - \eta_c) \tau_g \beta_c \frac{A_{am}}{A_{rm}}; \\
(\alpha\tau)_{2,eff} &= \alpha_p \tau_g^2 (1 - \beta_c) \frac{A_{am}}{A_{rm}}; \\
(\alpha\tau)_{m,eff} &= [(\alpha\tau)_{1,eff} + PF_1 (\alpha\tau)_{1,eff}]; \\
A_{rm} &= b L_{rm}; A_{am} = b_o L_{am}; \\
A_c F_{RC} &= \frac{m_f c_f}{U_{L,C}} \left[1 - \exp \left(\frac{-F' U_{L,C} A_c}{m_f c_f} \right) \right]; \\
A_m F_{Rm} &= \frac{m_f c_f}{U_{L,C}} \left[1 - \exp \left(\frac{-F' U_{L,m} A_m}{m_f c_f} \right) \right]; \\
K_p &= \left(1 - \frac{(AF_R U_L)_1}{(m_f c_f)} \right); K_m = \left(1 - \frac{A_m F_{Rm} U_{L,m}}{m_f c_f} \right); \\
(AF_R (\alpha\tau))_{m1} &= PF_2 (\alpha\tau)_{m,eff} A_m F_{rm}; \\
(AF_R U_L)_{m1} &= A_m F_{Rm} U_{L,m}; \\
\alpha &= \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) + \left(\frac{U_{tc,p} P F_1}{(U_{L2} + F' h_{pf})} \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) \right) \\
\beta &= \frac{U_{tc,p} F' h_{pf}}{2 m_f c_f (U_{L2} + F' h_{pf})} P F_1 P F_2 \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) A_m F_{rm} \\
\gamma &= 1 + (1 + K_m) \left[1 - \left(\frac{A_c F_{rc} U_{L,C}}{m_f c_f} \right) \right] \left(\frac{1 - K_K^{n-1}}{1 - K_K} \right) \\
X &= \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) + \frac{U_{tc,p}}{U_{L2} + F' h_{pf}} \\
&\left\{ (\alpha\tau)_{2,eff} + P F_1 \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) \right\} + \frac{U_{tc,p} F' h_{pf}}{2 m_f c_f (U_{L2} + F' h_{pf})} \\
&\left\{ P F_2 (\alpha\tau)_{2,eff} + P F_1 P F_2 \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) \right\} A_m F_{rm} \\
&\left\{ A_c F_{rc} (\alpha\tau)_{c,eff} + \left[\frac{P F_2 (\alpha\tau)_{2,eff} + P F_1 P F_2 \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right)}{1 - \frac{A_c F_{rc} U_{L,C}}{m_f c_f}} \right] A_m F_{rm} \right\} \\
&\left(\frac{1 - K_K^{n-1}}{1 - K_K} \right)
\end{aligned}$$

$$\begin{aligned}
Y &= U_{tc,a} + \frac{U_{tc,p} U_{L2}}{U_{L2} + F' h_{pf}} + \frac{U_{tc,p} F' h_{pf}}{2 m_f c_f (U_{L2} + F' h_{pf})} \\
&\left\{ (AF_R U_L)_{m1} + (1 + K_m) (AF_R U_L)_1 \left(\frac{1 - K_K^{n-1}}{1 - K_K} \right) \right\} \\
Z &= \frac{U_{tc,p} F' h_{pf} (1 + K_m) K_K^{n-1}}{2 (U_{L2} + F' h_{pf})};
\end{aligned}$$

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