The efficient collection and long term storage of solar energy in the UK, using air as the working fluid

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The efficient collection and long term storage of solar energy in the UK, using air as the working fluid

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Volume 2

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Nomenclature

Chapter 2

\( A_c \) Collector area (m²)
\( A_s \) Storage tank surface area (m²)
\( c \) Appropriate specific heat (J kg⁻¹ °C⁻¹)
\( c_p \) Volume heat capacity at constant pressure (J kg⁻¹ °C⁻¹)
\( C_h \) Initial capital expenditure per house (£)
\( E_T \) Total (accumulated sum) of the radiation falling over a time period of one month on an inclined surface which is above the threshold radiation (J m⁻²)
\( f \) Differential fuel inflation
\( F_h \) Fuel cost per year per house (£)
\( F_R \) Collector/heat-exchanger efficiency factor
\( F' \) Collector efficiency factor
\( i \) Discount rate
\( I_{th} \) Threshold solar irradiance (W m⁻²)
\( K_h \) Repeated capital expenditure per house (£)
\( L \) Monthly total heating demand for space heating and hot water (J)
\( L_s \) Energy lost from storage tank during the month (J)
\( M_C \) Storage heat capacity (J °C⁻¹)
\( N \) Lifetime of hardware (years)
\( n \) Number of years
\( P_{VCh} \) Present value cost per house
\( Q \) Heat energy (J)
\( Q_N \) Net heat transferred to storage during the month (J)
\( Q_T \) Solar energy collected during the month (J)
\( R_h \) Running costs per year per house (£)
\( s \) Pebble shape factor
\( T_a \) Ambient temperature (°C)
\( T_{at} \) Ambient temperature averaged over periods when the radiation level is above the threshold (°C)
\( T_g \) Monthly average ground temperature (°C)
\( T_s \) Store temperature (°C)
\( \overline{T_s} \) Monthly average store temperature (°C)
\( T_{so} \) Store temperature at the beginning of the month (°C)
\( \Delta T \) Temperature change (\(^{\circ}\)C)

\( t_m \) Total number of seconds in a month

\( t_t \) Total number of seconds collector is in operation in month, i.e. when radiation level is above threshold

\( U_L \) Collector overall loss coefficient (W m\(^{-2}\) °C\(^{-1}\))

\( U_s \) Storage tank heat loss coefficient (W m\(^{-2}\) °C\(^{-1}\))

\( V \) Volume (m\(^3\))

\( \rho \) Density (kgm\(^{-3}\))

\( (\tau\alpha) \) Monthly average transmittance-absorptance product
Nomenclature
Chapter 3

\( A_C \)  Collector area (m\(^2\))
\( P_R \)  Collector heat-exchanger efficiency factor
\( f \)  Fraction of monthly total demand met by solar energy
\( H_T \)  Monthly average daily radiation incident on the collector surface per unit area (Jm\(^{-2}\))
\( L \)  Monthly total heating demand for space heating and hot water (J)
\( N \)  Days in month
\( T_a \)  Monthly average ambient temperature (°C)
\( T_{ref} \)  An empirically derived reference temperature (100° C)
\( t_m \)  Total number of seconds in a month
\( U_L \)  Collector overall loss coefficient (Wm\(^{-2}\) °C\(^{-1}\))
\( (\tau\alpha) \)  Monthly average transmittance-absorptance product
Nomenclature

Chapter 4

A Aperture area, or transparent frontal area of collector (m²)

Cp Specific heat of transfer fluid at constant pressure (Jkg⁻¹ °C⁻¹)

Dh Characteristic length (m)

F' Absorber plate (or collector) efficiency factor

FR Collector heat removal factor

g Acceleration of gravity (ms⁻²)

h₁ Convective heat transfer coefficient, duct top to heat transfer fluid (Wm⁻² °C⁻¹)

h₂ Convective heat transfer coefficient, duct base to heat transfer fluid (Wm⁻² °C⁻¹)

hr Radiative heat transfer coefficient (Wm⁻² °C⁻¹)

hw Wind heat transfer coefficient (Wm⁻² °C⁻¹)

H Duct height (m)

I Equivalent normal solar irradiance (Wm⁻²)

k Thermal conductivity (Wm⁻¹ °C⁻¹)

L Collector length (m)

m Mass flow rate of transfer fluid (Kg s⁻¹)

Nu Nusselt number

Pr Prandtl number

Qu Energy per unit time, useful (W)

Ra Rayleigh number

Re Reynolds number

T₁ Duct top, temperature (°C)

T₂ Duct base, temperature (°C)

Ta Ambient air-temperature (°C)

Tc Cover temperature (°C)

Te Exit fluid temperature (°C)

T₁ Inlet fluid temperature (°C)

Tm Mean fluid temperature (Te + T₁)/2 (°C)

Tp Average absorber temperature (°C)

Ub Bottom loss heat transfer coefficient (Wm⁻² °C⁻¹)

Ue Edge loss heat transfer coefficient (Wm⁻² °C⁻¹)

UL Collector overall heat transfer (loss) coefficient (Wm⁻² °C⁻¹)
\( U_t \) Top loss heat transfer coefficient (Wm\(^{-2}\) °C\(^{-1}\))
\( V \) Wind velocity (ms\(^{-1}\))
\( W \) Collector width (m)
\( x \) Insulation thickness (m)
\( \alpha \) Absorptance of the collector absorber surface for solar radiation
\( \beta \) Volume thermal expansion coefficient (K\(^{-1}\))
\( \varepsilon_c \) Cover emissivity
\( \varepsilon_p \) Absorber plate emissivity
\( \eta \) Efficiency
\( \mu \) Absolute (dynamic) coefficient of viscosity (Kg m\(^{-1}\) s\(^{-1}\))
\( \rho \) Density (Kgm\(^{-3}\))
\( \tau \) Transmittance of the solar collector
\( (\tau \alpha) \) The product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance
\( \sigma \) Stefan-Boltzmann constant
Nomenclature

Chapter 5

A  Aperture area, or transparent frontal area for collector (m$^2$)

$A_c$  Collector area (m$^2$)

$C_p$  Volume heat capacity at constant pressure (J/Kg$^{-1}$°C$^{-1}$)

$P'$  Absorber plate (or collector) efficiency factor

$P''$  Collector flow factor

$F_1$  Correction factor for partial shading of the collector

$F_2$  Correction factor for variation of $\tau_a$ with the angle of incidence

$F_3$  Correction factor for variation in optical properties from normal for diffuse irradiance

$F_R$  Collector heat removal factor

$h_w$  Wind heat transfer coefficient (Wm$^{-2}$°C$^{-1}$)

$I$  Equivalent normal solar irradiance (Wm$^{-2}$)

$I_b$  Direct solar irradiance in plane of collector (Wm$^{-2}$)

$I_d$  Diffuse solar irradiance in plane of collector (Wm$^{-2}$)

$I_m$  Measured total solar irradiation incident upon the aperture plane of the collector (Wm$^{-2}$)

$m$  Mass flow rate of transfer fluid (Kg s$^{-1}$)

$m_t$  Mass flow rate of leak (Kg s$^{-1}$)

$M$  Fluid capacity of collector (Kg)

$(mc)_e$  Effective heat capacity of collector (J °C$^{-1}$)

$q$  Output power per unit aperture area conveyed by the heat transfer fluid (Wm$^{-2}$)

$Qu$  Energy per unit time, useful (W)

$(Qu)_t$  Energy per unit time under transient conditions (W)

$r$  Correlation coefficient

$t$  Time (s)

$T_a$  Ambient air temperature (°C)

$T_b$  Average back plate temperature (°C)

$T_e$  Exit fluid temperature (°C)

$T_f$  Average temperature of the fluid in the collector (°C)

$T_i$  Inlet fluid temperature (°C)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{im}}$</td>
<td>Measured fluid inlet temperature (°C)</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Mean fluid temperature ($T_e + T_i)/2$ (°C)</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Absorber plate temperature (°C)</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Mean absorber temperature (°C)</td>
</tr>
<tr>
<td>$T_{\text{sky}}$</td>
<td>Equivalent black body sky temperature (°C)</td>
</tr>
<tr>
<td>$T^*$</td>
<td>Reduced temperature ($T_i - T_a)/I$ ($\text{m}^2 \text{ °C w}^{-1}$)</td>
</tr>
<tr>
<td>$U_L$</td>
<td>Collector overall heat transfer (loss) coefficient ($\text{Wm}^{-2} \text{ °C}^{-1}$)</td>
</tr>
<tr>
<td>$V$</td>
<td>Wind velocity ($\text{ms}^{-1}$)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$\tau_o$</td>
<td>Product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance.</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>Collector time constant under flow conditions (s)</td>
</tr>
<tr>
<td>$\tau_d$</td>
<td>Cut off time (s)</td>
</tr>
<tr>
<td>$(\tau_o)_e$</td>
<td>Effective transmittance absorptance product</td>
</tr>
<tr>
<td>$(\tau_o)_s$</td>
<td>Product of the absorptance and transmittance for normal irradiance</td>
</tr>
<tr>
<td>$\Delta T^*$</td>
<td>Time increment</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of incidence; degrees from normal</td>
</tr>
</tbody>
</table>
Nomenclature
Chapter 6

\( F_R \) Collector heat removal factor

\( h_{p-c} \) Convection coefficient between absorber plate and cover \((\text{Wm}^{-2} \cdot \text{C}^{-1})\)

\( h_{rp-c} \) Radiation coefficient between absorber plate and cover \((\text{Wm}^{-2} \cdot \text{C}^{-1})\)

\( h_{rc-a} \) Radiation coefficient from the cover to sky \((\text{Wm}^{-2} \cdot \text{C}^{-1})\)

\( h_w \) Wind heat transfer coefficient. \((\text{Wm}^{-2} \cdot \text{C}^{-1})\)

\( I \) Equivalent normal solar irradiance \((\text{Wm}^{-2})\)

\( I_{th} \) Threshold solar irradiance \((\text{Wm}^{-2})\)

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

\( T_i \) Inlet fluid temperature \((^\circ \text{C})\)

\( U \) Collector heat loss coefficient \( P'U_L \) \((\text{Wm}^{-2} \cdot \text{C}^{-1})\)

\( U_L \) Collector overall heat transfer (loss) coefficient \((\text{Wm}^{-2} \cdot \text{C}^{-1})\)

\( \varepsilon_t \) Thermal emissivity

\( \eta \) Efficiency steady state

\( \bar{\eta} \) Daily averaged efficiency

\( \eta_0 \) Zero loss collector efficiency, \( P'(\alpha \tau) \)

\( \tau_s \) Solar transmissivity

\((\tau\alpha)\) Product of the absorptance and transmittance for normal irradiance
Nomenclature

Chapter 7

A  Aspect ratio or area of main heater
a  Accommodation coefficient
\( \bar{c} \)  Average velocity of molecules (ms\(^{-1}\))
\( c_p \)  Specific heat at constant pressure (J Kg\(^{-1}\) °C\(^{-1}\))
\( c_v \)  Specific heat at constant volume (J Kg\(^{-1}\) °C\(^{-1}\))
d  Molecular diameter (m)
\( D_h \)  Hydraulic diameter (m)
g  Acceleration of gravity (ms\(^{-2}\))
Gr  Grashof number
h  Combined heat transfer coefficient from absorber to cover (Wm\(^{-2}\) °C\(^{-1}\))
\( h' \)  Heat transfer coefficient of material of known conductivity (Wm\(^{-2}\) °C\(^{-1}\))
\( h_b \)  Heat transfer coefficient for flow across panel wall (Wm\(^{-2}\) °C\(^{-1}\))
\( h_c \)  Heat transfer coefficient for flow across the inside of the panel due to convection and conduction (Wm\(^{-2}\) °C\(^{-1}\))
\( h_p \)  Heat transfer coefficient for flow across panel (Wm\(^{-2}\) °C\(^{-1}\))
\( h_r \)  Heat transfer coefficient for flow across the inside of the panel due to radiation (Wm\(^{-2}\) °C\(^{-1}\))
\( h_s \)  Heat transfer coefficient for flow across standard insulation (Wm\(^{-2}\) °C\(^{-1}\))
k  Thermal conductivity (Wm\(^{-1}\) °C\(^{-1}\))
L  Linear dimension (m)
m  Wall molecule mass (Kg)
m'  Gas molecule mass (Kg)
M  Mass of one mole (kg mol\(^{-1}\))
\( N_A \)  Avogadro's number
Nu  Nusselt number
p  Gas pressure (Nm\(^{-2}\))
\( P_c \)  Critical pressure when Ra = Ra\(_c\)
Pr  Prandtl number
q  Power dissipated in central heater (W)
$Q$  
Energy per unit time, rate of heat supply to main heater (W)

$Q_p$  
Rate of heat supply to panel from main heater (w)

$r$  
Specific gas constant (R/M)

$R$  
Gas constant

$Ra$  
Rayleigh number

$Ra_c$  
Critical Rayleigh number, for $Ra < Ra_c$ no convection, $Nu = 1$

$Re$  
Reynolds number

$s$  
Absorber plate to cover separation (m)

$t$  
Panel wall thickness (m)

$T$  
Average of plate and cover temperature ($^\circ$C)

$T_1$  
Inside panel temperature nearest to cold plate ($^\circ$C)

$T_2$  
Inside panel temperature nearest to main heater ($^\circ$C)

$T_g$  
Guard ring temperature ($^\circ$C)

$T_i$  
Temperature of main heater, also fluid inlet temperature ($^\circ$C)

$T_0$  
Temperature of cold plates ($^\circ$C)

$\alpha$  
Thermal diffusivity ($m^2/s$)

$\beta$  
Thermal volume expansion coefficient ($\approx 1/T$ for a perfect gas), ($K^{-1}$)

$\gamma$  
$cp/cv$

$\Delta \theta$  
Hot plate temperature unbalance ($T_i - T_g$), ($^\circ$C)

$\Delta T$  
Temperature difference across panel ($^\circ$C)

$\epsilon_1$  
Emissivity of surface at temperature $T_1$ ($^\circ$C)

$\epsilon_2$  
Emissivity of surface at temperature $T_2$ ($^\circ$C)

$\mu$  
Viscosity (Pa s)

$\nu$  
Kinematic viscosity ($\mu/\rho$) (Pa s m$^3$Kg$^{-1}$)

$\rho$  
Density (Kg m$^{-3}$)

$\sigma$  
Stefan-Boltzmann constant (Wm$^{-2}$ K$^{-4}$)

$\lambda$  
Mean free path (m)
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[17] Redfoot, H.L. et al
'Glazing solar collectors with acrylic and double walled polycarbonate plastics'

[18] Duffie, J.A. and Beckman, W.A.

[19] Larson, D.C.
TABLE 2.1  Energy input by fuel and sector in Petajoules for U.K. low grade heat needs (≤80°C) for 1976 and 2025 as predicted by Leach [1]

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### TABLE 2.3 Basic Prometheus configuration to heat 100 houses

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<td>height</td>
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<td>volume</td>
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<td>storage material pebbles, density</td>
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<td>storage material pebbles; specific heat capacity</td>
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<td>store insulation; thermal conductivity</td>
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#### Collector

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<td>optical efficiency averaged over useful incident angles (τα₀)</td>
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<th>Quantity</th>
<th>Unit</th>
<th>Energy Intensity</th>
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TOTAL 6 (1978) 45862.7

Refer to chapter 2 references.
TABLE 2.5 Present value of the costs per house of 3 space and water heating systems, \( N = 45 \) years, \( n_1 = 15 \) years, \( n_2 = 30 \) years. Domestic space and water heating requirement = 27.5 G J/yr, costs in £ 1980.

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<td>( K_h / £ )</td>
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<td>( F_h / £ )</td>
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<td>( R_h / £ )</td>
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<td>( i = 0.05 )</td>
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<td>6000</td>
<td>6300</td>
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<td>( PVCh )</td>
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<tr>
<td>Insulation thickness/m</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
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<tr>
<td>Operating temperature of store/°C</td>
<td>72-42</td>
<td>95-60</td>
<td>70-30</td>
</tr>
<tr>
<td>Number of houses heated by system</td>
<td>50</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Energy consumption GJ/annum per house</td>
<td>32.4</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
<td>Cost of collectors £1980/m²</td>
<td>60</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Cost of store £1980/m³</td>
<td>16</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Collector area/Storage volume (m²/m³)</td>
<td>0.28</td>
<td>0.26</td>
<td>0.36</td>
</tr>
<tr>
<td>Total system capital cost £1980</td>
<td>322900</td>
<td>659000</td>
<td>1740000</td>
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Collector area required to heat type A5 house (27.5 GJ/annum)/m²  
Storage volume required for type A5 house /m³  
Cost per A5 house/£1980
### TABLE 2.7 Specific investment costs for water storage systems as reported by Per-Olov Karlsson*

<table>
<thead>
<tr>
<th>Store temperature rise/(°C)</th>
<th>Cost/$E_{1982}$ per KWh recovered energy seasonal storage</th>
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<tbody>
<tr>
<td>Steel tank</td>
<td>80</td>
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<td>Pit storage</td>
<td>50</td>
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<td>Rock cavern</td>
<td>70</td>
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<td>Storage in clay</td>
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<tr>
<td>Multiple well systems in rock</td>
<td>50</td>
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<td>Aquifers</td>
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<tr>
<td>Prometheus (pebble bed, using data from Table 2.6)</td>
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</table>

<table>
<thead>
<tr>
<th>Name Location of Store/or Centre of Study</th>
<th>Design Study or Constructed</th>
<th>Storage Material</th>
<th>Number of Houses Per Store</th>
<th>% of Annual House Heating Supplied by System</th>
<th>Cost Per House £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambohov, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>56</td>
<td>100</td>
<td>27 000</td>
</tr>
<tr>
<td>Inglestad, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td>19 320</td>
</tr>
<tr>
<td>Studsvik, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>400</td>
<td>93</td>
<td>5 150</td>
</tr>
<tr>
<td>Lyckebo, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>500</td>
<td>100</td>
<td>10 500</td>
</tr>
<tr>
<td>Arizona, USA</td>
<td>Design Study</td>
<td>Water</td>
<td>250</td>
<td>100</td>
<td>3 012</td>
</tr>
<tr>
<td>Northampton, USA</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>10 000</td>
<td>100</td>
<td>6 000</td>
</tr>
<tr>
<td>Sussex, UK</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>100</td>
<td>100</td>
<td>10 000</td>
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<tr>
<td>City University, London, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>100</td>
<td>78</td>
<td>4 000</td>
</tr>
<tr>
<td>ERR, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>300</td>
<td>100</td>
<td>2 416</td>
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<tr>
<td>PCL, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>50</td>
<td>100</td>
<td>5 480</td>
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</table>
### TABLE 3.1 Thermal Characteristics of Basic Type AO House

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<tr>
<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (W m⁻² °C⁻¹)</th>
<th>UA (W °C⁻¹)</th>
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<tbody>
<tr>
<td>Wall</td>
<td>88.5</td>
<td>1.0</td>
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<tr>
<td>Roof</td>
<td>48.6</td>
<td>0.6</td>
<td>29.2</td>
</tr>
<tr>
<td>Floor</td>
<td>48.6</td>
<td>0.5</td>
<td>24.3</td>
</tr>
<tr>
<td>Window</td>
<td>15.0</td>
<td>5.5</td>
<td>82.5</td>
</tr>
<tr>
<td><strong>Total fabric specifics loss</strong></td>
<td></td>
<td><strong>224W °C⁻¹</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Ventilation specific loss</strong></td>
<td></td>
<td><strong>80W °C⁻¹</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total house specific loss</strong></td>
<td></td>
<td><strong>304W °C⁻¹</strong></td>
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TABLE 3.2 Average weather data (1969-1977) for Kew, London, Latitude 51°N

<table>
<thead>
<tr>
<th>Month</th>
<th>Days in month</th>
<th>Solar radiation on a South-facing vertical surface (KWh/m²/month)</th>
<th>Solar radiation on a South-facing surface 30° to horizontal (KWh/m²/month)</th>
<th>Ambient Temperature (°C)</th>
<th>Degree days baseline 15.5°C</th>
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<td>Jan</td>
<td>31</td>
<td>28</td>
<td>25.2</td>
<td>5.2</td>
<td>346</td>
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<tr>
<td>Feb</td>
<td>28</td>
<td>42</td>
<td>45</td>
<td>4.6</td>
<td>304</td>
</tr>
<tr>
<td>March</td>
<td>31</td>
<td>74</td>
<td>91</td>
<td>5.7</td>
<td>282</td>
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<tr>
<td>April</td>
<td>30</td>
<td>75</td>
<td>115</td>
<td>8.2</td>
<td>197</td>
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<tr>
<td>May</td>
<td>31</td>
<td>87</td>
<td>146</td>
<td>11.8</td>
<td>113</td>
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<tr>
<td>June</td>
<td>30</td>
<td>90</td>
<td>166</td>
<td>14.9</td>
<td>113</td>
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<tr>
<td>July</td>
<td>31</td>
<td>84</td>
<td>150</td>
<td>17.2</td>
<td>113</td>
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<tr>
<td>Aug</td>
<td>31</td>
<td>78</td>
<td>123</td>
<td>16.8</td>
<td>113</td>
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<tr>
<td>Sept</td>
<td>30</td>
<td>72</td>
<td>95</td>
<td>13.9</td>
<td>56</td>
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<td>31</td>
<td>59</td>
<td>66</td>
<td>10.8</td>
<td>132</td>
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<tr>
<td>Nov</td>
<td>30</td>
<td>39</td>
<td>37</td>
<td>6.7</td>
<td>256</td>
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<tr>
<td>Dec</td>
<td>31</td>
<td>25</td>
<td>22</td>
<td>5.3</td>
<td>333</td>
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<tr>
<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss (W m⁻¹°C⁻¹)</td>
<td>Net annual space and water heating demand (GJ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------------------</td>
<td>--------------------------------------</td>
<td>---------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A0</td>
<td>Basic (1975 Building Regs.)</td>
<td>304</td>
<td>46.4</td>
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<tr>
<td>A1</td>
<td>A0 + orientate house north-south</td>
<td>304</td>
<td>41.7</td>
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<tr>
<td>A2</td>
<td>A1 + 50 mm loft insulation (100 mm total)</td>
<td>291</td>
<td>39.5</td>
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<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
<td>255</td>
<td>33.7</td>
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</tr>
<tr>
<td>A4</td>
<td>A3 + 50 mm loft insulation (150 mm total)</td>
<td>251</td>
<td>33.0</td>
<td></td>
<td></td>
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<tr>
<td>A5</td>
<td>A4 + extra layer of glazing (i.e. double)</td>
<td>213</td>
<td>27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>A5 + cavity increased to 100 mm</td>
<td>186</td>
<td>23.5</td>
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<tr>
<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
<td>182</td>
<td>20.2</td>
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<tr>
<td>A8</td>
<td>A7 + all windows on south side</td>
<td>177</td>
<td>19.7</td>
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<tr>
<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
<td>164</td>
<td>18.4</td>
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<tr>
<td>A10</td>
<td>A9 + extra layer of glazing (i.e. triple)</td>
<td>150</td>
<td>16.7</td>
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</tr>
<tr>
<td>A11</td>
<td>A10 + cavity increased to 200 mm</td>
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### TABLE 3.4 Thermal characteristics of Basic Type BO house

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<tr>
<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (Wm⁻²°C⁻¹)</th>
<th>UA (W°C⁻¹)</th>
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<tr>
<td>Wall</td>
<td>73.9</td>
<td>1.0</td>
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<tr>
<td>Roof</td>
<td>41.2</td>
<td>0.6</td>
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<td>Floor</td>
<td>41.2</td>
<td>0.5</td>
<td>20.6</td>
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<tr>
<td>Window</td>
<td>13.3</td>
<td>5.5</td>
<td>73.2</td>
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<tr>
<td>Total fabric specific loss</td>
<td></td>
<td></td>
<td>192 W°C⁻¹</td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td></td>
<td>68 W°C⁻¹</td>
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<tr>
<td>Total house specific loss</td>
<td></td>
<td></td>
<td>260 W°C⁻¹</td>
</tr>
<tr>
<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss ($W^0C^{-1}$)</td>
<td>Net annual space water heating demand (GJ)</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------</td>
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<tr>
<td>BO</td>
<td>Basic (average UK housing stock)</td>
<td>260</td>
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<tr>
<td>B1</td>
<td>BO + 50 mm of loft insulation (100 mm total)</td>
<td>249</td>
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<td>B2</td>
<td>B1 + fibre-fill cavity (50 mm)</td>
<td>219</td>
<td>28.3</td>
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<td>B3</td>
<td>B2 + 50 mm of loft insulation (150 mm total)</td>
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<td>B3 + extra layer of glazing (i.e. double)</td>
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**Table 4.1** Art Collector, Tax Collector and Treasurer in the United Kingdom.
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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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</tbody>
</table>

**Table 5.1** Data collected during steady state testing of the D.C. Hall collector

**Column**

<table>
<thead>
<tr>
<th>Column 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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<td>1250</td>
<td>1251</td>
<td>1252</td>
<td>1253</td>
</tr>
</tbody>
</table>

**Column Index**

1. Time (hrs : min)
2. Mass flow rate (kg hr⁻¹)
3. Total insulation (W/m²)
4. Air temperature rise passing through collector (T₂ - T₁), (°C)
5. Ambient air temperature (°C)
6. Inlet air temperature (°C)
7. Outlet air temperature (°C)
8. Absorber temperature (°C)
9. Wind speed (m/s⁻¹)
10. Efficiency (n)
11. (T₂ - T₁)/T
12. Absorber temperature - T₂/1
TABLE 5.2(a) Results of steady state testing on D.C. Hall collector

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date</th>
<th>Time of test</th>
<th>Air mass flow rate</th>
<th>Air temp. at inlet</th>
<th>Air temp. at outlet</th>
<th>Air temp. increase ((T_e - T_i))</th>
<th>Ambient Temp.</th>
<th>Total irradiance in plate of collector ((I_m))</th>
<th>(\frac{(T_e - T_i)}{I_m})</th>
<th>Collector efficiency</th>
<th>Wind speed</th>
<th>Absorber Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21/6/83</td>
<td>1344-1354</td>
<td>65.5</td>
<td>51.1</td>
<td>66.0</td>
<td>14.9</td>
<td>21.1</td>
<td>788</td>
<td>0.0409</td>
<td>43.4</td>
<td>1.6</td>
<td>77.2</td>
</tr>
<tr>
<td>2</td>
<td>25/6/83</td>
<td>1434-1443</td>
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<td>83.5</td>
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<td>22.1</td>
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<td>0.0745</td>
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<td>&lt;0.4</td>
<td>95.3</td>
</tr>
<tr>
<td>3</td>
<td>26/6/83</td>
<td>1123-1132</td>
<td>79.1</td>
<td>22.9</td>
<td>39.6</td>
<td>16.7</td>
<td>22.9</td>
<td>730</td>
<td>0.0000</td>
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<td>&lt;0.4</td>
<td>50.1</td>
</tr>
<tr>
<td>4</td>
<td>5/7/83</td>
<td>1151-1200</td>
<td>61.9</td>
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<td>84.3</td>
<td>9.2</td>
<td>27.7</td>
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<td>78.1</td>
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<td>19/8/83</td>
<td>1209-1218</td>
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<td>59.9</td>
<td>68.6</td>
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<td>1.0</td>
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<td>1.0</td>
</tr>
</tbody>
</table>

Table 5.2(b) Results of steady state testing of structured poly carbonate collector.
TABLE 5.3 Collector configuration modelled for transient analysis by RRDCT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector length (along flow)</td>
<td>4.00 m</td>
</tr>
<tr>
<td>Collector width</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Cover to plate spacing</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Rear Duct gap</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Back insulation dry glass fibre</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Edge insulation dry glass fibre</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Material of plate and duct-back duraluminium HS 15 TB</td>
<td></td>
</tr>
<tr>
<td>Plate absorbance</td>
<td>0.95 at θ = 0 falling slightly as θ increases</td>
</tr>
<tr>
<td>Emissivity of upper surface of the plate (diffuse)</td>
<td>0.10</td>
</tr>
<tr>
<td>Emissivity of duct surface (diffuse)</td>
<td>0.91</td>
</tr>
<tr>
<td>Emissivity of cover (diffuse)</td>
<td>0.85</td>
</tr>
<tr>
<td>Cover polycarbonate thickness</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>0.06 kg s⁻¹</td>
</tr>
<tr>
<td>Thickness of plate and of duct-back</td>
<td></td>
</tr>
<tr>
<td>DY1</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>DY2</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>DY3</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>DY4</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>DY5</td>
<td>5.0 mm</td>
</tr>
</tbody>
</table>

TABLE 5.4 Results of transient and steady state testing with multi node model

<table>
<thead>
<tr>
<th></th>
<th>Steady state</th>
<th>Transient 0.5mm (DY2)</th>
<th>Transient 2mm (DY4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆t/(min)</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>τC/(min)</td>
<td></td>
<td>2.8</td>
<td>9.7</td>
</tr>
<tr>
<td>FRUL/(Wm⁻²K⁻¹)</td>
<td>2.83*</td>
<td>2.768</td>
<td>2.604</td>
</tr>
<tr>
<td>FRα</td>
<td>0.683</td>
<td>0.585</td>
<td>0.569</td>
</tr>
<tr>
<td>KFRα</td>
<td>0.683</td>
<td>0.706</td>
<td>0.686</td>
</tr>
<tr>
<td>̂σ FRUL</td>
<td>-</td>
<td>0.012</td>
<td>0.036</td>
</tr>
<tr>
<td>̂σ FRα</td>
<td></td>
<td>0.0008</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

K = correction factor for equivalent normal direct radiation = \( \frac{(\tau α)_{\text{direct}}}{(\tau α)_{\text{diffuse}}} \) = \( \frac{0.830}{0.688} = 1.206 \)

* = at low fluid inlet temperatures
### Table 5.5

**Transient test data for SP collector input to PANS**

<table>
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<tr>
<th>Column 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Index</th>
<th>Output power per unit aperture area, $g$ (kw/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>n</td>
<td>$F_R(1a)_n$</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
</tr>
<tr>
<td>1</td>
<td>0.432800115133</td>
</tr>
</tbody>
</table>

**TABLE 5.6** Data Output from 'TRANS' for SP collector, n = 1, in the format specified in Table F.6.1 of British Standard DD 77: 1982

**DATA SETS ACCEPTED FOR ANALYSIS**

- n = 1, $k_n = 1$
- F = 0.84211694868
- ETA0 = 0.513943000497

**POINTS ON THERMAL PERFORMANCE CHARACTERISTIC**

- FROM LEAST SQUARES FITS EACH WAY
- MINIMUM ETA0 = 0.2545318781
- MAXIMUM ETA0 = 0.714184616622

**U = 7.33893217894**

**U = 13.9616808148**
### TABLE 5.8  
Temperature distribution within DY1 collector (0.2mm thick plate and duct back) during ASHRAE steady state testing, $T_a = 293k$, $I = 700$ $\text{wm}^{-2}$, $\text{Wind} = 1 \text{m s}^{-1}$, $T_{\text{sky}} = 273k$

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\overline{T}_p/k$</th>
<th>$\overline{T}_b/k$</th>
<th>$T_m/k$</th>
<th>$F_{RUL}$ ($\text{Wm}^{-2} \text{OC}^{-1}$)</th>
<th>$\eta$</th>
<th>$F_{aveU}L$ ($\text{Wm}^{-2} \text{OC}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>332.73</td>
<td>333.01</td>
<td>322.1</td>
<td>317.86</td>
<td>2.762</td>
<td>0.645</td>
<td>3.111</td>
</tr>
<tr>
<td>343</td>
<td>364.98</td>
<td>365.28</td>
<td>357.16</td>
<td>354.00</td>
<td>2.902</td>
<td>0.476</td>
<td>3.230</td>
</tr>
<tr>
<td>383</td>
<td>396.47</td>
<td>396.94</td>
<td>391.47</td>
<td>389.73</td>
<td>3.044</td>
<td>0.293</td>
<td>3.362</td>
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<tr>
<td>423</td>
<td>427.23</td>
<td>428.06</td>
<td>425.00</td>
<td>425.11</td>
<td>3.185</td>
<td>0.095</td>
<td>3.503</td>
</tr>
<tr>
<td>433</td>
<td>435.13</td>
<td>435.94</td>
<td>433.57</td>
<td>434.06</td>
<td>3.226</td>
<td>0.037</td>
<td>3.564</td>
</tr>
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</table>

### TABLE 5.9  
Temperature distribution and energy lost from DY1 collector (0.2mm thick plate and duct back) during zero radiation testing, $T_a = 293k$, $\text{Wind} = 1 \text{m s}^{-1}$, $T_{\text{sky}} = 273k$

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\overline{T}_p/k$</th>
<th>$\overline{T}_b/k$</th>
<th>$T_m/k$</th>
<th>Energy lost per unit time per unit area $\text{W m}^{-2}$</th>
<th>$F_{RUL}$ ($\text{Wm}^{-2} \text{OC}^{-1}$)</th>
<th>$F_{aveU}L$ ($\text{Wm}^{-2} \text{OC}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>300.34</td>
<td>300.41</td>
<td>301.23</td>
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<td>40.34</td>
<td>4.034</td>
<td>4.653</td>
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<td>333.32</td>
<td>333.79</td>
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<td>338.16</td>
<td>146.66</td>
<td>2.932</td>
<td>3.247</td>
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<td>366.41</td>
<td>370.42</td>
<td>374.20</td>
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<td>2.961</td>
<td>3.282</td>
</tr>
<tr>
<td>423</td>
<td>396.74</td>
<td>398.43</td>
<td>403.88</td>
<td>409.87</td>
<td>397.80</td>
<td>3.060</td>
<td>3.404</td>
</tr>
<tr>
<td>433</td>
<td>404.46</td>
<td>406.34</td>
<td>412.12</td>
<td>418.73</td>
<td>432.40</td>
<td>3.088</td>
<td>3.439</td>
</tr>
<tr>
<td>*303</td>
<td>301.62</td>
<td>301.71</td>
<td>302.03</td>
<td>302.31</td>
<td>20.98</td>
<td>2.098</td>
<td>2.035</td>
</tr>
<tr>
<td>*433</td>
<td>405.92</td>
<td>407.78</td>
<td>413.13</td>
<td>419.46</td>
<td>410.30</td>
<td>2.93</td>
<td>3.245</td>
</tr>
</tbody>
</table>

* $T_{\text{sky}} = 293k$
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Wind Speed (m/s)</th>
<th>Radiant Flux (W/m²)</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>0.4</td>
<td>0.520</td>
<td>Indoor</td>
</tr>
<tr>
<td>16</td>
<td>0.4</td>
<td>0.557</td>
<td>Transient</td>
</tr>
<tr>
<td>15</td>
<td>0.4</td>
<td>0.545</td>
<td>Steady State</td>
</tr>
<tr>
<td>23</td>
<td>0.5</td>
<td>0.592</td>
<td>ASHRAE</td>
</tr>
</tbody>
</table>

Structured Polycarbonate Collector

D.C. Hall Collector

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Wind Speed (m/s)</th>
<th>Radiant Flux (W/m²)</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.639</td>
<td>0.508</td>
<td>Theory</td>
</tr>
<tr>
<td>12</td>
<td>0.553</td>
<td>0.508</td>
<td>Zero Radiation Transient</td>
</tr>
<tr>
<td>13</td>
<td>0.583</td>
<td>0.508</td>
<td>ASHRAE</td>
</tr>
<tr>
<td>26</td>
<td>0.627</td>
<td>0.508</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.10: Summary of Collector Testing Results
### TABLE 6.1 Thermal and radiative properties of cover materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflective index ($n$)</th>
<th>Solar (0.2-4.0μm) (%)</th>
<th>Infrared (3.0-500μm) (%)</th>
<th>Expansion coefficient ($^{0}C^{-1}$)</th>
<th>Temperature Limits ($^{0}C$)</th>
<th>Weather-ability (comments)</th>
<th>Chemical Resistance (comments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lexan (Polycarbonate)</td>
<td>1.586</td>
<td>125 mil</td>
<td>125 mil</td>
<td>7.98 x 10^{-5}</td>
<td>120-130</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Plexiglass (Acrylic)</td>
<td>1.49</td>
<td>125 mil</td>
<td>125 mil</td>
<td>8.29 x 10^{-5}</td>
<td>80-90</td>
<td>Average to good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Teflon F.F.P. (Fluorocarbon)</td>
<td>1.343</td>
<td>5 mil</td>
<td>5 mil</td>
<td>12.55 x 10^{-5}</td>
<td>200-220</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Tedlar P.V.F. (fluorocarbon)</td>
<td>1.46</td>
<td>4 mil</td>
<td>4 mil</td>
<td>5.95 x 10^{-5}</td>
<td>110-170</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mylar (Polyester)</td>
<td>1.64-1.67</td>
<td>5 mil</td>
<td>5 mil</td>
<td>2.0 x 10^{-5}</td>
<td>150-200</td>
<td>Poor</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunlite (Fibre glass)</td>
<td>1.54</td>
<td>25 mil</td>
<td>25 mil</td>
<td>2.98 x 10^{-5}</td>
<td>95-100</td>
<td>Fair to good</td>
<td>Good</td>
</tr>
<tr>
<td>Float glass (Glass)</td>
<td>1.518</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.21 x 10^{-6}</td>
<td>230</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Temper glass (Glass)</td>
<td>1.518</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.21 x 10^{-6}</td>
<td>230-250</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear limesheet glass (Low iron glass)</td>
<td>1.51</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.64 x 10^{-6}</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear lime temper glass (Low iron glass)</td>
<td>1.51</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.64 x 10^{-6}</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunade white crystal glass (0.01% iron glass)</td>
<td>1.50</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.00 x 10^{-6}</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Substrate</th>
<th>Supporting Reagent</th>
<th>Process</th>
<th>Most Selective Pat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper/Graphite</td>
<td>Stainless Steel</td>
<td>CC</td>
<td>Blue Stainless Steel</td>
<td>CC</td>
</tr>
<tr>
<td>Copper Oxide</td>
<td>Copper</td>
<td>CC</td>
<td>Copper Oxide Coated Black Enamel</td>
<td>CC</td>
</tr>
<tr>
<td>Alumina</td>
<td>Alumina</td>
<td>CC</td>
<td>Alumina Coated Black Enamel</td>
<td>CC</td>
</tr>
<tr>
<td>Black Coating</td>
<td>ED</td>
<td>ED</td>
<td>Black Coating</td>
<td>ED</td>
</tr>
<tr>
<td>Black Nickel</td>
<td>Black Nickel</td>
<td>Black Nickel</td>
<td>Black Nickel</td>
<td>Black Nickel</td>
</tr>
<tr>
<td>Electrodeposited</td>
<td>Electrodeposited</td>
<td>Electrodeposited</td>
<td>Electrodeposited</td>
<td>Electrodeposited</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Substrate</th>
<th>Supporting Reagent</th>
<th>Process</th>
<th>Most Selective Pat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Stainless Steel</td>
<td>CC</td>
<td>Blue Stainless Steel</td>
<td>CC</td>
</tr>
<tr>
<td>Copper Oxide</td>
<td>Copper</td>
<td>CC</td>
<td>Copper Oxide Coated Black Enamel</td>
<td>CC</td>
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<tr>
<td>Alumina</td>
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<td>CC</td>
<td>Alumina Coated Black Enamel</td>
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<td>Electrodeposited</td>
<td>Electrodeposited</td>
<td>Electrodeposited</td>
<td>Electrodeposited</td>
</tr>
</tbody>
</table>

**Table 6.2**

Optical Properties of Selective Absorber Surface Coatings

<table>
<thead>
<tr>
<th>Trade Name</th>
<th>Absorptance</th>
<th>Supporter</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Solar</td>
<td>Solar</td>
<td>Solar</td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermal</td>
<td>Thermal</td>
<td>Thermal</td>
</tr>
</tbody>
</table>
### TABLE 6.3  Key to collector variable features, used to obtain Figure 6.19

<table>
<thead>
<tr>
<th>Cover Material:</th>
<th>Plate Glass, Thickness</th>
<th>Polycarbonate, Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover 1</td>
<td>6.0 mm</td>
<td></td>
</tr>
<tr>
<td>Cover 2</td>
<td>2.0 mm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness of the Plate and of the Duct-back:</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY1</td>
</tr>
<tr>
<td>0.2 mm</td>
</tr>
<tr>
<td>DY2</td>
</tr>
<tr>
<td>0.5 mm</td>
</tr>
<tr>
<td>DY3</td>
</tr>
<tr>
<td>1.0 mm</td>
</tr>
<tr>
<td>DY4</td>
</tr>
<tr>
<td>2.0 mm</td>
</tr>
<tr>
<td>DY5</td>
</tr>
<tr>
<td>5.0 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Air Flow in the Rear-duct:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow 0</td>
</tr>
<tr>
<td>Stagnation ((M = 0))</td>
</tr>
<tr>
<td>Flow 1</td>
</tr>
<tr>
<td>all (T_i = M = 0.0600 \text{ kg s}^{-1}) (PON irrelevant)</td>
</tr>
<tr>
<td>Flow 2</td>
</tr>
<tr>
<td>(T_i = 303 \text{ K} \quad M = 0.0600 \text{ kg s}^{-1}) (PON = 128W)</td>
</tr>
<tr>
<td>Flow 3</td>
</tr>
<tr>
<td>(T_i = 323 \text{ K} \quad M = 0.0562 \text{ kg s}^{-1}) (PON = 124W)</td>
</tr>
<tr>
<td>Gas</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Air</td>
</tr>
<tr>
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<tr>
<td></td>
</tr>
</tbody>
</table>

### TABLE 7.2 Convection and conduction heat transfer coefficients for various gases at different temperatures as measured with guarded hot plate.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$T_s/°C$</th>
<th>$T_i/°C$</th>
<th>$h_p$ Nm$^{-2}$°C$^{-1}$</th>
<th>$Q_p$ Nm$^{-2}$°C$^{-1}$</th>
<th>$T_f/°C$</th>
<th>$h_r$ Nm$^{-2}$°C$^{-1}$</th>
<th>$h_c$ Nm$^{-2}$°C$^{-1}$</th>
<th>$ΔT/°C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air at atmospheric pressure</td>
<td>10</td>
<td>14</td>
<td>0.798</td>
<td>3.19</td>
<td>10.1</td>
<td>13.84</td>
<td>0.163</td>
<td>0.704</td>
</tr>
<tr>
<td></td>
<td>10.1</td>
<td>20.7</td>
<td>1.910</td>
<td>20.05</td>
<td>11.10</td>
<td>19.70</td>
<td>0.168</td>
<td>2.193</td>
</tr>
<tr>
<td></td>
<td>10.1</td>
<td>21.3</td>
<td>1.725</td>
<td>19.32</td>
<td>11.07</td>
<td>20.33</td>
<td>0.169</td>
<td>1.915</td>
</tr>
<tr>
<td></td>
<td>10.5</td>
<td>33.3</td>
<td>2.195</td>
<td>50.05</td>
<td>13.00</td>
<td>30.80</td>
<td>0.180</td>
<td>2.632</td>
</tr>
<tr>
<td>Air, p = 82 torr</td>
<td>10.35</td>
<td>37.9</td>
<td>1.60</td>
<td>44.08</td>
<td>12.55</td>
<td>35.70</td>
<td>0.185</td>
<td>1.720</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
<td>38.8</td>
<td>1.621</td>
<td>46.12</td>
<td>12.66</td>
<td>36.49</td>
<td>0.185</td>
<td>1.750</td>
</tr>
<tr>
<td>Air, p = 81 torr</td>
<td>10.3</td>
<td>43</td>
<td>1.567</td>
<td>51.24</td>
<td>12.86</td>
<td>40.44</td>
<td>0.189</td>
<td>1.669</td>
</tr>
<tr>
<td>Air, p = 71 torr</td>
<td>10.2</td>
<td>24.9</td>
<td>0.925</td>
<td>13.60</td>
<td>10.88</td>
<td>24.22</td>
<td>0.172</td>
<td>0.847</td>
</tr>
<tr>
<td>Freon/Air</td>
<td>10.3</td>
<td>22.1</td>
<td>1.685</td>
<td>19.88</td>
<td>11.29</td>
<td>21.11</td>
<td>0.170</td>
<td>1.856</td>
</tr>
<tr>
<td></td>
<td>10.1</td>
<td>17.8</td>
<td>1.635</td>
<td>12.59</td>
<td>10.73</td>
<td>17.17</td>
<td>0.166</td>
<td>1.789</td>
</tr>
<tr>
<td>Carbon Tet/Air</td>
<td>10.1</td>
<td>17.9</td>
<td>1.645</td>
<td>12.83</td>
<td>10.74</td>
<td>17.26</td>
<td>0.166</td>
<td>1.803</td>
</tr>
<tr>
<td></td>
<td>10.4</td>
<td>27.9</td>
<td>1.986</td>
<td>34.75</td>
<td>12.14</td>
<td>26.16</td>
<td>0.175</td>
<td>2.303</td>
</tr>
<tr>
<td></td>
<td>10.5</td>
<td>31.3</td>
<td>2.081</td>
<td>43.28</td>
<td>12.66</td>
<td>29.14</td>
<td>0.178</td>
<td>2.450</td>
</tr>
<tr>
<td></td>
<td>10.6</td>
<td>34.9</td>
<td>2.461</td>
<td>59.80</td>
<td>13.59</td>
<td>33.91</td>
<td>0.182</td>
<td>3.082</td>
</tr>
<tr>
<td></td>
<td>10.6</td>
<td>36.7</td>
<td>2.245</td>
<td>58.59</td>
<td>13.53</td>
<td>33.77</td>
<td>0.183</td>
<td>2.712</td>
</tr>
<tr>
<td>Air p = 0.3 torr</td>
<td>10.2</td>
<td>16.6</td>
<td>0.547</td>
<td>3.504</td>
<td>10.38</td>
<td>16.42</td>
<td>0.165</td>
<td>0.414</td>
</tr>
<tr>
<td>Air P = 0.35 torr</td>
<td>10.9</td>
<td>45.7</td>
<td>1.135</td>
<td>39.51</td>
<td>12.87</td>
<td>43.72</td>
<td>0.193</td>
<td>1.088</td>
</tr>
<tr>
<td>Air P = 16 torr and changing</td>
<td>11.2</td>
<td>51.2</td>
<td>1.186</td>
<td>47.46</td>
<td>13.57</td>
<td>48.83</td>
<td>0.198</td>
<td>1.148</td>
</tr>
</tbody>
</table>
FIGURE 1.1(a) PHYSICAL QUALITY OF LIFE INDEX VERSUS ENERGY CONSUMPTION PER CAPITA FOR THE COUNTRIES OF THE WORLD. SOURCES OF DATA: PQLI, BOOK OF WORLD RANKINGS1 BY G.T. KURIAN 1979, ENERGY CONSUMPTION 'EUROPEAN YEARBOOK' 1983.
Figure 1.1(b) Histogram of energy consumption per capita for different physical quality of life index (PQLI) for the people of the world. The percentages shown in each bar are the percentages within that range of PQLI.
**Figure 2.1** UK low grade heat, fuel consumption and end use.

**Figure 2.2** Domestic space and hot water demand.
Figure 2.3 Distribution of annual gas consumption for 90 similar houses in Milton Keynes, from 'The Performance of Domestic Wet Heating Systems', Pickup, G.A.C.7]

Figure 2.4 Weekly consumption of hot water for one household, from 'The Performance of Domestic Wet Heating Systems', Pickup, G.A.C.7]
Total No of dwellings: 87
Overall mean weekly consumption: 0.841 m³/week
Standard deviation: 0.351 m³/week

Contribution due to OAPs flats (for 2 occupants)

Dwelling mean weekly hot water consumption m³

**Figure 2.5** Mean Weekly Hot Water Consumption for 87 Various Sites. From 'The Performance of Domestic Wet Heating Systems' by G.A. Rickett [9]

**Figure 2.6** Solar and Thermal Radiation Spectral Distributions. Air mass m = 0 is for Extra-Terrestrial Radiation, m = 2 is a typical city distribution.
**Figure 2.7**
Annual variation of mean daily totals of direct and diffuse insolation on a horizontal surface.

**Figure 2.8**
Average global solar radiation on a horizontal surface (kWh/m²/year).
FIGURE 2.9  DEMONSTRATION PROJECT IN STUDSVIK, [26]


FIGURE 2.11  SEASONAL HEAT STORAGE AND A CENTRAL SHORT TERM STORAGE RESERVOIR (C.S.T.) CONSTRUCTED FOR TNO DELFT [35]

ONE-FAMILY HOUSES (SMALL SCALE)

with heat storage in preferably soft ground or clay solid rock

APARTMENT BUILDING (INTENSE POPULATED AREAS) (LARGE SCALE)

with heat storage in
• preferably solid rock
• most types of ground

FIGURE 2.12  DIFFERENT APPLICATIONS FOR 'SUNSTORE' [37], SEASONAL STORAGE IN THE GROUND
Figure 2.13 Plan of Prometheus retrofitted to supply 83 houses with all their space heating and hot water.

Figure 2.14 Collector mounted on top of store, part of Prometheus design.
PROTOTYPE OF A PROMETHEUS TYPE SOLAR AIR-COLLECTOR/HEAT STORE, INSTALLED AT THE OPEN UNIVERSITY, MILTON KEYNES, UK.
FIGURE 2.16  INSOLATION INCIDENT ON PROTO-PROMETHEUS, 28TH SEPTEMBER 1981

FIGURE 2.17  COLLECTOR, STORE AND AMBIENT TEMPERATURES FOR PROTO-PROMETHEUS ON 28TH SEPTEMBER 1981.
Figure 2.12 Proto-Prometheus temperature distribution (with fan on), on 22nd September 1981 at 14:25 hrs.
Sample size: 2.64
Average: 1.6 cm.
Standard deviation: 0.7 cm.

**Figure 2.19 Frequency Distribution of Pebble Smallest Dimension.**
FIGURE 2.20  FREQUENCY DISTRIBUTION OF PEBBLE LARGEST DIMENSION

SAMPLE SIZE 204
AVERAGE 3.8 cm
STANDARD DEVIATION 0.95 cm
**Figure 2.21** Proto-Prometheus store temperature, from 22nd September 1981 to 2nd October 1981 under stagnation (fan off).

**Figure 2.22** Energy demand for a 3-bedroom house built to B75 building regulations (type A) with solar heating supplied by a basic type Prometheus.
Figure 2.23  Effect of changing the collector overall heat loss coefficient on the % of annual energy supplied by Prometheus to a Type A1 house

Figure 2.24  Effect of changing the collector area on the % of annual energy supplied by Prometheus to a Type A1 house
**FIGURE 2.25**  The effect of changing the storage tank insulation thickness on the % of solar energy supplied by Prometheus to a Type A house.

**FIGURE 2.26**  The effect of changing the storage volume on the % of solar energy supplied by Prometheus to a Type A house.
**Figure 2.27** The effect of increasing the number of houses served by a single cubic Prometheus (size, 112 m² per house and 2.8 m² of collector per house) for a type A1 house.

**Figure 2.28** The effect of changing the collector overall heat loss on the % of energy supplied by a cubic Prometheus heating a type A5 house.
FIGURE 2.29 DESIGN OF COSTED PROMETHEUS TO PROVIDE 100% OF THEIR ANNUAL HEATING DEMAND (27.5 GJ) WITH SOLAR ENERGY.

FIGURE 2.30 IMPROVED COLLECTOR ORIENTATION
**Figure 3.1** Design of Basic Type AO House

**Figure 3.2** Net space heating demand for Type AO, A5 and A11

3 bedroom end of terrace house.
**Figure 3.3**

Useful energy saved and extra cost for various insulation options and solar systems installed while constructing a basic type A0 house.

**Figure 3.4**

Energy demand for a 3 bedroom terrace built to 1975 building regulations and energy supplied by 4, 12 and 24 m² of solar collector.
Figure 3.5 Energy demand for a well insulated 3-bedroom house, and energy supplied by 4.12 and 24m² of solar collector.

Figure 3.6 Comparison of predicted solar energy supply for a house using the F-chart method with the measured solar supply for the Milton Keynes solar house.
Insulation measures

Active solar system with short term storage

**Figure 37** USEFUL ENERGY SAVED AND EXTRA COSTS FOR VARIOUS INSULATION OPTIONS AND SOLAR SYSTEMS RETROFITTED TO AN EXISTING TYPE B0 HOUSE
**FIGURE 4.1**  **NONPOROUS ABSORBER-TYPE AIR HEATERS.**

**FIGURE 4.2**  **POROUS ABSORBER-TYPE AIR HEATERS.**
FIGURE 4.3 HYBRID PHOTOVOLTAIC AND AIR HEATING SOLAR COLLECTOR

FIGURE 4.4 COLLECTOR HEAT LOSSES
**Figure 4.5** Rear Duct Collector Configuration

**Figure 4.6** Top Duct Collector Configuration
The curves correspond to the following relations:

**McAdam**

\[ h_\omega = 5.7 + 3.5v \]

**Watmuff**

\[ h_\omega = 2.8 + 3.0v \]

**Lloyd**

\[ h_\omega = 0.15 \times 0.08 \times \frac{k}{L + W} \] for \( T_a = 10^\circ C, T_s = 15^\circ C, L = 1 \text{m}, W = 1 \text{m} \)

**Sparrow**

\[ h_\omega = \frac{k \times 0.86 \times 10^{0.6} - T_w}{L + W} \] for \( T_a = 10^\circ C, T_s = 15^\circ C, L = 1 \text{m}, W = 1 \text{m} \)

**Green**

\[ h_\omega = (h_{15} + h_{15})^{0.5} \] for \( A = 1.4 \text{m}, 45^\circ \text{inclination} \)

**KIND**

\[ h_\omega = \text{for collector length 2.4m, width 1.2m, height 4.5m, } T_s = 25^\circ C \]

**Figure 4.7** Correlations for wind heat loss coefficient.
**Figure 4.8** Flow diagram of 'EFFIC2' (see Appendix B) a program to calculate the efficiency of a flat plate air heating collector.
Figure 4.9 Flow diagram of 'EFFIC' (See Appendix B) a program to calculate the efficiency of a top duct air heating collector.
**Figure 4.10** Response of zero and long time constant collector to changing insolation.
FIGURE 4.11 NODAL CONFIGURATION OF A FLAT PLATE, REAR-DUCT AIR HEATING, SOLAR COLLECTOR AS USED IN 'RRAICT'.

FIGURE 4.12 COMPARISON OF AIR OUTLET TEMPERATURE TO PREDICTED BY THE COMPUTER MODEL (SOLID CURVE) AND LABORATORY MEASUREMENTS, ON A SIMILAR, THOUGH NOT IDENTICAL, COLLECTOR (CROSSES).
Figure 4.13: Efficiency curve generated by transient model operating under steady-state conditions and steady-state model. For collector parameters, see Table 5.3.
FIGURE 5.1  PERCENTAGE OF ENERGY FALLING ABOVE A THRESHOLD INTENSITY AVERAGED OVER A PERIOD OF ONE HOUR EACH MONTH ON A HORIZONTAL SURFACE (AT RH 1966-1975)
SECTION X-X

**FIGURE 5.2  D.C. HALL COLLECTOR**
FIGURE 5.3  ANGULAR VARIATION OF TRANSMITTANCE OF 2 mm THICK POLYCARBONATE (REFRACTIVE INDEX = 1.586, EXTINCTION COEFFICIENT ≈ 20 m⁻¹)

FIGURE 5.4  TEE-PIECES USED FOR ABSORBER FINS IN D.C. HALL COLLECTOR
**Figure 5.5-5.6** Air heating collector made of structured polycarbonate

**Figure 5.7** Solar transmittance of structured polycarbonate versus incident angle. Source: H.L. Redfoot et al., 'Glazing solar collectors with acrylic and double walled polycarbonate plastics'
Figure 5.8  Orifice Plate and Its Location for Measuring Mass Flow Rate
Figure 5.9 ASHRAE Standard 93-77 Testing Configuration for a Solar Collector When the Transfer Fluid is Air.

Figure 5.10 Open University Air Collector Testing Configuration.
FIGURE 5.11 RESPONSE OF STRUCTURED POLYCARBONATE COLLECTOR TO A STEP CHANGE IN INSOLATION FROM 750 W/m² TO ZERO WITH A FLUID FLOW RATE OF 7.2 kg/hr⁻¹.

FIGURE 5.12 UNINTERRUPTED INSOLATION AS DEFINED BY ASHRAE STANDARD 93-77 [2].
FIGURE 5.13  RECORD OF INCIDENT SOLAR RADIATION ON A HORIZONTAL SURFACE
AT THE OPEN UNIVERSITY ON 19/6/83.

FIGURE 5.14  RECORD OF INCIDENT SOLAR RADIATION ON A HORIZONTAL SURFACE
AND WIND SPEED ON 21/6/83 (CONTINUED ON NEXT PAGE).
FIGURE 5.14 CONTINUED
FIGURE 5.15
ANGLE OF INCIDENCE OF SOLAR RADIATION ONTO D.C. HALL COLLECTOR DURING STEADY STATE EFFICIENCY TEST, POSITION OF COLLECTOR MILTON KEYNES, LATITUDE 52°, LONGITUDE 0.75° (HORIZONTAL).

FIGURE 5.16 ANGLE CORRECTION FOR D.C. HALL COLLECTOR
FIGURE 5.17(a) AIR HEATING COLLECTOR UNDER TEST WITH A LEAK AT THE INLET

FIGURE 5.17(b) AIR HEATING COLLECTOR UNDER TEST WITH A LEAK AT THE OUTLET
**Figure 5.18**
The effect of air leaks on the measured value of \( F_{\text{mV}} \), for
\[
\dot{m} = 0.5 \, \text{kg/hr}
\]

**Figure 5.19**
Calibration curve for periflow orifice plate for air at 20°C
**Figure 5.20** Pressure distribution within collector test configuration with and without fluid flow.

**Figure 5.21** Sample output of D.C. hall collector to testing outdoors not under steady state conditions.
FIGURE 5.22. STEADY STATE EFFICIENCY CURVE FOR D.C. HALL COLLECTOR TESTED OUTDOORS.

FIGURE 5.23. STEADY STATE EFFICIENCY CURVE FOR STRUCTURED POLYCARBONATE COLLECTOR TESTED OUTDOORS.
**Figure 5.24** Uncorrected Efficiency Curve with Variation of Wind Speed between 0 - 4 m/s. Source: [25].

**Figure 5.25** Efficiency Curve Corrected for Variation in Wind Speed using a Normalizing Function. Source: [25].
FIGURE 5.26 VARIATION OF MASS FLOW RATE CAUSED BY CHANGE IN WIND SPEED
**Figure 5.27** Round Robin Testing of liquid flat plate collectors. The combined effect of meteorological extremes and measurement uncertainty. Source: Taylor [28]

**Figure 5.28** Measured dependency of $\eta_{\text{CO}_2}$ on the diffuse fraction for a single-glazed flat-plate collector. Source: Foreski [34]
Figure 5.29  
COMPUTER GENERATED STEADY STATE AND TRANSIENT EFFICIENCY CURVE FOR 0.5 mm ABSORBER PLATE
**FIGURE 5.30** TRANSIENT DIFFUSE RADIATION

**FIGURE 5.31** FLUID OUTLET TEMPERATURE UNDER TRANSIENT CONDITIONS.

**FIGURE 5.32** INTEGRATED RESPONSE OF COLLECTOR OVER 1 AND 2 MINUTES TO TRANSIENT RADIATION.
FIGURE 5.33

The variation in $F_{uL}$, $F_u(CW)$, and $\delta F_{uL}$ with the number of increments used in the transient analysis.
**Figure 5.34** Collector response functions for optimum values of n.

**Figure 5.35** Calculated collector time constants. For different collector configurations see Table 5.3.
**FIGURE 5.36** EFFICIENCY CURVE GENERATED FROM TRANSIENT TESTING RESULTS OF THE SP COLLECTOR AND PROCESSED BY 'TRANS' FOR \( N = 1 \).
UNCORRECTED FOR ANGLE OF INCIDENCE OF RADIATION.

**FIGURE 5.37** TRANSIENT INSOLATION DURING TESTING OF SP COLLECTOR ON 17/6/83, CONTINUED ON NEXT PAGE.
FIGURE 5.37 CONTINUED. TRANSIENT INSOLATION DURING TESTING OF 3P COLLECTOR ON 14/6/83-15/6/83.
Figure 5.38  Standard Error in $F_{UL}$ versus $N$, the number of previous time steps influencing the collector's present performance under transient conditions for the structured polycarbonate collector.

Figure 5.39  Efficiency curve for outdoor transient testing of structured polycarbonate collector, data generated from 'TRANS' for $N=7$, uncorrected for angle of incidence of radiation.
Figure 5.40 Collector response function for S.P. collector N=7.

Figure 5.41 Efficiency curve for outdoor transient testing of D.C. Hall collector (manual absorber). Data generated from 'TRANS' for N=7, uncorrected for incident angle of radiation.
**Figure 5.42** Indoor Solar Collector Test Facility.

**Figure 5.53** Relative Spectral Intensity of 'Cool Ray' Lamps, Transmittance of Polycarbonate and Reflectance of Maxorb.
### FIGURE 5.44

**Intensity Distribution Across Collector During Indoor Testing in W/m².**
Average intensity 2.11 W/m², standard deviation ± 0.4 W/m².

### FIGURE 5.45

**Wing Generator.**
Figure 5.46: Variation of wind speed (ms⁻¹), 5 mm above collector surface.

Figure 5.47: Measured and predicted heat loss U, for D.C. wall collector (non-selective) with varying wind speed indoors.
FIGURE 5.48  EFFICIENCY CURVE OF STRUCTURED POLYCARBONATE COLLECTOR MEASURED INDOORS AND OUTDOORS.

FIGURE 5.49  EFFICIENCY CURVE OF D.C. MALL COLLECTOR WITH NON-SELECTIVE ABSORBER (NEKTOL). INDOOR MEASUREMENTS AND COMPUTER PREDICTIONS.
**Figure 5.59** ReDesigned Indoor Collector Test Facility

**Figure 5.51** Steady State and Zero Testing Efficiency Curves.
Figure 5.52: Steady state and efficiency curve plotted against mean absorber plate temperature ($T_p$) for simulated collector.
FIGURE 5.53 STEADY STATE AND ZERO TESTING EFFICIENCY CURVE PLOTTED AGAINST MEAN FLUID TEMPERATURE ($T_m$) FOR SIMULATED COLLECTOR.
Figure 5.54: Collector temperature profile for model collector under steady state and zero testing conditions for the same fluid inlet temperature (30°C).

Figure 5.55: Collector temperature profile for model collector under steady state and zero testing conditions for the same mean absorber plate temperature (36°C).
**Figure 5.56** Temperature of absorber and rear duct for the same average fluid temperature with the collector under zero and steady state testing.

**Figure 5.57** $F_{wU}$ versus mean fluid temperature for collector dye under zero testing and average steady state testing.
FIGURE 5.58 EFFICIENCY CURVES FOR D.C. HALL COLLECTOR USING DIFFERENT TEST METHODS
Figure 5.59 Efficiency curve for structured polycarbonate collector under different test conditions.

Figure 5.60 Top loss coefficient versus absorber temperature for P&O Chalm type collector (maxima absorber).
Figure 5.6. Steady state efficiency of solar collector (black chrome) measured during operation and indoor testing. Source: Taylor, P.J. 'Performance of Selective and Non-Selective Solar Thermal Absorbers in a Working Installation', Solar World Congress Ed. by S.V. Szovák, Vol. 2, pp 1149 - 1153.
Figure 6.1  Efficiency curve for 'conventional' and 'high performance' collector.

Figure 6.2  Typical construction of a flat plate collector.
Figure 6.4
Percentage of energy falling above a threshold intensity averaged over a period of one hour each month on a horizontal surface (AJWNN-NJ88).

Figure 6.5
Maximum improvement to flat-plate collector performance by increasing $\tau$ and $\alpha$. 
**Figure 6.6** Reflectance of Solar Collector Coatings

**Figure 6.8**

Efficiency curves for different methods of heat loss reduction.

**Figure 6.9**

FIGURE 6.10  
EFFICIENCY CURVE OF ADVANCED FLAT PLATE COLLECTOR WITH XENON BETWEEN THE ABSORBER AND COVER AT A PRESSURE OF 1 TORR.  
[27+]

FIGURE 6.11  
EFFICIENCY VERSUS MASS FLOW RATE FOR STRUCTURED POLYCARBONATE COLLECTOR, \( I_{\text{inc}} = 211 \text{Wm}^{-2} \), \( T_a = 28^\circ\text{C} \), \( T_{\text{in}} > T_e \), \( T_e = T_a \) and AIR VELOCITY = 1.5 m s\(^{-1}\)
FIGURE 6.12  PRESSURE DROP ACROSS S.P COLLECTOR VERSUS MASS FLOW RATE

FIGURE 6.13  THEORETICAL SYSTEM EFFICIENCY VERSUS MASS FLOW RATE FOR A FLUID INLET TEMPERATURE OF 60°C, FOR THREE DUCT SECTIONS Z, AND TWO LEVELS OF INCIDENT INSOLATION.
FIGURE 6.14  EFFICIENCY CURVE FOR A COMBINED PARABOLIC CONCENTRATOR COMPARED WITH A FLAT PLATE COLLECTOR. SOURCE: ARROWHEAD NATIONAL LABORATORY TECH REPORT.

FIGURE 6.15  GLOBAL AND DIFFUSE INSOLATION MONTH BY MONTH AT 45° SOUTH FACING SLOPE.
**Figure 6.16**
Annual energy collected versus collector temperature. Comparison of five types of collector. Source [33].

**Figure 6.17**
Simulated ambient conditions. For further details see text in Appendix C.
Figure 6.14  Steady-state efficiency ($\eta$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\bar{\eta}$ are for a variety of simulated conditions (see Table 4 and Figure 3).$^{14}$

(i) SÜJ/TAJ, flow 2   (ii) SÜM/TAM, flow 2   (iii) SÜD/TAD1, flow 2
(iv) SÜM/TAM, flow 3   (v) SÜM/TAM, flow 2   (vi) SÜD/TAD1, flow 3
(vii) SÜD/TAD1, flow 2   (viii) SÜD/TAD2, flow 3   (ix) SÜD2/TAD1, flow 2
(x) SÜD3/TAD1, flow 2   (xi) SÜD/TAD1, flow 2.
Figure 6.20 'EMTC' air heating solar collector developed by G.E. [42]

Figure 6.21 Incident angle modifier for the EMTC prototype. This depends on the orientation of the cover. A - the maximum occurs when the plane of the angle of incidence is perpendicular to the cylindrical axes of the tube cover. B - the maximum value occurs when the plane of the angle of incidence is normal to the cylindrical axes of the tubes in the cover [42].
**Figure 6.22** Instantaneous efficiencies of the flat plate collector and a single glazed flat plate collector and their variation with insolation. [42]
**Figure 7.1** Thermal conductivity of various gases at 20°C versus molecular weight.

**Figure 7.2** Cellular convection for a liquid. For gases, due to their different temperature viscosity relationship, the gas falls in the centre of the cell.
FIGURE 7.3  OBSERVATION OF CELLULAR CONVECTION

FIGURE 7.4  BASE FLOW BETWEEN INCLINED PLATES
Figure 7.5  Local heat transfer coefficient between two inclined plates (see Figure 7.4). Source: Normand, C. and Pomarly, Y. Convective instability: A physicist's approach; Journal of Modern Physics, vol. 49, no. 3, July 1974.

Figure 7.6  Schematic depicting effect of gap spacing on conductance
Figure 7.2: Plot of $h_c$ versus plate separation $s$. $T_{\text{wind}} = 10^5$, $T_{\text{wall}} = 325^\circ F$, and $1.4\text{ mph}$.  

Figure 7.8: $h_c$ versus tilt angle to the horizontal for air absorption for various absorber temperatures ($T_a$) with cover temp = 10°C.
\[ h_r \text{ heat transfer due to radiation between a non-selective absorber (}\varepsilon = 0.9\text{) and a glass cover (}\varepsilon = 0.9\text{)} \]

\[ h_c \text{ heat transfer due to convection and conduction in air at atmospheric pressure} \]

\[ h_r \text{ heat transfer due to radiation between a selective absorber (}\varepsilon = 0.09\text{) and low iron glass cover (}\varepsilon = 0.08\text{)} \]

**Figure 7.9**

Heat transfer coefficient variation with absorber temperature for convection and radiation.
FIGURE 7.10 TRUE AND PREDICTED HEAT LOSS BETWEEN TWO PARALLEL PLATES 5 x 5 cm
COVER TEMPERATURE 10 °C
Figure 7.11 Effective Rayleigh Number versus molecular weight for different gases, at atmospheric pressure between two parallel plates, spacing 3:0 cm, cold plate temperature 10°C, hot plate 30°C.
FIGURE 7.12: Heat transfer coefficient for gases of different molecular weight. For $S = 5 \text{ cm}$, cold plate temperature $10^\circ C$, hot plate temperature $30^\circ C$. 
FIGURE 7.13  COST VERSUS HEAT TRANSFER COEFFICIENT FOR DIFFERENT GASES.
$\$ = 5 \text{cm}^3$, VOLUME OF GAS REQUIRED FOR EACH SQUARE METRE ON COLLECTOR IS 50 LITRES.
**Figure 7.14** Variation of heat transfer coefficient $h_c$ with pressure for a flat plate collector, $s = 5 \text{ cm}$, $T_0 = 293 \text{K}$, $T_1 = 823 \text{K}$ for curve 1, 273K for curve 2 and 473K for curve 3.

**Figure 7.15** Description of two cover system.
**Figure 7.16** Variation of heat transfer with gap across a two cover and a single cover system. Source: Monotria, A and Garg, H.P. "Minimizing convective heat loss". Solar Energy, Vol. 25, No. 6, p. 523.

**Figure 7.17** Reflected solar rays for a multi-cover solar collector.
FIGURE 7.19  HEAT TRANSFER COEFFICIENT $h_c$ DUE TO NATURAL CONVECTION FOR AIR AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL FLAT PLATES SPACING 5 cm, $T_c = 293 K$, WITH A HONEYCOMB PADDLED PANELS. ASPECT RATIO 5.
Figure 7.21 Rayleigh Number versus temperature for argon and air at atmospheric pressure between two parallel flat plates, spacing $s = 5\, \text{cm}$, cold plate temperature $T_c = 10^\circ\text{C}$.
**Figure 7.22** Heat Transfer Coefficients for Several Collector Configurations

- Convection and conduction, air, atmospheric pressure, tilt angle 0°.
- Convection and conduction, air, atmospheric pressure, tilt angle 60°.
- Convection and conduction, argon, atmospheric pressure, tilt angle 0°.
- Convection and conduction, air, honeycomb, tilt angle 60°.
- Radiation, maxorb absorber (E, 0.09) low iron glass cover (R, 0.98).
- Conduction only, air, at 4 x 10^5 Pa.
- Conduction only, argon at 3 x 10^5 Pa.

$S = 5$ cm, $T_s = 10^6$. 
FIGURE 7.25 ACYCLIC TEST PANEL

FIGURE 7.26 SCHEMATIC DIAGRAM OF GUARDED HOT PLATE APPARATUS
FIGURE 7.27 COPPER COLD PLATES.
Figure 7.28: Measured and theoretical heat transfer coefficients for different gases between two parallel plates, \( s = 5 \text{ cm} \) versus temperature difference.
FIGURE 7.29 THEORETICAL AND MEASURED HEAT TRANSFER $h_c$ FOR AIR AND ARGON
FIGURE 7.30  THEORETICAL HEAT TRANSFER ACROSS STRUCTURED POLYCARBONATE
OF VARIOUS THICKNESSES. BOTH RADIATION AND CONVECTION, ASSUMING
FLAT CONVECTION AND A MEASURED EMISIVITY OF 0.72.
PLATE 2.1
PROTO PROMETHEUS - 1. COLLECTOR, 2. STORE TOP INSULATION AND COLLECTOR REAR INSULATION, 3. FAN MOTOR 4... MONITORING EQUIPMENT 5. SPACE FOR INSULATION.
PLATE 2.2  PROTO PROMETHEUS STORAGE TANK FILLED WITH PEBBLES.
PLATE 5.1

SOLAR SIMULATOR TESTING A STRUCTURED POLYCARBONATE COLLECTOR.
17: STRUCTURED POLYCARBONATE COLLECTOR, 16: WIND GENERATOR,
19: COOL RAY LAMPS.
Plate 5.2: Indoor collector test facility.
7. Data logger, 8. Structured polycarbonate collector,
9. Pressure taps, 10. Site of orifice plate.
PLATE 7.1

VIEW OF HEATED OIL FILM FROM AN INFRARED CAMERA. THE BRIGHTER THE SPOT THE HOTTER THE SPOT.
PLATE 7.2

GUARDED HOT PLATE THERMAL CONDUCTIVITY RIG

11. INSULATED GUARD RING AND TEST CELL, 12. GAS CYLINDER
13. WATER COOLER, 14. HEATER POWER SUPPLY
APPENDIX A

SUNSTORE: Computer model of interseasonal store and sample output.
10 REM **************************** SUNSTORE ****************************
20 REM
30 SHORT DEMAND(12)
40 SHORT SOL(14,24)
50 ASSIGN 1 TO "SUN DATA"
60 READ 1 1 SOL()
70 SHORT TEM(12,24)
80 ASSIGN 2 TO "TEM DATA"
90 READ 2 1 TEM()
100 DIM MONTHS(12)
110 ASSIGN 3 TO "MONTH"
120 READ 3 3 MONTHS()
130 SHORT DAYS(12)
140 ASSIGN 4 TO "DAYS"
150 READ 4 4 DAYS()
160 PRINT USING 200
170 TOTSUN= total annual solar radiation
180 PRINT ****************************
190 PRINT "**************************
200 IMAGE //**** SOLAR RADIATION AT KEN DISTRIBUTION OF HOURSLY GLOBAL IRRIGATION *******
210 PRINT USING 220
220 IMAGE //**** ON A HORIZONTAL SURFACE IN MJ/m2 ****************************
230 FOR M=1 TO 12  ! print month heading
240 PRINT TAB (6&M): MONTHS(M):
250 NEXT M
260 FOR H=1 TO 24  ! print level of solar rad for each hour in each month
270 FOR M=1 TO 12
280 PRINT TAB (M&M): SOL(M, H):
290 TOTSUN=TOTSUN+SOL(M, H):DAYS(M)  ! calculate total annual solar radiation.
300 NEXT M
310 PRINT ****************************
320 NEXT H
330 PRINT "TOTAL ANNUAL SOLAR RADIATION = " TOTSUN "MJ/m2"
340 REM **************************** DATA INPUT ****************************
350 FJ=.9  ! HEAT TRANSFER FACTOR
360 c=.837  ! SPECIFIC HEAT OF STORE MATERIAL (KJ/KGC)
370 METE="Pebbles"  ! STORAGE MATERIAL
380 WIDTH=10  ! STORAGE WIDTH IN METERS
390 HEIGHT=4  ! STORAGE HEIGHT IN METERS
400 LENGTH=280  ! STORAGE LENGTH IN METERS
410 HOUSE=100  ! NUMBER OF HOUSES SERVED BY STORE
420 DENSITY=1600  ! DENSITY OF STORAGE MATERIAL (Kg/m3)
430 K=1  ! OVERALL COLLECTOR HEAT LOSS COEFFICIENT(W/m2)
440 COLAREA=2800  ! TOTAL AREA OF COLLECTORS SERVING STORE (m2)
450 COND=.036  ! THERMAL CONDUCTIVITY OF STORAGE INSULATING MATERIAL(W/m2C)
460 THIC=6.4  ! THICKNESS OF INSULATING MATERIAL (Cm)
470 Ta=8  ! OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES
480 YEARS=1  ! NUMBER OF YEARS PROGRAM TO RUN DO NOT USE MORE THAN 1 IF qaux<>0
490 q=10  ! TEMPERATURE OF GROUND SURROUNDING STORE (C)
500 TS=30  ! MINIMUM STORAGE TEMPERATURE (C)
510 REM **************************** DATA OVERVIEW ****************************
520 REM
530 M=12  ! MONTH
540 M=0  ! HOUSE
550 T=30  ! TOTAL
560 TOTD=0
570 TOTG=0
580 qD1=0
590 qD2=0
600 qD3=0
610 qD4=0  ! TOTD=0
620 qD5=0
630 PLOT IS 1
640 GRAPH
650 LIMIT 0,150,0,70
660 MSCALE 0,0
670 GRID 1,1,0,10,10
680 QTO=0
690 NUT=0
700 EXTRA=0
710 COUNT=0
720 qaux=0
730 VOL=WIDTH*HEIGHT*LENGTH  ! calculate storage volume
740 VOLH=VOL/HOUSE  ! storage volume per house
750 MASS=VOLH/DENSITY/1000  ! normalized mass
760 m=MASS/(COLAREA/HOUSE)  ! normalized mass per m2 collect;
770 AREA=HEIGHT*WIDTH  ! store surface area;
780 gSA=AREA/CO/LAREA  ! store heat loss(U-value)
790 US=COND/THICK  ! store heat loss(U-value)
800 qaux=0
810 PRINT USING 820
820 B20 IMAGE //**************************** STORE ****************************
830 PRINT "STORE LENGTH:"LENGTH:"Meters";" WIDTH:"WIDTH:"Meters";" HEI;"HEIGHT:"Meters"
840 PRINT "VOLUME:"VOL:"m3"
850 PRINT "STORAGE MATERIAL "MET="DENSITY="Kg/m3" SPECIFI
860 PRINT "STORE INSULATION THICKNESS:"THICK="m,"THERMAL CONDUCTIVITY="CONI
870 PRINT USING 880
880 IMAGE //**************************** COLLECTOR ****************************
890 PRINT "TOTAL COLLECTOR AREA="COLAREA:"m2"
900 PRINT "FHEAT TRANSFER FACTOR=equivalent to Fr heat removal factor if st; has a good heat; changes"":=F
910 PRINT "UL-OVERALL HEAT LOSS COEFFICIENT="UL"
920 PRINT "Ta-OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES="Ta
930 PRINT USING 940
940 IMAGE //**************************** HOUSE ****************************
950 PRINT "NUMBER OF HOUSES=":HOUSE
960 PRINT "THE MONTHLY HEATING LOAD FOR EACH HOUSE IS (heating and hot water)"
970 FOR KM TO 12
980 REM **************************** DATA OVERVIEW ****************************
990 READ DEMAND(K); Reads MONTHLY DATA OF HEATING LOAD FOR EACH HOUSE(MJ)
1000 REM
1010 PRINT TAB(160): "MONTHS(1):"; "=DEMAND(1):"; print heating demand each month
1020 TOTD=TOTD+DEMAND(1): calculate total annual heating demand
1030 DEMAND(1)=DEMAND(1)/icolarea*house: heating demand per m2 of collector
1040 GOTO 1020
1050 PRINT "TOTAL ENERG Y COLLECTED PER ANNUAL =TOD/TOD/1000:";GJ:" (TODT)" +e:Kwh
1060 PRINT "--
1070 PRINT USING 1080
1080 IMAGE """ SYSTEM OPERATION ""
1090 PRINT "ITH = Threshold Level (collector will only operate above this input) (W/m2)
1100 PRINT "Tso = Original Store Temperature at the beginning of month (°C)
1110 PRINT "Ta = Ambient Temperature Averaged over periods of collector operation (°C)
1120 PRINT "Ti = Time Period of Collector Operation (Ms)
1130 PRINT "IT = Total Radiation which is above Threshold (M3/m2)
1140 PRINT "qN = Normalized Net Heat to Storage =qt-1ms (M3/m2)
1150 PRINT "qT = Useful Heat Collected = qN+1m (M3/m2)
1160 PRINT "qL = Normalized Total Monthly Load (M3/m2)
1170 PRINT "qA = Normalized Total Monthly Storage Lloses (M3/m2)
1180 PRINT "qR = Normalized Total Monthly Radiant Lloses (M3/m2)
1190 PRINT "qG = Normalized Total Monthly Heat Losses (M3/m2)
1200 PRINT "...
1210 M = ITH Tso Ta TT It qN tsf qT im qAUX "
1220 PRINT "...
1230 FOR i=1 TO 12
1240 TiM=0
1250 TSOL=0
1260 TEMP=0
1270 FOR J=1 TO 24
1280 ITM=Ti=TAE(TSI-TEM(I,J))!
1290 IF ITM+0.056 THEN GOTO 1330 test if radiation level is above all threshold
1300 TiM=TiM+1000000
1310 TSOL=TSOL+1.0+TSOL
1320 TEMP=TEMP+TEM(I,J)!
1330 NEXT J
1340 IF TiM=0 THEN GOTO 1260
1350 TEMP=TEMP/TI
1360 TiM=TiM+3600*DAYS(I)!
1370 TSOL=TSOL+600
1380 IF TiM=0 AND COUNT=0 THEN GOTO 1770 print out if month is on
1390 t=-3600*DAYS(I)/1000000
1400 qT=(FIT+TSL+ULS(TSO-TEM)ET)!
1410 qN=USST(TSO-TG)ET!
1420 qW=qN+(DEM(I)-1)m(I)+(FIT+ULS+USST)(EM(I))!
1430 Tsf=TSS(TSI-EM(I))!
1440 IF Tsf=350 THEN GOTO 1530
1450 Tsf=350
1460 T=10
1470 T=10
1480 IF COUNT=0 THEN GOTO 1770
1490 IF NUT=1 THEN GOTO 1520
1500 EXRA=TSO-TSIF*EM(I)
1510 NJ=I
1520 GOTO 1540
1530 Tsman=(TSO+TSF)/2!
1540 Ts=USST(Tsman-TG)ET!
1550 qW=qN+qT+qST!
1560 qW=qN+qT+qST!
1570 qW=qN+qT+qST!
1580 COUNT=1
1590 qAUX=qN+qEXTRA!
1600 EXTRA=0
1610 IF qAUX>0 THEN qAUX=0!
1620 PRINT USING 1960: "MONTHS(1),ITH,TSM,TEMP,tTTSO,qT,qN,qAUX,qEXTRA." +e:Kwh
1630 x=1410
1640 Y=TSO/2
1650 PLOT X,Y
1660 TOTAL=TOTAL+TSOL
1670 qT=qT+qT!
1680 qT=qT
1690 qT=qT
1700 qT=qT
1710 qT=qT
1720 qAUX=qAUX+qAUX
1730 MDI=MDI+1
1740 IF fortnight#12 THEN GOTO 1780
1750 TSO=Tsf!
1760 IF J=12 THEN I=0!
1770 NEXT I
1780 THSD=TSOL+TOTAL#100!
1790 TOTSUN=qT+TOTSUN+400!
1800 PRINT "...
1810 PRINT USING 1970: "TOTAL",qN,qT,qST,qT,qST,qT,qST,qAUX,qAUX!
1820 PRINT "...
1830 SUN=(1-(qAUX/TOTSUN))/100! % energy supplied by solar system
1840 PRINT USING 1980: % OF ENERGY SUPPLIED BY SOLAR SYSTEM=SUN%"!
1850 PRINT USING 1990: % OF SOLAR ENERGY COLLECTED ABOVE THRESHOLD="SOLAR/%"!
1860 PRINT USING 2000: % OF SOLAR ENERGY COLLECTED="TOTSUN%"!
1870 PRINT "TOTAL AUXILIARY ENERGY FOR SYSTEM=",(qAUX+TCOLAREA/2.6)/Kwh
1880 PRINT "AUXILIARY ENERGY PER HOUSE=",(qAUX+TCOLAREA/2.6)/Kwh!
1890 PRINT "...
1900 PRINT "...
1910 GOTO 1000!
1920 ASSIGNEND 1 TO #
1930 ASSIGNEND 2 TO #
1940 ASSIGNEND 3 TO #
1950 ASSIGNEND 4 TO #
1960 IMAGE 1DDDDDDDDDD,2,6,DDD.D,14X.D,13X.A,A,B,DD
1970 IMAGE 1DDDDDDDDDD,2,6,DDD.D,14X.D,13X.A,A,B,DD
1980 IMAGE 1DDDDDDDDDD,2,6,DDD.D,14X.D,13X.A,A,B,DD
1990 IMAGE 1DDDDDDDDDD,2,6,DDD.D,14X.D,13X.A,A,B,DD
2000 IMAGE 20A1DDD.D,2,6,DDD.D,14X.D,13X.A,A,B,DD
2010 IMAGE DATA 7750,6490,5560,3320,980,770,770,770,770,1760,5270,7450!
2020 END
### SOLAR RADIATION AT NEW DISTRIBUTION OF HOURLY-GLOBAL IRRADIATION ON A HORIZONTAL SURFACE IN MJ/m2

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TOTAL ANNUAL SOLAR RADIATION = 410.94 MJ/m2

### SYSTEM OPERATION

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TOTAL = 462.00

1026.80 1488.93 390.2 -462.0

| % OF ENERGY SUPPLIED BY SOLAR SYSTEM | 69.0% |
| % OF SOLAR ENERGY COLLECTED ABOVE THRESHOLD | 42.0% |
| % OF SOLAR ENERGY COLLECTED | 41.5% |

TOTAL AUXILIARY ENERGY FOR SYSTEM = 129360.7846 MJ (359433.551803 KWh)

### HOUSE

**NUMBER OF HOUSES** = 100

THE MONTHLY HEATING LOAD FOR EACH HOUSE IS (heating and hot water) MJ

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TOTAL ENERGY DEMAND OF HOUSE FOR ANNUALLY 41.69 GJ (11580.555556 kWh)
Computer models used to predict steady state performance of air heating collectors.

**TOPAIR:** calculates the top heat loss $U_t$ for different absorber temperatures.

**EFFIC:** Calculates the efficiency of a top duct air heating collector.

**EFFIC2:** Calculates the efficiency of a rear duct air heating collector.
20 REM ~~~~~~~~~~~~~ CALCULATE THE TOP LOSS COEFFICIENT FOR A SINGLE GLASS TUBE
30 REM
40 !
50 FOR I=0 TO 30
60 TP=I*185! ABSORBER TEMP
70 TA=10! Ambient temp (C)
80 WIND=1! Wind speed (m/s)
90 E=0.95! Absorber emissivity
100 EC=0.8! Cover plate emissivity
110 S=5! Plate separation (cm)
120 G=9.812! Acceleration due to gravity (m/s^2) at LONDON
130 K=.0257! Thermal conductivity of gas at Tave (W/m-C)
140 B=0! tilt angle (Horizontal)
150 CP=1007! Heat capacity of air (J/kgK)
155 CP=1007! Heat capacity of GAS BETWEEN COVER AND ABSORBER (J/kgK)
160 S=5/100! CONVERT TO METERS
170 L=1
180 W=1
190 Sw=2*L*W/(L+W)
200 REM ~~~~~~~~~~~~~ THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFECT

210 TC=TA+(TP-TP)/2! guess the cover temp
220 Ti=273.15+TC! CONVERT TO KELVIN
230 Ta=273.15+TC! CONVERT TO KELVIN
240 TC=273.15+TC! CONVERT TO KELVIN
250 TP=TP+273.15! CONVERT TO KELVIN
260 T=TP! CONVERT TO KELVIN
270 DT=Ti-T! TEMP DIFFERENCE DELTA T
280 Tave=Ti+DT/2! AVERAGE GAS TEMPERATURE
290 DEN=352.9/Tave
300 k=Tave*.000071+.0034406
310 V=V*V*V! THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFECT

320 GAS
330 W=VIS/DEN! KINEMATIC VISCOSITY
340 Gr=G*W*L*S/0.02/2! GRASHOF NUMBER
350 Pr=CP*VIS/K
360 Ra=Gr*Pr! RAYLEIGH NO
370 REM ~~~~~~~~~~~~~ CALCULATE NUSSELT NUMBER
380 N=1+1700/(Ra*Cos (B))/58301.3
390 IF N<5 THEN N=5! TAKE ONLY POSITIVE TERMS
400 N=1+1700/(Ra*Cos (B))/58301.3
410 IF N<20 THEN N=20! TAKE ONLY POSITIVE TERMS
420 Nu=1.4441*1-SIN (1.818)+1.6*1700/(Ra*Cos (B))1+N2! NUSSELT NO
430 h/cos (SinU) = HEAT TRANSFER COEFFICIENT
440 h=0.0000000567*(TP+2*TC-2)/(TP+TC)/(1/EP+1/EC-1)! RAD FROM PLATE TO COVER
450 hsky=0.0000000567*EC/(TC+2*TA)2*(TC+TA)! RAD COVER TO SKY
470 DT=W-TC-TA
480 Tave=W-TC+DT/2
490 DENH=352.9/Tave
500 W=V*V*V+0.0034406
510 VIS=V*V*V+0.000046351
10 REM *********************** EFFIC ***********************
20 REM -- THIS PROGRAM CALCULATES THE STEADY STATE EFFICIENCY OF A TOP DUCT
30 REM AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
40 REM p237 Figure 6.12.1 (d)
50 REM
60 REM     INPUT VARIABLE DATA
70 FOR J=0 TO 10
80   T(J)=4+10 J  ' MASS FLOW RATE (kg/hr)
80 TA(J)=16.2  ' AMBIENT TEMP (°C)
90 TIN=T(2)+T(2)/2+TA  ' IN FLUID TEMPERATURE (°C)
100 T2=20.4  ' ABSORBER TEMPERATURE (°C) IF THIS CHANGES ALSO CHANGE T1
110 T1=T(2)-TA/2+TA  ' IN FLUID TEMPERATURE (°C)
120 WIND=5  ' WIND SPEED (m/s)
130 IRrad=236  ' INTENSITY OF SOLAR RAD (W/m2)
140 Eta=8  ' TRANSMISSIVITY # ABSORBIVITY OF COVER AND ABSORBER
150 Eta=8  ' EMISIVITY OF ABSORBER
160 Eta=95  ' CONDUCTIVITY OF REAR INSULATION (W/mK)
170 Eta=0.75  ' INSULATION THICKNESS (m)
190 A=1  ' COLLECTOR AREA (m2)
200 L=2  ' COLLECTOR LENGTH IN METERS
210 W=1  ' WIDTH OF COLLECTOR IN METERS
220 S=1  ' PLATE SEPARATION IN CM
230 D=1  ' FIN SEPARATION IN CM
240 DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????
245 IF Y=0 THEN GOTO 470
250 INFO A
260 IF A=N THEN GOTO 470
270 PRINTER IS 701
280 PRINT " "  ' COLLECTOR INITIAL PARAMETERS ARE
290 PRINT USING 930  ' "MASS FLOW RATE", "M/kg/hr"
300 PRINT USING 930  ' "AMBIENT TEMP", "TA", "C"
310 PRINT USING 930  ' "INLET FLUID TEMP", "TIN", "C"
320 PRINT USING 930  ' "ABSORBER TEMP", "T2", "C"
330 PRINT USING 930  ' "WIND SPEED", "WIND", "m/s"
340 PRINT USING 930  ' "SOLAR RADIATION", "I", "W/m2"
350 PRINT USING 930  ' "TRANSMISSIVITY # ABSORBIVITY", "Ta"
360 PRINT USING 930  ' "EMISIVITY OF COVER", "E1"
370 PRINT USING 930  ' "EMISIVITY OF ABSORBER", "E2"
380 PRINT USING 930  ' "INSULATION CONDUCTIVITY", "K", "W/mK"
390 PRINT USING 930  ' "INSULATION THICKNESS", "T", "m"
400 PRINT USING 930  ' "COLLECTOR AREA", "A", "m2"
410 PRINT USING 930  ' "COLLECTOR LENGTH", "L", "m"
420 PRINT USING 930  ' "COLLECTOR WIDTH", "W", "m"
430 PRINT USING 930  ' "PLATE SEPARATION", "S", "cm"
440 PRINT USING 930  ' "FIN SEPARATION", "D", "cm"
450 PRINT " "
460 REM " "  ' INPUT CONDENSE DATA
480 STM=0.0000000567  ' STEFAN-BOLTZMANN CONSTANT (W/m2K4)
490 V=0.000188  ' VISCOSITY OF AIR IN DUCT (N-s/m2)
500 K=0.0241  ' THERMAL CONDUCTIVITY OF AIR IN DUCT (W/mK)
510 E=1/1000  ' HEAT CAPACITY OF AIR AT CONSTANT PRESSURE (J/kg°C)
520 REM " "
550 T=11+273.15  ' HEVIN
REM --- THIS PROGRAM CALCULATES THE STEADY STATE EFFICIENCY OF A REAR DUCT
20 REM
30 REM
40 INPUT "INPUT VARIABLE DATA"
50 REM
60 FOR J=0 TO 100 STEP 5
70 M=1.16 ! MASS RATE FLOW (kg/hr)
80 T=20 ! AMBIENT TEMP (C)
90 T1=273.15 ! IN FLUID TEMPERATURE (C)
100 T2=273.15 ! ABSORBER TEMPERATURE (C) IF THIS CHANGES ALSO CHANGE T1
110 T=273.15 ! DIFFERENCE IN FLUID TEMPERATURE (C)
120 WIND=1 ! WIND SPEED (m/s)
130 TEM=700 ! INTENSITY OF SOLAR RAD (W/m2)
140 T=83 ! TRANSMISSIVITY & ABSORPTIVITY OF COVER AND ABSORBER
150 TF=T1 ! GUESSED MEAN FLUID TEMPERATURE
160 T=0.85 ! EMPTISSIVITY OF COVER
170 E3=91 ! EMPTISSIVITY OF REAR DUCT
180 E4=91 ! EMPTISSIVITY OF COVER
190 E5=91 ! EMPTISSIVITY OF REAR DUCT
200 E6=91 ! EMPTISSIVITY OF REAR DUCT
210 K=0.045 ! CONDUCTIVITY OF REAR INSULATION (W/m2)
220 K=1.1 ! FLUID INSULATION THICKNESS (M)
230 A=4 ! COLLECTOR AREA (m2)
240 L=4 ! COLLECTOR LENGTH IN METERS
250 W=1 ! WIDTH OF COLLECTOR IN METERS
260 S=1 ! PLATE SEPARATION IN CM
270 D=100 ! FIN SEPARATION IN CM
275 UE=0 ! DGE HEAT LOSS
280 DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"?
290 IF J=5 THEN GOTO 520
300 INPUT A$?
310 IF A=A$ THEN GOTO 520
320 PRINT 701
330 PRINT 701
340 PRINT 701
350 PRINT 701
360 PRINT 701
370 PRINT 701
380 PRINT 701
390 PRINT 701
400 PRINT 701
410 PRINT 701
420 PRINT 701
430 PRINT 701
440 PRINT 701
450 PRINT 701
460 PRINT 701
470 PRINT 701
480 PRINT 701
490 PRINT 701
500 PRINT 701
510 INPUT A$?
520 REM
530 REM
540 REM
550 REM
560 REM
570 REM
580 REM
590 REM
600 REM
610 REM
620 REM
630 REM
640 REM
650 REM
660 REM
670 REM
680 REM
690 REM
700 REM
710 REM
720 REM
730 REM
740 REM
750 REM
760 REM
770 REM
780 REM
790 REM
800 REM
810 REM
820 REM
830 REM
840 REM
850 REM
860 REM
870 REM
880 REM
890 REM
900 REM
910 REM
920 REM
930 REM
940 REM
950 REM
960 REM
970 REM
980 REM
990 REM
201
APPENDIX C

A multi-node dynamic computer model of a flat-plate, rear-duct, air-heating solar collector is described, and its verification is outlined. Results from the model are then presented of the daily averaged thermal efficiencies for a variety of simulated ambient conditions pertinent to mid to high maritime latitudes. The collectors differ significantly only in their thermal capacitances. The diurnal variation of insolation produces a modest spread of thermal efficiencies, the lower the thermal capacitance of the collector the higher the efficiency. More rapid fluctuations in insolation produce only a slightly further spread in the thermal efficiencies, though such fluctuations have a more significant effect on peak temperatures.

Keywords: air-heating solar collectors; thermal capacitance effects in solar collectors.

NOMENCLATURE

Dy1-5 plate and duct-back thicknesses (5)
f(θ) transmittance - absorbance function of the collector
FR collector heat-removal factor
HPA(I) heat-transfer coefficient plate (or duct-back) to air in the I'th segment of the duct
M duct air flow rate
NI number of duct segments
PON threshold power for switch on of air flow
S irradiance in cover plane
S0 solar beam irradiance
S1 diffuse irradiance on a horizontal surface
SP irradiance absorbed by plate
TA ambient temperature
INTRODUCTION

Low mass in solar collectors offers the advantage of low construction and installation costs. But the mass also influences the thermal capacitance and hence the thermal efficiency, because even a smooth diurnal variation of insolation prevents a collector from achieving a true steady-state, and the lower the mass the closer the varying conditions are followed. Earlier studies (for example {1}, {2}, {4}) have shown that lowering the mass will improve the thermal efficiency, though perhaps by not very much. However, there seem to be few data on the diurnal performance in various ambient conditions of collectors which differ only in their thermal capacitances. This is particularly the case for air-collectors.

Therefore we have developed and verified a dynamic computer model of a flat-plate, rear-duct, air-heating solar collector. We have used it to obtain daily averaged thermal efficiencies for a wide variety of simulated ambient conditions pertinent to maritime mid to high latitudes. The basic configuration of the collector was varied to yield a wide spread of thermal capacitances. The model is of the multi-node kind, because various studies (for example {1}, {3}, {4}) have shown that simple one-node models are unlikely to give accurate results in non steady-state conditions.

2 THE COLLECTOR MODEL

The collector is of the flat-plate rear-duct air-heating single-cover kind, with dimensions selected to give good performance. It is divided into nodes as shown in Figure 1. (This collector could be complete, or it could be a strip width W of a larger assembly.) Heat balance equations are defined at each node, and the equations are numerically integrated in sequence using the Adams-Bashforth-Moulton predictor-corrector method {5}.

The model was tested in a variety of ways, including a comparison of its predictions with the actual behaviour in the laboratory of a flat-plate rear-duct air-heating single-cover collector. In all cases the agreement between prediction and actuality was satisfactory.
### RESULTS

#### 5.1 The collectors

Table 1 specifies the collector configurations, and the rear-duct air flow conditions. The basic configuration was selected to give good steady-state performance, the configurations differing only in the thickness of the plate and duct-back (DY1 to DY5 in Table 1). The main effect of these changes in configuration is on the thermal capacitance of the components and hence of the whole collector.

#### Table 1 Collector configurations, and rear-duct air flow

<table>
<thead>
<tr>
<th>Collector length (along flow)</th>
<th>4.00 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector width (W)</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Cover to plate spacing</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Rear duct gap</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Back insulation</td>
<td>Dry glass fibre, thickness 0.10 m</td>
</tr>
<tr>
<td>Edge insulation</td>
<td>Dry glass fibre, thickness 0.05 m</td>
</tr>
<tr>
<td>Material of plate and duct-back cover</td>
<td>Duralumin HS15TB</td>
</tr>
<tr>
<td>Plate absorptance</td>
<td>0.95 at θ=0, falling slightly as θ increases</td>
</tr>
<tr>
<td>Emissivity of upper surface of the plate (diffuse)</td>
<td>0.10</td>
</tr>
<tr>
<td>Emissivity of duct surfaces (diffuse)</td>
<td>0.91</td>
</tr>
<tr>
<td>Emissivity of the cover (diffuse)</td>
<td>0.85</td>
</tr>
<tr>
<td>Thermal properties of air at 283 K for ambient air, at 303 K elsewhere</td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>52°N</td>
</tr>
<tr>
<td>Collector tilt (to horizontal)</td>
<td>35°</td>
</tr>
<tr>
<td>Collector orientation</td>
<td>South-facing</td>
</tr>
<tr>
<td>Thickness of plate and of duct-back</td>
<td>collector time-constant (flow 1)</td>
</tr>
<tr>
<td>DY1</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>DY2</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>DY3</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>DY4</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>DY5</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>85 s</td>
<td>170 s</td>
</tr>
<tr>
<td>300 s</td>
<td>580 s</td>
</tr>
<tr>
<td>1400 s</td>
<td></td>
</tr>
</tbody>
</table>

### Air flow in the rear-duct

<table>
<thead>
<tr>
<th>Flow</th>
<th>Stagnation (M=0)</th>
<th>TI</th>
<th>M</th>
<th>PON</th>
</tr>
</thead>
<tbody>
<tr>
<td>flow 0</td>
<td></td>
<td></td>
<td>0.0600 kg s⁻¹</td>
<td></td>
</tr>
<tr>
<td>flow 1</td>
<td></td>
<td>303 K</td>
<td>0.0600 kg s⁻¹</td>
<td>128 W</td>
</tr>
<tr>
<td>flow 2</td>
<td></td>
<td>323 K</td>
<td>0.0562 kg s⁻¹</td>
<td>124 W</td>
</tr>
</tbody>
</table>

The air flow rate is a compromise between attaining large values of HPA(I) and keeping low the power required to maintain the air flow in the rear-duct. At M = 0.0600 kg s⁻¹ and TI = 303 K (flow 2 in Table 1) this power is 6.4 W. The corresponding pressure drop across the duct is 12 mm water gauge. If it is
assumed that the circulation fan gives a constant volumetric flow rate then at other values of $T$ the value of $M$ will be different from $0.0600 \text{ kg s}^{-1}$ at $T = 323 \text{ K}$, $M = 0.0562 \text{ kg s}^{-1}$ (flow 3 in Table 1).

It is also necessary to specify the minimum power that must be delivered by a complete array of collectors in order for the air flow to either be switched on or be sustained. This power must be some multiple of the electrical power required by the fan to circulate air around the whole system incorporating the array. We adopted a multiple of two. In order to estimate the electrical power it is necessary to allow for the efficiency of the fan and for the pressure drop in the whole system. For a modest domestic system we ended up with a minimum power per collector of the sort specified in Table 1 of $128 \text{ W}$ for flow 2. For flow 3 $PON$ is slightly less. The values of $PON$ are shown in Table 1. Note that the values of $PON$ are for a $4 \text{ m} \times 1 \text{ m}$ collector, and not for the whole array. These values of $PON$ correspond to an air temperature rise of between $2 \text{ K}$ and $3 \text{ K}$ for the flow conditions specified.

The collector time-constants in Table 1 vary with ambient conditions and with operating conditions, particularly with the air flow rate. The values in the Table are representative for all ambient conditions considered here, and for the various (similar) air flow rates, except for flow $0$ (stagnation), in which case the time-constants in Table 1 should be multiplied by about a factor of 5. Note that the time-constants in Table 1 are the $1/e$ time-intervals following a step change in insolation. However, only in stagnation is the response very close to exponential. Note also that the thermal capacitance of the cover has a relatively small effect, because the cover is coupled to the plate via a rather large thermal resistance.

3.2 Steady-state efficiency curve

We obtained a standard steady-state thermal efficiency curve, of the form (6)

$$\eta = F_R \left( f(\theta) - U_L \frac{(T_I - T_A)}{S} \right)$$

(1)

where $f(\theta)$ is such that

$$SP = f(\theta) \cdot S$$

(2)

For the steady state efficiency curve $S$ is beam irradiance normal to the cover, such that $S = 700 \text{ W m}^{-2}$. Furthermore, $T_A = 293 \text{ K}$, $T_K = 273 \text{ K}$, $WIND = 1.0 \text{ m s}^{-1}$, $M = 0.0600 \text{ kg s}^{-1}$. These values lie within the ASHRAE specifications for steady-state collector testing (6).

In order to obtain the efficiency curve the value of $T_I$ was varied, everything else remaining constant. The outcome is shown in Figure 2 for collector configuration $DY1$ (Table 1), though the results for $DY2$ to $DY5$ are indistinguishable from those for $DY1$ on the scale of Figure 2. The intercept on the $\eta$-axis, 0.683 gives $F_R f(\theta)$ (equation (1)). The program yields a value of 0.830 for $f(\theta)$, and therefore $F_R$ is 0.823. The slope gives $-F_R U_L$, and at low values of $(T_I - T_A)/S$ this is $-2.83 \text{ W m}^{-2} \text{ K}^{-1}$, giving a value of $U_L$ of $3.44 \text{ W m}^{-2} \text{ K}^{-1}$. The value of $F_R U_L$ increases as $T_I$ increases ($T_A$, $S$ constant), largely because the radiative heat transfer coefficients increase with increasing temperature differences, and though $F_R$ decreases it does not offset the increase in $U_L$. These values of $f(\theta)$, $F_R$ and $U_L$ indicate good performance for a flat-plate rear-duct air-heating single-cover collector with a selective plate-surface.

We had a "quick look" at the effect of varying the wind speed on the steady-state
temperatures. The effect was fairly modest, because of the large thermal resistance between cover and plate. Wind speed variations will be deferred to a later study.

3.3 Daily-averaged efficiency

The collector configurations DY1 to DY5 were run under conditions flow 2 and flow 3 for a variety of simulated days 21 June (J), 21 March (M), 21 December (D). The simulated conditions of insolation and weather on these days are shown in Figure 3. The ambient temperature $T_A$ varies sinusoidally through the day (Figure 3(a)) with an amplitude of 5 K. Note that there are two temperature curves for 21 December, $T_{AD1}$ and $T_{AD2}$. The irradiance $S$ consists of a diffuse component from the ground, and of a sky component which can either correspond to clear sky conditions or to overcast diffuse conditions. Figure 3(b) shows some of the various insolutions, the prefix $S0$ denoting the clear sky irradiance normal to the beam, and the prefix $S1$ the overcast diffuse irradiance on a horizontal surface. In the cases in Figure 3(b) the only variation in insolation is the diurnal envelope shown. By contrast in Figures 3(c) and (d) the insolation flips between the two envelopes shown, the square wave periods being indicated, the conditions remaining diffuse throughout. In clear sky conditions the sky temperature is 20 K below $T_A$, and in overcast conditions it is 10 K below $T_A$. In all cases the wind speed is constant at 1.0 m s⁻¹.

For each "day" an average thermal efficiency was obtained, defined by

$$\tilde{\eta} = \text{total energy extracted by the air flow in the day/integration of } S \text{ over the day.} \quad (3)$$

Note that a day spans the time from sunrise to sunset. In no case did a collector deliver energy before or after sunset, and therefore $\tilde{\eta}$ is never being wrongly evaluated.

In order to plot $\tilde{\eta}$ on Figure 2 it is necessary to re-define the abscissa $(T_I - T_A)/S$. $T_I$ is constant (303 K or 323 K), and for $T_A$ and $S$ the arithmetic mean values for the period sunrise to sunset are taken. The outcome is shown in Figure 2, the results being coded in accord with Table 1 and Figure 3, except that the thermal capacitance configuration DY1 to DY5 is not shown. However, you can see that at each value of $(T_I - T_A)/S$ there is a column of results, and in every case DY1 is at the top, then comes DY2, and so on, to DY5, though in some cases DY1-DY3 merge on the scale of Figure 2. Clearly, the lower the thermal capacitance the better the performance.

Consider first those cases in which the insolation only varies over the diurnal envelope: this covers the cases (i)-(vi), (vii), (xi). The increase in $\tilde{\eta}$ is marked in going from the rather massive DY5 to the rather less massive DY4. However, the improvement in going from DY4 to the low mass DY1 is also significant, particularly in marginal conditions (large $(T_I - T_A)/S$). This general improvement, with reducing thermal capacitance arises because with a diurnal envelope the slower warm-up of a high mass collector in the morning is not compensated by the slower cool-down in the afternoon. Note that the sinusoidal variations in $T_A$ and $TK$ do not make an appreciable contribution to the spread of $\tilde{\eta}$ with thermal capacitance on the scale of Figure 2.

The advantage of low mass could, in principle, be more marked under intermittent insolation. SID1-SID3 provide such conditions (Figure 3), the periodicities lying within the range of time-constants in Table 1. However, Figure 2 shows that, even in marginal conditions, very little further advantage in low mass is obtained, though DY1-DY3 are more spread out than with the diurnal envelope alone. The
reason for such a slight improvement is that whereas a low mass collector will "follow" the insolation, possibly switching the air flow on and off, a high mass collector, once it has warmed to the point where the air flow switches on, will tend to stay at a fairly constant temperature. The overall effect, for a wide variety of conditions, is that the time-averaged temperatures of the air flow are not very sensitive to the mass. Therefore there is very little difference in the amount of heat extracted. A similar conclusion was reached by Klein et al [1].

Figure 2 also shows that the values of $\tilde{n}$ differ from those of $n$. This is particularly the case at low thermal capacitances, as can be seen from the performance of DY1, which is not very different from that which would have been obtained for a collector of zero thermal capacitance. Two prominent and opposing effects operating here are that for $n$ in Figure 2 the value of $\tilde{f}(\theta)$ is always zero, thus raising $f_e$, and, more importantly, that in insolation conditions which vary, intermittently or otherwise, a collector can "grab" peak insolation, yet entirely miss the corresponding steady state insolation which never reaches such peak values. Low thermal capacitance is again an advantage.

In addition to $\tilde{n}$, the daily average of $T_0$ was also obtained, such that only those periods were included in which air flowed in the rear duct. In general the lower the thermal capacitance of the collector the higher the daily average, though the improvement from DY5 to DY1 never exceeded 2 K. However, the peak temperatures for DY1 can be up to about 10 K higher than for DY5, the greatest difference occurring in intermittent conditions. In some circumstances this will be an important advantage of low thermal capacitance.

A set of results analogous to those in Figure 2 was obtained for lower flow rates, around 0.02 kg s$^{-1}$. This is a potentially useful domain, because in spite of the lower thermal efficiencies the values of $T_0$ are raised and can reach values such that useful energy can be extracted from ambient conditions which would yield no useful energy at higher flow rates, because of the lower values of $T_0$. However the variation of $\tilde{n}$ with thermal capacitance (DY1-DY5) was not remarkably different from that shown in Figure 2.

It can be concluded that collectors with low thermal capacitance can have significantly larger thermal efficiencies at non-small daily averaged values of $(T_1-T_A)/S$ in non-steady insolation, and that this is largely because of the diurnal variation, rather than because of more rapid fluctuations in insolation. Peak temperatures can also be significantly larger at low thermal capacitance, particularly when there are rapid fluctuations in insolation.

REFERENCES


2 M. Yusoff and D. J. Close, Transient studies of solar air heaters, presented at the Inter-regional symposium on solar energy for development, Tokyo 5-10 February (1979).


Figure 1  Flat-plate, rear duct, air heating solar collector.
Figure 2 Steady-state efficiency ($\eta$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\bar{\eta}$ are for a variety of simulated conditions (see Table 1 and Figure 3).

1. $S_{OJ}/TAJ$, flow 2
2. $S_{OM}/TAM$, flow 2
3. $S_{OD}/TAD1$, flow 2
4. $S_{OM}/TAM$, flow 3
5. $S_{LM}/TAM$, flow 2
6. $S_{OD}/TAD1$, flow 3
7. $S_{LD1}/TAD1$, flow 2
8. $S_{OD}/TAD2$, flow 3
9. $S_{LD2}/TAD1$, flow 2
10. $S_{LD3}/TAD1$, flow 2
11. $S_{LD}/TAD1$, flow 2
Figure 3  Simulated ambient conditions. For further details see text.
APPENDIX D

TRANS: Computer program for analysing collector data under transient conditions.
213

270 FOR I=1 TO NC
271 FOR J=1 TO NC
272 IF ABS(DENOM)<1 THEN GOTO 210
273 YY=YY+YY
274 FOR K=1 TO NC
275 ZY(K)=ZY(K)+Z(K)*Y
276 FOR L=1 TO NC
277 XX(K,L)=XX(K,L)+X(K)*X(L)
278 ZZ(K,L)=ZZ(K,L)+Z(K)*Z(L)
279 NEXT L
280 NEXT K
281 IF NC=NC THEN STOP 1 STOP IF NOT ENOUGH DATA POINTS
282 REM EVALUATES ESTIMATES OF PARAMETERS AND STANDARD ERRORS
283 FOR K=1 TO NC
284 XX(K)=0
285 NEXT K
286 FOR L=1 TO NC
287 XX(K,L)=XX(K,L)+X(K)*X(L)
288 NEXT L
289 NEXT K
290 FOR I=1 TO NC
291 IF I=0 AND X(I)=0 THEN GOTO 650
292 NEXT I
293 NEXT K
294 FOR K=1 TO NC
295 FOR L=1 TO NC
296 NEXT L
297 NEXT K
298 FOR I=1 TO NC
299 NEXT I
300 FOR X(NC)=0
301 NEXT K
302 XX(NC)=XX(NC)+T(F)
303 NEXT K
304 YY(NC)=YY(NC)+D/F
305 ZZ(NC)=ZZ(NC)+D/F
306 DENOM=1

010 BEGIN PROGRAM TO CALCULATE THE COLLECTOR EFF FROM TOUGH-MIT DATA
100 OPTION BASE 1
200 DIM F(16,16),X(16,16),Z(16,16),PT(16,16),ZY(16,16),XY(16,16)
300 DIM XX(16,16),ZZ(16,16),XY(16,16)
400 FOR NC=1 TO 8
450 65SIGN=1 TO "Produce 65000"
500 FOR I=1 TO 16
600 NEXT I
650 NEXT NC
700 NC=NC+1
750 NK=NK+1
800 FOR K=1 TO NC
850 P(K,K)=1
900 NEXT K
950 READ I:1,L,X(NK),Y(T(NK))
100 IF I=0 AND X(NK)=0 THEN GOTO 650
105 I=I+1
110 FOR K=1 TO NK
115 L=L+K+1
120 READ I:1,L,X(L),Y(T(L))
125 IF I=0 AND X(L)=0 THEN GOTO 650
130 IF I=1 THEN GOTO 110
135 I=1+I
140 Z(L)=INT(X(L)/100)/10
145 NEXT I
150 FOR K=1 TO NK
155 Z(K)=INT(X(K)/100)/10
160 NEXT K
165 FOR K=1 TO NC
170 NEXT K
175 IF I=0 AND X(I)=0 THEN GOTO 650
180 IF I=1 THEN GOTO 110
185 I=1+I
190 XX(I)=INT(X(I)/100)/10
195 NEXT I
200 NEXT K
205 WRITE
210 END