NOMENCLATURE

\( a \) cross sectional area of pipe, m\(^2\)
\( A_c \) area of greenhouse cover, m\(^2\)
\( A_d \) area of door, m\(^2\)
\( A_g \) area of greenhouse floor, m\(^2\)
\( A_h \) total area of ACCFHES, m\(^2\)
\( A_i \) area of \( i^{th} \) surface of greenhouse, m\(^2\)
\( A_p \) area of plant, m\(^2\)
\( A_v \) opening area of ventilator, m\(^2\)
\( c_a \) specific heat of air, J kg\(^{-1}\) °C\(^{-1}\)
\( C_c \) heat capacity of cold fluid, J °C\(^{-1}\)
\( c_f \) specific heat of fluid, J kg\(^{-1}\) °C\(^{-1}\)
\( C_h \) heat capacity of hot fluid, J °C\(^{-1}\)
\( c_p \) specific heat of plant, J kg\(^{-1}\) °C\(^{-1}\)
\( c_w \) specific heat of water, J kg\(^{-1}\) °C\(^{-1}\)
\( d \) diameter of pipe, m
\( d_j \) diameter of orifice, m
\( D \) average diameter of bed material, m
\( E \) effectiveness of ACCFHES, dimensionless
\( f \) coefficient of friction, dimensionless
\( F_c-a \) shape factor between the canopy cover and the sky
\( g \) acceleration due to gravity, m\(s^{-1}\)
\( h_a \) heat transfer coefficient from air to water, W m\(^{-2}\) °C\(^{-1}\)
\( h_b \) heat transfer coefficient between the greenhouse floor and the ground beneath, W/m\(^2\) °C
\( h_{cic} \) convective heat transfer coeff from inside air to canopy, W m\(^{-2}\) °C\(^{-1}\)
\( h_{coc} \) outside convective heat transfer coefficient, W m\(^{-2}\) °C\(^{-1}\)
\( h_d \) heat transfer coefficient from the greenhouse door to ambient air, W m\(^{-2}\) °C\(^{-1}\)
\( h_g \) radiative and convective heat transfer coefficient from greenhouse floor to room, W m\(^{-2}\) °C\(^{-1}\)
\( h_i \) total inside heat transfer coefficient, W m\(^{-2}\) °C\(^{-1}\)
\( h_o \) total outside heat transfer coefficient, W m\(^{-2}\) °C\(^{-1}\)
**heat transfer coefficient between the plant and the enclosed air**, $W m^{-2} °C^{-1}$

$h_{pr}$

**total convective and evaporative heat transfer coefficient from plant to the enclosed air**, $W m^{-2} °C^{-1}$

$h_{go}$

**outside radiative heat transfer coefficient**, $W m^{-2} °C^{-1}$

$h_{gi}$

**inside radiative heat transfer coefficient**, $W m^{-2} °C^{-1}$

$h_t$

**overall heat transfer coefficient from room air to ambient air through canopy**, $W m^{-2} °C^{-1}$

$h_v$

**volumetric heat transfer coefficient**, $W m^{-3} °C^{-1}$

$h_w$

**heat transfer coefficient from water to air**, $W m^{-2} °C^{-1}$

$G$

**mass velocity** $(4m_c/πD^2)$ kg s$^{-1}$m$^2$

$I_b$

**beam radiation on a horizontal surface**, $W m^2$

$I_b'$

**beam radiation on inclined surface**, $W m^2$

$I_d$

**diffuse radiation on horizontal surface**, $W m^2$

$I_{ext}$

**extra-terrestrial solar radiation**, $W m^2$

$I_g$

**global radiation on a horizontal surface**, $W m^2$

$I_t$

**total solar radiation on an inclined surface**, $W m^2$

$I_n$

**direct normal solar radiation**, $W m^2$

$I_{sc}$

**average value of solar constant**, 1367 $W m^2$, $I_I$

**incident solar radiation on greenhouse cover**, $W m^2$

$k_a$

**conductivity of air**, $W m^{-1} °C^{-1}$

$k_f$

**conductivity of fluid**, $W m^{-1} °C^{-1}$

$k_g$

**conductivity of ground**, $W m^{-1} °C^{-1}$

$K_i$

**thermal conductivity of the $i^{th}$ layer of the ground**, $W m^{-1} °C^{-1}$

$l_f$

**length of the greenhouse passage**, m

$L$

**length of pipe**, m

$L_{ti}$

**thickness of the $i^{th}$ layer of the ground**, m

$LMTD$

**logarithmic mean temperature difference**, °C

$m_a$

**mass flow rate of air**, kg s$^{-1}$

$m_b$

**mass of the bed** $= V (1-\phi) \rho_b$

$M_a$

**total mass of air**, kg

$M_p$

**total mass of plant**, kg

$m_r$

**mass of rock**, kg

$m_w$

**mass flow rate of water**, kg s$^{-1}$
\( n \)  
day of the year starting 1\textsuperscript{st} January as 1.

\( n_i \)  
refractive index of air (taken as 1)

\( n_2 \)  
refractive index of cover material (taken as 1.37 for polyethylene)

\( N \)  
number of air changes per hour

\( NTU \)  
number of transfer units, \((=U_h A_h/C_{min})\), dimensionless

\( Nu \)  
Nusselt number, dimensionless

\( Nu_a \)  
Nusselt number for air, dimensionless

\( p \)  
partial vapor pressure at saturation, \( \text{pa} \)

\( P \)  
pumping power, \( \text{W} \)

\( Pr \)  
Prandtl number, dimensionless

\( Pr_a \)  
Prandtl number at mean air temperature \((= \mu c_a / k_a)\), dimensionless

\( P(T_p) \)  
partial vapor pressure at plant temperature, \( \text{N/m}^2 \)

\( P(T_c) \)  
partial vapor pressure at canopy temperature, \( \text{N/m}^2 \)

\( q_{co} \)  
outside heat transfer due to convection, \( \text{W} \)

\( q_{ri} \)  
inside radiative heat transfer, \( \text{W} \)

\( Q_p \)  
thermal energy transfer from or to the system, \( \text{W} \)

\( r \)  
reflection coefficient of ground (taken as 0.2)

\( R_0 \)  
radius of heat exchanger pipe, \( \text{m} \)

\( R_i \)  
regression coefficient

\( R_2 \)  
regression coefficient

\( R_b \)  
configuration factor for beam radiation, dimensionless

\( R_d \)  
configuration factor for diffuse radiation, dimensionless

\( Re_a \)  
Reynolds number for air \((= v_c d / \nu_a)\), dimensionless

\( R_r \)  
configuration factor for reflected component, dimensionless

\( S \)  
average heat flux conducted into the soil, \( \text{W} \)

\( S_t \)  
total solar radiation falling on the greenhouse through each wall and roof, \( \text{W/m}^2 \)

\( t_{solar} \)  
local solar time

\( T_1 \)  
initial temperature of fluid, \( ^\circ\text{C} \)

\( T_2 \)  
final temperature of fluid, \( ^\circ\text{C} \)

\( T_a \)  
ambient air temperature, \( ^\circ\text{C} \)

\( T_c \)  
temperature of cover, constant temperature of soil around pipe \( ^\circ\text{C} \)

\( T_{ci} \)  
inlet temperature of cold fluid, \( ^\circ\text{C} \)

\( T_{co} \)  
outlet temperature of cold fluid, \( ^\circ\text{C} \)
$T_d$ delivery air temperature, °C
$T_f$ temperature of fluid, °C
$T_{ht}$ inlet temperature of hot fluid, °C
$T_{ho}$ outlet temperature of hot fluid, °C
$T_i$ inlet temperature of greenhouse air, °C
$T_m$ mean temperature, °C
$T_o$ outlet temperature of greenhouse air, °C
$T_p$ plant temperature, °C
$T_{po}$ initial temperature of plant, °C
$T_r$ turbidity factor for different months
$T_R$ greenhouse room air temperature, °C
$T_{sa}$ sol-air temperature, °C
$T_{sky}$ sky temperature, °C
$T_{j=0}$ temperature of greenhouse floor surface, °C
$T_\infty$ temperature at larger depth, °C
$TF$ transmission factor of greenhouse
$U_h$ overall heat transfer coefficient of ACCFHES, W m$^{-2}$ °C$^{-1}$
$U_t$ overall heat transfer coefficient of the greenhouse, W m$^{-2}$ °C$^{-1}$
$v$ wind velocity, m s$^{-1}$
$V$ volume of the bed, m$^3$
$V_0$ rate of heat transfer due to infiltration, W
$V_i$ rate of heat transfer due to ventilation, W
$v_a$ velocity of air through pipe, m s$^{-1}$
$V_{fa}$ volume flow rate of air, m$^3$ s$^{-1}$
$V_g$ total volume of greenhouse, m$^3$
$V_w$ volume of water stored, m$^3$

**Greek symbols**

$\alpha$ absorptivity
$\alpha_g$ absorptivity of ground, dimensionless
$\alpha_p$ absorptivity of plant, dimensionless
$\alpha_s$ altitude angle of sun above the horizon in degrees.
$\beta$ slope of the surface with horizontal plane in degrees, coefficient of thermal expansion, °K$^{-1}$
\( \gamma \)  
- solar azimuth angle measured from south, relative humidity, decimal

\( \delta \)  
- declination angle

\( \epsilon \)  
- emissivity of the surface, void fraction of the bed

\( \epsilon_{\text{eff}} \)  
- effective emissivity

\( \epsilon_c \)  
- emissivity of canopy cover

\( \epsilon_f \)  
- emissivity of floor

\( \epsilon_{\text{sky}} \)  
- emissivity of sky

\( \theta_1 \)  
- angle of incidence of sun ray with normal

\( \theta_2 \)  
- angle of refraction of sun ray with normal

\( \theta_3 \)  
- zenith angle of sun on inclined surface.

\( \theta_z \)  
- zenith angle of sun on horizontal surface.

\( \mu_a \)  
- dynamic viscosity of air, N-s m\(^{-2}\)

\( \mu_f \)  
- dynamic viscosity of fluid, N-s m\(^{-2}\)

\( \nu_a \)  
- kinematic viscosity of air at mean air temperature, m\(^{-2}\)s\(^{-1}\)

\( \rho \)  
- density of the fluid, kg m\(^{-3}\)

\( \rho_a \)  
- density of air, kg m\(^{-3}\)

\( \rho_b \)  
- density of rocks, Kg/m\(^3\)

\( \sigma \)  
- Stefan Boltsman constant, 5.67 \( \times \) 10\(^{-8}\), Wm\(^{-2}\)K\(^{-4}\)

\( \tau \)  
- transmissivity of greenhouse cover, dimensionless

\( \tau_a \)  
- absorption component of solar radiation

\( \tau_r \)  
- average transmittance of perpendicular and parallel (non-equal) components

\( \phi \)  
- north latitude of location

\( \omega \)  
- hour angle in degrees which is equal to 15° times the number of hours from solar noon, positive from 12 noon to midnight.

\( \infty \)  
- infinity (at larger depth)

\( \Delta P \)  
- pressure drop through the pipe, cm.

\( \Delta T' \)  
- difference in the greenhouse room and ambient temperature

**Subscripts**

- \( a \) air
- \( c \) cold fluid
- \( h \) hot fluid
- \( i \) inlet
- \( o \) outlet
$R$ room air
$w$ water
$E$ east
$W$ west
$N$ north
$S$ south
$NR$ north roof
$SR$ south roof