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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 \((m^2)\)
\( A_s \)  Storage tank surface area \(m^2\)
\( c \)  Appropriate specific heat \((J \text{ Kg}^{-1} °\text{C}^{-1})\)
\( c_p \)  Volume heat capacity at constant pressure \((J \text{ Kg}^{-1} °\text{C}^{-1})\)
\( C_h \)  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 \((J \text{ m}^{-2})\)
\( f \)  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 \((W \text{ m}^{-2})\)
\( K_h \)  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 \((J °\text{C}^{-1})\)
\( N \)  Lifetime of hardware (years)
\( n \)  Number of years
\( P_{VC_h} \)  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 \((°\text{C})\)
\( T_{at} \)  Ambient temperature averaged over periods when the radiation level is above the threshold \((°\text{C})\)
\( T_g \)  Monthly average ground temperature \((°\text{C})\)
\( T_s \)  Store temperature \((°\text{C})\)
\( \bar{T}_s \)  Monthly average store temperature \((°\text{C})\)
\( T_{so} \)  Store temperature at the beginning of the month \((°\text{C})\)
\( \Delta T \)  \hspace{1cm} \text{Temperature change (°C)}

\( t_m \)  \hspace{1cm} \text{Total number of seconds in a month}

\( t_t \)  \hspace{1cm} \text{Total number of seconds collector is in operation in month, i.e. when radiation level is above threshold}

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

\( U_S \)  \hspace{1cm} \text{Storage tank heat loss coefficient (W m}^{-2} \cdot \text{°C}^{-1})

\( V \)  \hspace{1cm} \text{Volume (m}^3\text{)}

\( \rho \)  \hspace{1cm} \text{Density (kg m}^{-3}\text{)}

\( (\bar{\tau\alpha}) \)  \hspace{1cm} \text{Monthly average transmittance-absorptance product}
## Nomenclature

### Chapter 3

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

Ti Inlet fluid temperature (°C)

Tm Mean fluid temperature (Te + Ti)/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)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_t$</td>
<td>Top loss heat transfer coefficient ($\text{Wm}^{-2} \cdot \text{C}^{-1}$)</td>
</tr>
<tr>
<td>$V$</td>
<td>Wind velocity ($\text{ms}^{-1}$)</td>
</tr>
<tr>
<td>$W$</td>
<td>Collector width (m)</td>
</tr>
<tr>
<td>$x$</td>
<td>Insulation thickness (m)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Absorptance of the collector absorber surface for solar radiation</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Volume thermal expansion coefficient ($\text{K}^{-1}$)</td>
</tr>
<tr>
<td>$\epsilon_c$</td>
<td>Cover emissivity</td>
</tr>
<tr>
<td>$\epsilon_p$</td>
<td>Absorber plate emissivity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Absolute (dynamic) coefficient of viscosity ($\text{Kg m}^{-1} \text{s}^{-1}$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density ($\text{Kgm}^{-3}$)</td>
</tr>
<tr>
<td>$\tau \alpha$</td>
<td>Transmittance of the solar collector and the transmittance of the cover for normal irradiance</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant</td>
</tr>
</tbody>
</table>
**Nomenclature**

**Chapter 5**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aperture area, or transparent frontal area for collector (m²)</td>
</tr>
<tr>
<td>Ac</td>
<td>Collector area (m²)</td>
</tr>
<tr>
<td>c_p</td>
<td>Volume heat capacity at constant pressure (J/kg°C⁻¹)</td>
</tr>
<tr>
<td>F'</td>
<td>Absorber plate (or collector) efficiency factor</td>
</tr>
<tr>
<td>F''</td>
<td>Collector flow factor</td>
</tr>
<tr>
<td>F₁</td>
<td>Correction factor for partial shading of the collector</td>
</tr>
<tr>
<td>F₂</td>
<td>Correction factor for variation of (\tau a) with the angle of incidence</td>
</tr>
<tr>
<td>F₃</td>
<td>Correction factor for variation in optical properties from normal for diffuse irradiance</td>
</tr>
<tr>
<td>F_R</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>h_w</td>
<td>Wind heat transfer coefficient (W/m²°C⁻¹)</td>
</tr>
<tr>
<td>I</td>
<td>Equivalent normal solar irradiance (W/m²)</td>
</tr>
<tr>
<td>I₇b</td>
<td>Direct solar irradiance in plane of collector (W/m²)</td>
</tr>
<tr>
<td>I_d</td>
<td>Diffuse solar irradiance in plane of collector (W/m²)</td>
</tr>
<tr>
<td>I_m</td>
<td>Measured total solar irradiation incident upon the aperture plane of the collector (W/m²)</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate of transfer fluid (kg/s⁻¹)</td>
</tr>
<tr>
<td>m_l</td>
<td>Mass flow rate of leak (kg/s⁻¹)</td>
</tr>
<tr>
<td>M</td>
<td>Fluid capacity of collector (kg)</td>
</tr>
<tr>
<td>(mc)ₑ</td>
<td>Effective heat capacity of collector (J°C⁻¹)</td>
</tr>
<tr>
<td>q</td>
<td>Output power per unit aperture area conveyed by the heat transfer fluid (W/m²)</td>
</tr>
<tr>
<td>Q_u</td>
<td>Energy per unit time, useful (W)</td>
</tr>
<tr>
<td>(Q_u)ₜ</td>
<td>Energy per unit time under transient conditions (W)</td>
</tr>
<tr>
<td>r</td>
<td>Correlation coefficient</td>
</tr>
<tr>
<td>t</td>
<td>Time (s)</td>
</tr>
<tr>
<td>T_a</td>
<td>Ambient air temperature (°C)</td>
</tr>
<tr>
<td>T_b</td>
<td>Average back plate temperature (°C)</td>
</tr>
<tr>
<td>T_e</td>
<td>Exit fluid temperature (°C)</td>
</tr>
<tr>
<td>T_f</td>
<td>Average temperature of the fluid in the collector (°C)</td>
</tr>
<tr>
<td>T_i</td>
<td>Inlet fluid temperature (°C)</td>
</tr>
</tbody>
</table>
Measured fluid inlet temperature (°C)
Mean fluid temperature \((T_e + T_i)/2\) (°C)
Absorber plate temperature (°C)
Mean absorber temperature (°C)
Equivalent black body sky temperature (°C)
Reduced temperature \((T_i - T_a)/I\) (°C)
Collector overall heat transfer (loss) coefficient
Efficiency
Product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance.
Collector time constant under flow conditions (s)
Cut off time (s)
Effective transmittance absorptance product
Product of the absorptance and transmittance for normal irradiance
Time increment
Angle of incidence; degrees from normal
Nomenclature

Chapter 6

**FR**  Collector heat removal factor

**hp-c**  Convection coefficient between absorber plate and cover (Wm\(^{-2}\cdot°C^{-1}\))

**hrp-c**  Radiation coefficient between absorber plate and cover (Wm\(^{-2}°C^{-1}\))

**hrc-a**  Radiation coefficient from the cover to sky (Wm\(^{-2}°C^{-1}\))

**hw**  Wind heat transfer coefficient. (Wm\(^{-2}°C^{-1}\))

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

**Ith**  Threshold solar irradiance (Wm\(^{-2}\))

**Ta**  Ambient air temperature (°C)

**Ti**  Inlet fluid temperature (°C)

**U**  Collector heat loss coefficient P'UL (Wm\(^{-2}°C^{-1}\))

**UL**  Collector overall heat transfer (loss) coefficient (Wm\(^{-2} °C^{-1}\))

**ε_t**  Thermal emissivity

**η**  Efficiency steady state

**η̅**  Daily averaged efficiency

**η_0**  Zero loss collector efficiency, P'(ατ)。

**τ_s**  Solar transmissivity

(τα)  Product of the absorptance and transmittance for normal irradiance
**Nomenclature**

**Chapter 7**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aspect ratio or area of main heater</td>
</tr>
<tr>
<td>a</td>
<td>Accommodation coefficient</td>
</tr>
<tr>
<td>c̄</td>
<td>Average velocity of molecules (ms⁻¹)</td>
</tr>
<tr>
<td>cp</td>
<td>Specific heat at constant pressure (J Kg⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>cv</td>
<td>Specific heat at constant volume (J Kg⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>d</td>
<td>Molecular diameter (m)</td>
</tr>
<tr>
<td>Dh</td>
<td>Hydraulic diameter (m)</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration of gravity (ms⁻²)</td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof number</td>
</tr>
<tr>
<td>h</td>
<td>Combined heat transfer coefficient from absorber to cover (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>h'</td>
<td>Heat transfer coefficient of material of known conductivity (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hb</td>
<td>Heat transfer coefficient for flow across panel wall (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hc</td>
<td>Heat transfer coefficient for flow across the inside of the panel due to convection and conduction (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hp</td>
<td>Heat transfer coefficient for flow across panel (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hr</td>
<td>Heat transfer coefficient for flow across the inside of the panel due to radiation (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hs</td>
<td>Heat transfer coefficient for flow across standard insulation (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity (Wm⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>L</td>
<td>Linear dimension (m)</td>
</tr>
<tr>
<td>m</td>
<td>Wall molecule mass (Kg)</td>
</tr>
<tr>
<td>m'</td>
<td>Gas molecule mass (Kg)</td>
</tr>
<tr>
<td>M</td>
<td>Mass of one mole (kg mol⁻¹)</td>
</tr>
<tr>
<td>NA</td>
<td>Avogadro's number</td>
</tr>
<tr>
<td>Nu</td>
<td>Nussult number</td>
</tr>
<tr>
<td>p</td>
<td>Gass pressure (Nm⁻²)</td>
</tr>
<tr>
<td>Pc</td>
<td>Critical pressure when Ra = Ra_c</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>q</td>
<td>Power dissipated in central heater (W)</td>
</tr>
</tbody>
</table>
\begin{align*}
Q & \quad \text{Energy per unit time, rate of heat supply to main heater (W)} \\
Q_p & \quad \text{Rate of heat supply to panel from main heater (W)} \\
r & \quad \text{Specific gas constant (R/M)} \\
R & \quad \text{Gas constant} \\
\text{Ra} & \quad \text{Rayleigh number} \\
\text{Ra}_C & \quad \text{Critical Rayleigh number, for } \text{Ra} < \text{Ra}_C \text{ no convection, } \text{Nu} = 1 \\
\text{Re} & \quad \text{Reynolds number} \\
s & \quad \text{Absorber plate to cover separation (m)} \\
t & \quad \text{Panel wall thickness (m)} \\
T & \quad \text{Average of plate and cover temperature (°C)} \\
T_1 & \quad \text{Inside panel temperature nearest to cold plate (°C)} \\
T_2 & \quad \text{Inside panel temperature nearest to main heater (°C)} \\
T_g & \quad \text{Guard ring temperature (°C)} \\
T_i & \quad \text{Temperature of main heater, also fluid inlet temperature (°C)} \\
T_0 & \quad \text{Temperature of cold plates (°C)} \\
\alpha & \quad \text{Thermal diffusivity (m}^2\text{s}^{-1}) \\
\beta & \quad \text{Thermal volume expansion coefficient (} = 1/T \text{ for a perfect gas), (K}^{-1}) \\
\gamma & \quad \text{cp/cv} \\
\Delta T & \quad \text{Hot plate temperature unbalance (T}_i - T_g\text{), (°C)} \\
\Delta T & \quad \text{Temperature difference across panel (°C)} \\
\varepsilon_1 & \quad \text{Emissivity of surface at temperature T}_1 \text{ (°C)} \\
\varepsilon_2 & \quad \text{Emissivity of surface at temperature T}_2 \text{ (°C)} \\
\mu & \quad \text{Viscosity (Pa s)} \\
\nu & \quad \text{Kinematic viscosity (μ/ρ) (Pa s m}^3\text{Kg}^{-1}) \\
\rho & \quad \text{Density (Kg m}^{-3}) \\
\sigma & \quad \text{Stefan-Boltzmann constant (Wm}^{-2}\text{ K}^{-4}) \\
\lambda & \quad \text{Mean free path (m)}
\end{align*}
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<td>Gas</td>
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<td></td>
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<td>18.1</td>
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<td>21.3</td>
</tr>
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<td>2025</td>
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<td>4.2</td>
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<td>1.2</td>
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<td></td>
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<td>TOTAL</td>
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<td></td>
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<td>Substance</td>
<td>Comments</td>
<td>Density</td>
<td>Specific heat capacity</td>
</tr>
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<td>----------------------------------------------------</td>
<td>----------</td>
<td>------------------------</td>
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<td>7.90</td>
<td>0.53</td>
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<td>Steel</td>
<td></td>
<td>7.9</td>
<td>0.5</td>
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<td>Magnetite, Fe$_2$O$_3$</td>
<td>Zero voids (at 30% void $\rho C_p = 2.7$)</td>
<td>5.16</td>
<td>0.75</td>
</tr>
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<td>Fe$_3$O$_4$</td>
<td></td>
<td>5.20</td>
<td>0.75</td>
</tr>
<tr>
<td>Wet earth</td>
<td></td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>Water and salt</td>
<td>(brine)</td>
<td>1.2</td>
<td>3.0</td>
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<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td></td>
<td>4.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Scrap Aluminium</td>
<td>Zero voids (30% void $\rho C_p = 1.8$)</td>
<td>2.74</td>
<td>0.963</td>
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<tr>
<td>Therminol 55 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caloria HT43 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oils</td>
<td>Cracking occurs at high temp.</td>
<td>1.0</td>
<td>2.51</td>
</tr>
<tr>
<td>MgCO$_3$·6H$_2$O</td>
<td></td>
<td>1.7</td>
<td>1.60</td>
</tr>
<tr>
<td>MgCO$_3$</td>
<td></td>
<td>3.0</td>
<td>0.84</td>
</tr>
<tr>
<td>Concrete</td>
<td>Zero voids (30% void $\rho C_p = 1.7$)</td>
<td>2.25</td>
<td>1.13</td>
</tr>
<tr>
<td>Stone</td>
<td>Zero voids (30% void $\rho C_p = 1.7$)</td>
<td>2.74</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Density</td>
<td>Void Ratio</td>
<td>Cost (1980) £25/m³</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.74</td>
<td>0.92</td>
<td>2.26</td>
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<td>Marble</td>
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<td>0.75</td>
<td>2.39</td>
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<td>Granite</td>
<td>2.70</td>
<td>0.796</td>
<td>2.12</td>
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<td>Sulphur Liquid</td>
<td>2.1</td>
<td>1.0</td>
<td>2.1</td>
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<td>Rock</td>
<td>2.5</td>
<td>0.84</td>
<td>2.09</td>
</tr>
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<td>Concrete</td>
<td>2.4</td>
<td>0.8</td>
<td>1.9</td>
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<td>Brick</td>
<td>2.23</td>
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<td>0.8</td>
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<td>3.0</td>
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<td>2.9</td>
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<tr>
<td>Sulphur</td>
<td>2.1</td>
<td>0.7</td>
<td>1.5</td>
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<td>Sodium</td>
<td>0.95</td>
<td>0.963</td>
<td>0.95</td>
</tr>
<tr>
<td>Mitec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molten salt</td>
<td>-</td>
<td></td>
<td>1.55</td>
</tr>
<tr>
<td>Cost £0.28/Kg (1980)</td>
<td></td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>Draw salt</td>
<td></td>
<td></td>
<td>1.55</td>
</tr>
<tr>
<td>Molten salt</td>
<td>-</td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>Cost £0.32/Kg (1980)</td>
<td></td>
<td></td>
<td>590</td>
</tr>
<tr>
<td>Dry earth</td>
<td>1.26</td>
<td>0.8</td>
<td>1.0</td>
</tr>
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</table>
### TABLE 2.3 Basic Prometheus configuration to heat 100 houses

<table>
<thead>
<tr>
<th>Store</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>280 m</td>
<td></td>
</tr>
<tr>
<td>width</td>
<td>10 m</td>
<td></td>
</tr>
<tr>
<td>height</td>
<td>4 m</td>
<td></td>
</tr>
<tr>
<td>volume</td>
<td>11200 m³</td>
<td></td>
</tr>
<tr>
<td>storage material pebbles, density</td>
<td>1600 kg m⁻³</td>
<td></td>
</tr>
<tr>
<td>storage material pebbles; specific heat capacity</td>
<td>837 J kg⁻¹°C⁻¹</td>
<td></td>
</tr>
<tr>
<td>store insulation; thickness</td>
<td>0.6 m</td>
<td></td>
</tr>
<tr>
<td>store insulation; thermal conductivity</td>
<td>0.036 Wm⁻²°C⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collector</th>
<th></th>
<th></th>
</tr>
</thead>
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<tr>
<td>area</td>
<td>2,900 m²</td>
<td></td>
</tr>
<tr>
<td>heat transfer factor (F_R)</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>overall heat loss coefficient</td>
<td>1.0 Wm⁻²°C⁻¹</td>
<td></td>
</tr>
<tr>
<td>optical efficiency averaged over useful incident angles (\tau_a)</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
<td>Quantity</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>----------</td>
</tr>
<tr>
<td>1800</td>
<td>12.6 x 10^7</td>
<td>154.9</td>
</tr>
<tr>
<td>500</td>
<td>0.00000</td>
<td></td>
</tr>
<tr>
<td>0.94</td>
<td>16800</td>
<td>7.69</td>
</tr>
<tr>
<td>1.00</td>
<td>103000</td>
<td>6.89</td>
</tr>
<tr>
<td>1.55</td>
<td>2250</td>
<td>2.75</td>
</tr>
<tr>
<td>2.42</td>
<td>5370</td>
<td>1.13</td>
</tr>
<tr>
<td>1.80</td>
<td>5100</td>
<td>1.20</td>
</tr>
<tr>
<td>0.90</td>
<td>2510</td>
<td>0.61</td>
</tr>
<tr>
<td>1.03</td>
<td>2340</td>
<td>0.65</td>
</tr>
<tr>
<td>0.94</td>
<td>880</td>
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</tr>
<tr>
<td>1.18</td>
<td>9357</td>
<td>0.60</td>
</tr>
</tbody>
</table>

This is the average value from several references of the average of several values quoted from the same reference.

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.

<table>
<thead>
<tr>
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<th>Prometheus</th>
<th>Gas</th>
<th>Electricity (Economy 7)</th>
</tr>
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<tr>
<td>( C_h/£ )</td>
<td>5700</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>( K_h/£ )</td>
<td>0</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>( F_h/£ \ yr^{-1} )</td>
<td>18</td>
<td>117</td>
<td>146</td>
</tr>
<tr>
<td>( R_h/£ \ yr^{-1} )</td>
<td>11</td>
<td>24</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ i=0.05 \quad f=0.04 \quad 6600 \quad 6000 \quad 6300 \]

\[ \text{PVC}_h \]

\[ i=0 \quad f=0.04 \quad 8500 \quad 17800 \quad 20200 \]

\[ i=0 \quad f=0.02 \quad 7500 \quad 11700 \quad 12500 \]
TABLE 2.6 Costs and inventory of various interseasonal solar heating systems modelled along with the cost, collector area and storage volume required to provide 27.5 GJ per annum.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Collector type</td>
<td>Flat plate selective</td>
<td>Evacuated tube collector</td>
<td>Concentrating collector</td>
<td>High performance evacuated</td>
</tr>
<tr>
<td>Collector area /m²</td>
<td>2100</td>
<td>4600</td>
<td>14000</td>
<td>2800</td>
</tr>
<tr>
<td>Storage volume /m³</td>
<td>7500</td>
<td>17700</td>
<td>38500</td>
<td>11200</td>
</tr>
<tr>
<td>Insulation thickness/m</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Operating temperature of store/°C</td>
<td>72-42</td>
<td>95-60</td>
<td>70-30</td>
<td>130-30</td>
</tr>
<tr>
<td>Number of houses heated by system</td>
<td>50</td>
<td>300</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>Energy consumption GJ/annum per house</td>
<td>32.4</td>
<td>25</td>
<td>54</td>
<td>27.5</td>
</tr>
<tr>
<td>Cost of collectors £1980/m²</td>
<td>60</td>
<td>64</td>
<td>64</td>
<td>72</td>
</tr>
<tr>
<td>Cost of store £1980/m³</td>
<td>16</td>
<td>11</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Collector area/Storage volume (m²/m³)</td>
<td>0.28</td>
<td>0.26</td>
<td>0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>Total system capital cost £1980</td>
<td>322900</td>
<td>659000</td>
<td>1740000</td>
<td>570000</td>
</tr>
<tr>
<td>Collector area required to heat type A5 house (27.5 GJ/annum)/m²</td>
<td>35.7</td>
<td>16.9</td>
<td>17.8</td>
<td>28</td>
</tr>
<tr>
<td>Storage volume required for type A5 house /m³</td>
<td>127</td>
<td>65</td>
<td>49</td>
<td>112</td>
</tr>
<tr>
<td>Cost per A5 house/£1980</td>
<td>5480</td>
<td>2416</td>
<td>2215</td>
<td>5700</td>
</tr>
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</table>

[ ] Chapter 2 reference numbers
<table>
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<tr>
<th>Store Type</th>
<th>Temperature Rise (°C)</th>
<th>Cost (£ 1982 per KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel tank</td>
<td>80</td>
<td>0.28 - 0.39</td>
</tr>
<tr>
<td>Pit storage</td>
<td>50</td>
<td>0.19 - 0.30</td>
</tr>
<tr>
<td>Rock cavern</td>
<td>70</td>
<td>0.11 - 0.21</td>
</tr>
<tr>
<td>Storage in clay</td>
<td>12</td>
<td>0.07 - 0.13</td>
</tr>
<tr>
<td>Multiple well systems in rock</td>
<td>50</td>
<td>0.07 - 0.12</td>
</tr>
<tr>
<td>Aquifers</td>
<td>15</td>
<td>0.025 - 0.08</td>
</tr>
<tr>
<td>Prometheus (pebble bed, using data from Table 2.6)</td>
<td>100</td>
<td>0.43</td>
</tr>
</tbody>
</table>

### TABLE 2.8 Summary of domestic communal interseasonal storage systems

<table>
<thead>
<tr>
<th>Name</th>
<th>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></td>
<td>Constructed</td>
<td>Water</td>
<td>56</td>
<td>100</td>
<td>27 000</td>
</tr>
<tr>
<td>Inglestad, Sweden</td>
<td></td>
<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td>19 320</td>
</tr>
<tr>
<td>Studsvik, Sweden</td>
<td></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></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></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></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></td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>100</td>
<td>100</td>
<td>10 000</td>
</tr>
<tr>
<td>City University, London, UK</td>
<td></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></td>
<td>Design Study</td>
<td>Water</td>
<td>300</td>
<td>100</td>
<td>2 416</td>
</tr>
<tr>
<td>PCL, UK</td>
<td></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

<table>
<thead>
<tr>
<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (Wm⁻²°C⁻¹)</th>
<th>UA (W°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>88.5</td>
<td>1.0</td>
<td>88.5</td>
</tr>
<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>Total fabric specific loss</td>
<td></td>
<td>224W°C⁻¹</td>
<td></td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td>80W°C⁻¹</td>
<td></td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td>304W°C⁻¹</td>
<td></td>
</tr>
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</table>
### 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 (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>31</td>
<td>28</td>
<td>25.2</td>
<td>5.2</td>
<td>346</td>
</tr>
<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>
</tr>
<tr>
<td>April</td>
<td>30</td>
<td>75</td>
<td>115</td>
<td>8.2</td>
<td>197</td>
</tr>
<tr>
<td>May</td>
<td>31</td>
<td>87</td>
<td>146</td>
<td>11.8</td>
<td>113</td>
</tr>
<tr>
<td>June</td>
<td>30</td>
<td>90</td>
<td>166</td>
<td>14.9</td>
<td>-</td>
</tr>
<tr>
<td>July</td>
<td>31</td>
<td>84</td>
<td>150</td>
<td>17.2</td>
<td>-</td>
</tr>
<tr>
<td>Aug</td>
<td>31</td>
<td>78</td>
<td>123</td>
<td>16.8</td>
<td>-</td>
</tr>
<tr>
<td>Sept</td>
<td>30</td>
<td>72</td>
<td>95</td>
<td>13.9</td>
<td>56</td>
</tr>
<tr>
<td>Oct</td>
<td>31</td>
<td>59</td>
<td>66</td>
<td>10.8</td>
<td>132</td>
</tr>
<tr>
<td>Nov</td>
<td>30</td>
<td>39</td>
<td>37</td>
<td>6.7</td>
<td>256</td>
</tr>
<tr>
<td>Dec</td>
<td>31</td>
<td>25</td>
<td>22</td>
<td>5.3</td>
<td>333</td>
</tr>
<tr>
<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss ($W^0C^{-1}$)</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>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>A0 + orientate house north-south</td>
<td>304</td>
<td>41.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>A1 + 50 mm loft insulation (100 mm total)</td>
<td>291</td>
<td>39.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
<td>255</td>
<td>33.7</td>
<td></td>
<td></td>
</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>
</tr>
<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>
<td></td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
<td>182</td>
<td>22.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>A7 + all windows on south side</td>
<td>182</td>
<td>20.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
<td>177</td>
<td>19.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>A9 + extra layer of glazing (i.e. triple)</td>
<td>164</td>
<td>18.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A11</td>
<td>A10 + cavity increased to 200 mm</td>
<td>150</td>
<td>16.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 3.4 Thermal characteristics of Basic Type BO house

<table>
<thead>
<tr>
<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (W·m⁻²·°C⁻¹)</th>
<th>UA (W·°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>73.9</td>
<td>1.0</td>
<td>73.9</td>
</tr>
<tr>
<td>Roof</td>
<td>41.2</td>
<td>0.6</td>
<td>24.7</td>
</tr>
<tr>
<td>Floor</td>
<td>41.2</td>
<td>0.5</td>
<td>20.6</td>
</tr>
<tr>
<td>Window</td>
<td>13.3</td>
<td>5.5</td>
<td>73.2</td>
</tr>
<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>
</tr>
<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>
<td>----------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>B0</td>
<td>Basic (average UK housing stock)</td>
<td>260</td>
<td>34.9</td>
</tr>
<tr>
<td>B1</td>
<td>B0 + 50 mm of loft insulation (100 mm total)</td>
<td>249</td>
<td>33.1</td>
</tr>
<tr>
<td>B2</td>
<td>B1 + fibre-fill cavity (50 mm)</td>
<td>219</td>
<td>28.3</td>
</tr>
<tr>
<td>B3</td>
<td>B2 + 50 mm of loft insulation (150 mm total)</td>
<td>215</td>
<td>27.7</td>
</tr>
<tr>
<td>B4</td>
<td>B3 + extra layer of glazing (i.e. double)</td>
<td>182</td>
<td>23.1</td>
</tr>
<tr>
<td>B5</td>
<td>B4 + extra layer of glazing (i.e. triple)</td>
<td>170</td>
<td>21.7</td>
</tr>
<tr>
<td>B6</td>
<td>B5 + 100 mm external wall insulation</td>
<td>156</td>
<td>19.6</td>
</tr>
</tbody>
</table>

TABLE 3.5 Thermal Characteristics of existing houses with different levels of retrofitted insulation.
<table>
<thead>
<tr>
<th>Year</th>
<th>Amount ($)</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1986</td>
<td>100.00</td>
<td>Item 1</td>
</tr>
<tr>
<td>1987</td>
<td>200.00</td>
<td>Item 2</td>
</tr>
<tr>
<td>1988</td>
<td>300.00</td>
<td>Item 3</td>
</tr>
</tbody>
</table>

Table 4.4: Item collector, test facilities and installed systems in the United Kingdom.
<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>(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>
<td>59.6</td>
<td>73.2</td>
<td>83.5</td>
<td>10.3</td>
<td>22.1</td>
<td>737</td>
<td>0.0745</td>
<td>29.2</td>
<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>
<td>63.4</td>
<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>
<td>75.1</td>
<td>84.3</td>
<td>9.2</td>
<td>27.7</td>
<td>745</td>
<td>0.0684</td>
<td>26.8</td>
<td>&lt;0.4</td>
<td>93.9</td>
</tr>
<tr>
<td>5</td>
<td>19/8/83</td>
<td>1235-1244</td>
<td>64.7</td>
<td>60.1</td>
<td>69.9</td>
<td>9.8</td>
<td>28.6</td>
<td>624</td>
<td>0.0543</td>
<td>33.1</td>
<td>1.5</td>
<td>78.1</td>
</tr>
<tr>
<td>6</td>
<td>19/8/83</td>
<td>1209-1218</td>
<td>63.9</td>
<td>59.9</td>
<td>68.6</td>
<td>8.7</td>
<td>27.5</td>
<td>614</td>
<td>0.0567</td>
<td>31.7</td>
<td>2.3</td>
<td>76.8</td>
</tr>
<tr>
<td>7</td>
<td>19/8/83</td>
<td>1343-1352</td>
<td>63.8</td>
<td>76.1</td>
<td>80.7</td>
<td>4.6</td>
<td>28.8</td>
<td>583</td>
<td>0.0872</td>
<td>17.6</td>
<td>2.2</td>
<td>88.6</td>
</tr>
<tr>
<td>8</td>
<td>19/8/83</td>
<td>1430-1439</td>
<td>63.8</td>
<td>79.7</td>
<td>83.1</td>
<td>3.4</td>
<td>29.8</td>
<td>572</td>
<td>0.0938</td>
<td>13.3</td>
<td>1.6</td>
<td>91.1</td>
</tr>
<tr>
<td>9</td>
<td>18/8/83</td>
<td>1142-1151</td>
<td>69.1</td>
<td>24.9</td>
<td>42.0</td>
<td>17.1</td>
<td>25.2</td>
<td>667</td>
<td>-0.0005</td>
<td>62.1</td>
<td>&lt;0.4</td>
<td>51.4</td>
</tr>
<tr>
<td>Test Day</td>
<td>Date</td>
<td>No.</td>
<td>Air mass flow rate at inlet (m³/h)</td>
<td>Air temp. inlet (°C)</td>
<td>Air temp. outlet (°C)</td>
<td>Ambient temp. (°C)</td>
<td>Total length (m)</td>
<td>Collected energy (megajoules)</td>
<td>Energy efficiency (%)</td>
<td>Wind speed (m/s)</td>
<td>Absorber temp. (°C)</td>
<td></td>
</tr>
<tr>
<td>---------</td>
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<td>-----------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12/26-1330</td>
<td>1</td>
<td>8.6/83</td>
<td>19/6/83</td>
<td>16/6/83</td>
<td>15/4-14/3</td>
<td>77.6</td>
<td>0.0013</td>
<td>57.4</td>
<td>1.8</td>
<td>55.2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12/26-1330</td>
<td>2</td>
<td>8.6/83</td>
<td>19/6/83</td>
<td>16/6/83</td>
<td>15/4-14/3</td>
<td>77.6</td>
<td>0.0013</td>
<td>57.4</td>
<td>1.8</td>
<td>55.2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>12/26-1330</td>
<td>3</td>
<td>8.6/83</td>
<td>19/6/83</td>
<td>16/6/83</td>
<td>15/4-14/3</td>
<td>77.6</td>
<td>0.0013</td>
<td>57.4</td>
<td>1.8</td>
<td>55.2</td>
<td></td>
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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</td>
<td>Duraluminium HS 15 TB</td>
</tr>
<tr>
<td>Plate absorbtance</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 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>
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</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steady state</th>
<th>Transient 0.5mm (DY2)</th>
<th>Transient 2mm (DY4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δt/(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>FRτα</td>
<td>0.683</td>
<td>0.585</td>
<td>0.569</td>
</tr>
<tr>
<td>KFRτα</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>
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K = correction factor for equivalent normal direct radiation = \( \frac{(τα)\text{direct}}{(τα)\text{diffuse}} \) = 0.830 / 0.688 = 1.206

* = at low fluid inlet temperatures
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<th>(T^*)</th>
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**POINTS ON THERMAL PERFORMANCE CHARACTERISTIC**

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<th>(cF_R(10, k_n))</th>
<th>(n/F^*)</th>
<th>(T^*)</th>
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**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**

**BO FROM LEAST SQUARES FITS EACH WAY**

**MINIMUM ETA = 0.225453187816**

**MAXIMUM ETA = 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, $T_a = 293k$, $I = 700\text{w}m^{-2}$, $V_{\text{wind}} = 1\text{m} \text{s}^{-1}$, $T_{\text{sky}} = 273k$

<table>
<thead>
<tr>
<th>$T_{i}/k$</th>
<th>$T_{e}/k$</th>
<th>$T_{p}/k$</th>
<th>$T_{b}/k$</th>
<th>$T_{m}/k$</th>
<th>$F_{R\cdot U/L}$ (Wm$^{-2}$ $^o\text{C}^{-1}$)</th>
<th>$\eta$</th>
<th>$F_{\text{ave} \cdot U/L}$ (Wm$^{-2}$ $^o\text{C}^{-1}$)</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>.645</td>
<td>3.111</td>
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<td>343</td>
<td>364.98</td>
<td>365.28</td>
<td>357.16</td>
<td>354.00</td>
<td>2.902</td>
<td>.476</td>
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<td>396.94</td>
<td>391.47</td>
<td>389.73</td>
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<td>.293</td>
<td>3.362</td>
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<td>427.23</td>
<td>428.06</td>
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<td>425.11</td>
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<td>434.06</td>
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### TABLE 5.9
Temperature distribution and energy lost from DY1 collector (0.2mm thick plate and duct base) during zero radiation testing, $T_a = 293k$, $V_{\text{wind}} = 1\text{m} \text{s}^{-1}$, $T_{\text{sky}} = 273k$

<table>
<thead>
<tr>
<th>$T_{i}/k$</th>
<th>$T_{e}/k$</th>
<th>$T_{p}/k$</th>
<th>$T_{b}/k$</th>
<th>$T_{m}/k$</th>
<th>Energy lost per unit time per unit area W m$^{-2}$</th>
<th>$F_{R\cdot U/L}$ (Wm$^{-2}$ $^o\text{C}^{-1}$)</th>
<th>$F_{\text{ave} \cdot U/L}$ (Wm$^{-2}$ $^o\text{C}^{-1}$)</th>
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<tbody>
<tr>
<td>303</td>
<td>300.34</td>
<td>300.41</td>
<td>301.23</td>
<td>301.67</td>
<td>40.34</td>
<td>4.034</td>
<td>4.653</td>
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<tr>
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<td>333.32</td>
<td>333.79</td>
<td>336.20</td>
<td>338.16</td>
<td>146.66</td>
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<td>383</td>
<td>365.41</td>
<td>366.41</td>
<td>370.42</td>
<td>374.20</td>
<td>266.50</td>
<td>2.961</td>
<td>3.282</td>
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<td>423</td>
<td>396.74</td>
<td>398.43</td>
<td>403.88</td>
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<tr>
<td>433</td>
<td>404.46</td>
<td>406.34</td>
<td>412.12</td>
<td>418.73</td>
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<td>*303</td>
<td>301.62</td>
<td>301.71</td>
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<td>*433</td>
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<td>407.78</td>
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<td>419.46</td>
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* $T_{\text{sky}} = 293k$
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<th>(mm)²/</th>
<th>(m)²/</th>
<th>(m/s)</th>
<th>C&lt;sub&gt;0&lt;/sub&gt;/</th>
<th>C&lt;sub&gt;0&lt;/sub&gt;/</th>
<th>(m)²/</th>
<th>P&lt;sub&gt;UL&lt;/sub&gt;/</th>
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<td></td>
<td>IM</td>
<td>Wind</td>
<td>Test</td>
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<td>1/4</td>
<td>IM</td>
<td>1/4</td>
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<td>Indoor</td>
<td>2.11</td>
<td>1.6</td>
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<td>28</td>
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<td>7.77</td>
<td>8.48</td>
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<td>Transient</td>
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<td>0.4</td>
<td>0.4</td>
<td>0.639</td>
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<td>0.362</td>
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**Structured Polycarbonate Collector**

**D.C. Hall Collector**

**Table 5.10** Summary of collector testing results.
<table>
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<th>Material</th>
<th>Reflective index (n)</th>
<th>Solar (0.2-4.0 um)</th>
<th>Infrared (3.0-500 um)</th>
<th>Expansion coefficient (°C⁻¹)</th>
<th>Temperature Limits (°C)</th>
<th>Weather-ability (comments)</th>
<th>Chemical Resistance (comments)</th>
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<tr>
<td>Lexan (Polycarbonate)</td>
<td>1.586</td>
<td>125 mil</td>
<td>125 mil</td>
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<td>120-130</td>
<td>Good</td>
<td>Good</td>
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<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</td>
<td>Good to excellent</td>
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<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>
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<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>2.00 x 10⁻⁵</td>
<td>150-200</td>
<td>Poor</td>
<td>Good to excellent</td>
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<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>
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<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>
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<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>
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<td>Excellent</td>
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</tr>
<tr>
<td>Clear lime temper glass (Low iron glass)</td>
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<td>125 mil</td>
<td>10.64 x 10⁻⁶</td>
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<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunade white crystal glass (0.01% iron glass)</td>
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<td>125 mil</td>
<td>10.00 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
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Source: Gary, H.P. 'Treatise on solar energy' Vol.1, A Wiley Interscience Publication, Chichester, 1982
<table>
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<th>Compat (Sputter)</th>
<th>Supporting Reagent</th>
<th>Copper/Glass</th>
<th>Blue Stainless Steel</th>
<th>Stainless Steel</th>
<th>Copper Oxide</th>
<th>Copper</th>
<th>Black Nickel</th>
<th>Black Nickel (BC)</th>
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<td>0.05 - 0.03</td>
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<td>Copper Oxide</td>
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<td>Copper</td>
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<td>Black Nickel (BC)</td>
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<td>0.96</td>
<td>0.90</td>
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<td>Copper</td>
<td>Copper</td>
<td>Copper</td>
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<td>Black Nickel (BC)</td>
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<td></td>
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<tr>
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<td>0.96</td>
<td>0.90</td>
<td>Electrodeposited</td>
<td>Copper</td>
<td>Copper</td>
<td>Copper</td>
<td>Black Nickel</td>
<td>Black Nickel (BC)</td>
<td></td>
<td></td>
</tr>
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</table>
### TABLE 6.3 Key to collector variable features, used to obtain Figure 6.19

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<tr>
<td><strong>Cover material:</strong></td>
<td><strong>Plate glass, thickness</strong></td>
<td><strong>6.0 mm</strong></td>
</tr>
<tr>
<td><strong>Cover 1</strong></td>
<td><strong>Polycarbonate, thickness</strong></td>
<td><strong>2.0 mm</strong></td>
</tr>
<tr>
<td><strong>Cover 2</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **Thickness of the plate and of the duct-back:** |                  |
| **DY1** | **0.2 mm** |                  |
| **DY2** | **0.5 mm** |                  |
| **DY3** | **1.0 mm** |                  |
| **DY4** | **2.0 mm** |                  |
| **DY5** | **5.0 mm** |                  |

| **Air flow in the rear-duct:** |                  |
| **Flow 0** | **Stagnation (M = 0)** |                  |
| **Flow 1** | **All TI M = 0.0600 kg s\(^{-1}\) (PON irrelevant)** |                  |
| **Flow 2** | **TI = 303 K M = 0.0600 kg s\(^{-1}\) PON = 128W** |                  |
| **Flow 3** | **TI = 323 K M = 0.0562 kg s\(^{-1}\) PON = 124W** |                  |
### TABLE 7.1 Some typical thermal accommodation coefficients

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<td>Indeterminate</td>
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<td>Indeterminate</td>
<td>-</td>
<td>0.87 - 0.96</td>
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<td>Indeterminate</td>
<td>-</td>
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Table 7.2 Convection and conduction heat transfer coefficients for various gases at different temperatures as measured with guarded hot plate.
FIGURE 1.1(a)

PHYSICAL QUALITY OF LIFE INDEX VERSUS ENERGY CONSUMPTION PER CAPITA FOR THE COUNTRIES OF THE WORLD. SOURCES OF DATA:

PQI, 'BOOK OF WORLD RANKINGS' BY G.T. KURIAK 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. [7]

**Figure 2.4**

WEEKLY CONSUMPTION OF HOT WATER FOR ONE HOUSEHOLD, FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS', PICKUP, G.A. [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
(1 or 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. PICKUP [7]

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 2.9** Demonstration Project in Studsvik. [26]

**Figure 2.10**

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)

APARTMENT BUILDING (INTENSE POPULATED AREAS) (LARGE SCALE)

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 2.15 PROTO-PROMETHEUS
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 2.18  PROTO-PROMETHEUS TEMPERATURE DISTRIBUTION (WITH FAN ON), ON 22ND SEPTEMBER 1981 AT 14:25 HRS.
SAMPLE SIZE 254
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 A75 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 on 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 A1 house.

Figure 2.26  The effect of changing the storage volume on the % of solar energy supplied by Prometheus to a Type A1 house.
FIGURE 2.27  THE EFFECT OF INCREASING THE NUMBER OF HOUSES SERVED BY A SINGLE CUBIC PROMETHEUS (SIZE, 112 m² per house and 28 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, AS and AI 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 24 m$^2$ 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.
FIGURE 3.7 USEFUL ENERGY SAVED AND EXTRA COSTS FOR VARIOUS INSULATION OPTIONS AND SOLAR SYSTEMS RETROFITTED TO AN EXISTING TYPE 80 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:

McAdams

\[ h_w = 5.7 + 3.5V \]

Watmuff

\[ h_w = 2.8 + 3.0V \]

Lloyd

\[ h_w = 0.15 \times \frac{R_e^{0.8} \times k}{2LW} \]

Sparrow

\[ h_w = k \times 0.86 \times \frac{R_e^{0.8} \times T_e^{0.4}}{2LW} \]

Green

\[ h_w = \left( h_{w0} + h_{w1} T_e^{0.75} \right) \]

Kind

For collector length 2.4 m, width 1.2 m, height 4.5 m, \( T_e = 25^\circ C \)

Figure 4.7 Correlations for wind heat loss coefficient
Figure 4.8 Flow Diagram of 'EFFICZ' (See Appendix B) A Program to Calculate the Efficiency of a Air-Duct Air Heating Collector.
**INPUT**

ENVIRONMENTAL PARAMETERS: $I, V, T_a$

COLLECTOR CONFIGURATION: $E_1, E_2, k, H, A, L, W, D$

COLLECTOR VARIABLES: $T_c, m$

**INITIAL ESTIMATE OF** $T_f, T_m$

**CALCULATE**

- $R_c$: see Equation 4.25
- $N_a$: 4.23
- $h_1, h_2$: 4.22
- $h_r$: 4.27
- $U_b$: 4.4
- $U_e$: 4.15
- $U_L$: 4.16
- $F'$: 4.20
- $F_r$: 4.19
- $Q_u$: 4.18

**$\eta = Q_u / A_l$**

**CALCULATE NEW ABSORBER TEMPERATURE**

$$T_p = T_c + \frac{Q_u}{A_l} \frac{1 - F_r}{U_L F_r}$$

**[Flowchart Diagram]**

- $T_f = T_{f\infty}$

**OUTPUT**

$\eta, T_p, U_c, U_e, U_b, U_e, F_r, F', Q_u$

**Figure 4.9** Flow diagram of 'Effic' (see Appendix B) a program to calculate the efficiency of a top duct evacuated 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 we used in 'RRDCT'.

**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 H.W. 1966-1975).
SECTION X-X

DIRECTION OF FLUID FLOW

'MAXORB'
ABSORBER
HEXTEL
BEHN DUCT BOTTOM

INSULATION

FIGURE 5.2  D.C. HALL COLLECTOR
**Figure 5.3** Angular variation of transmittance of 2mm 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 TEST 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 TOLYCARBONATE 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 $F_{ul}$, 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.

TADJ  
D C HALL COLLECTOR WITH MAXORB ABSORBER 1 / 7 / 83

FIGURE 5.21  SAMPLE OUTPUT OF D.C. HALL COLLECTOR TO TESTING
OUTDOORS NOT UNDER STOPEAD STATE CONDITIONS.
Figure 5.22. Steady State Efficiency Curve for D.C. Hall Collector Tested Outdoors

Results for $I > 760 \text{ W/m}^2$

Results for $I < 360 \text{ W/m}^2$

Linear regression for $I > 760 \text{ W/m}^2$

$\gamma$ vs. $\frac{(T_c - T_a)}{I}$

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
Fig. 5.27 Round Robin testing of liquid flat plate collectors. The combined effect of meteorological extremes and measurement uncertainty. Source: Taylor [28].

Fig. 5.28 Measured dependence of $F(\phi)$ on the diffuse fraction for a single-glazed flat-plate collector. Source: Pordeski [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 $F_{nl}$, $F_n(0)$, and $F_{nl}$ 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 5.30. 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 5.31. 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 ABSTRACT). DATA GENERATED FROM 'TRANS' FOR N=7, UNCORRECTED FOR INCIDENT ANGLE OF RADIATION.
**Figure 5.42** INDOOR SOLAR COLLECTOR TEST FACILITY.

**Figure 5.43** RELATIVE SPECTRAL INTENSITY OF 'COOL RAY' LAMPS, TRANSMISSION OF POLYCARBONATE AND REFLECTANCE OF MAXORO.
**FIGURE 5.44** INTENSITY DISTRIBUTION ACROSS COLLECTOR DURING INDOOR TESTING IN Wm\(^{-2}\). AVERAGE INTENSITY 2.11 Wm\(^{-2}\), STANDARD DEVIATION ± 0.9 Wm\(^{-2}\).

**FIGURE 5.45** WING GENERATOR.
FIGURE 5.46  VARIATION OF WIND SPEED (ms⁻¹), 5mm ABOVE COLLECTOR SURFACE

MEASURED HEAT LOSS WITH COLLECTOR OPERATING UNDER STAGNATION AND ASSUMING (Pr) = 0.72 PLOTTED AGAINST AVERAGE AIR VELOCITY PARALLEL TO COLLECTOR PLANE AND MEASURED 5mm ABOVE COLLECTOR PLANE.

FIGURE 5.47  MEASURED AND PREDICTED HEAT LOSS u, FOR D.C. WALL COLLECTOR (HIGH-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. wall collector with non-selective absorber (Nextel). Indoor measurements and computer predictions.
FIGURE 5.50 REDESIGNED INDOOR COLLECTOR TEST FACILITY

FIGURE 5.51 STEADY STATE AND ZERO TESTING EFFICIENCY CURVES.
FIGURE 5.52  STATION AND EFFICIENCY CURVE PLOTTED AGAINST MEAN ABSORBER PLATE TEMPERATURE ($T_p$) FOR SIMULATED COLLECTOR.
FIGURE 5.53 STANDEY 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 (303 K).

Figure 5.55
Collector temperature profile for model collector under steady state and zero testing conditions for the same mean absorber plate temperature (366 K).
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  $F_{w,l}$ VERSUS MEAN FLUID TEMPERATURE FOR COLLECTOR TYP UNDER ZERO TESTING AND ASHARE 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 A-D Chall type collector (max. absorber).
\[ x \times 10^{11} \]

\[ \text{STEEPY STATE EFFICIENCY WHILE OPERATING AS PART OF A SOLAR HOT WATER SYSTEM.} \]

\[ \text{STEEPY STATE EFFICIENCY MEASURED OUTDOORS ACCORDING TO THE BRITISH STANDARD.} \]

\[ \text{FIGURE 5.61 STEEPLY STATE EFFICIENCY OF SOLAR COLLECTOR (BLACK CHROME) MEASURED DURING OPERATION AND INDOOR TESTING. SOURCE: TAYLOR, P.J. 'PERFORMANCE OF SELECTIVE AND NON-SELECTIVE SOLAR THERMAL ABSORBERS IN A WORKING INSTALLATION.' SOLAR WORLD CONGRESS ED BY S.V. CZYNOWSKY, VOL. 2, PP 1149 - 1153.} \]
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.

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

**Figure 6.7** Steady State Efficiency of Solar Collector 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.N. Sandgy, Vol 2, pp 1149-1159.
**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. $I_{in} = 2.11 \text{Wm}^{-2}$, $T_a = 28^\circ \text{C}$, $T_{in} > T_a$, $T_e = T_a$ 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 separations Z, and two levels of incident insolation.
Figure 6.14: Efficiency curve for a combined parabolic concentrator compared with a flat plate collector. Source: Argonne National Laboratory Tech Report.

Figure 6.15: Global and diffuse insolation month by month at noon on a 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 6.19 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).

(i) SÜJ/TAJ, flow 2  (ii) SOM/TAM, flow 2  (iii) SÜD/TAD1, flow 2  
(iv) SOM/TAM, flow 3  (v) SÜM/TAM, flow 2  (vi) SÜD/TAD1, flow 3  
(vii) SÜD1/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** 'FMTC' Air Heating Solar Collector Developed by Gem [42]

**Figure 6.21** Incident Angle Modifier for the FMTC 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 FMTC 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 7.6  SCHEMATIC DEPICTING EFFECT OF GAP SPACING ON CONDUCTANCE
Figure 7.2  PLOT OF $h_c$ VERSUS PLATE SEPARATION $s$. $T_{air} = 150^\circ C$, $T_{wall} = 325^\circ C$.

Figure 7.8  $h_c$ VERSUS TILT ANGLE TO THE HORIZONTAL FOR AIR ABSORPTION FOR VARIOUS ABSORBER TEMPERATURES ($T_a$) WITH COVER TEMP = 10$^\circ C$. 
$h_r$ heat-transfer due to radiation between a non-selective absorber ($\epsilon = 0.9$) and a glass cover ($\epsilon = 0.9$).

$h_c$ heat-transfer due to convection and conduction in air at atmospheric pressure.

$h_r$ heat-transfer due to radiation between a selective absorber ($\epsilon = 0.09$) and low iron glass cover ($\epsilon = 0.88$).

**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 3.11** Effective Rayleigh Number versus Molecular Weight for Different Gases, at Atmospheric Pressure between Two Parallel Plates, Separating \( \pm 0 \text{ osm} \), Cold Plate Temperature 10°C, Hot Plate 30°C.
**FIGURE 7.12**

Heat transfer coefficient for gases of different molecular weight for $S = 5$ cm, cold plate temperature $10^\circ C$, hot plate temperature $30^\circ C$.
FIGURE 7.13  COST VERSUS HEAT TRANSFER COEFFICIENT FOR DIFFERENT GASES. $S = 5$ cm, VOLUME OF GAS REQUIRED FOR EACH SQUARE METRE OF collector IS 50 LITRES.
FIGURE 7.14 VARIATION OF HEAT TRANSFER COEFFICIENT $h_c$ WITH PRESSURE FOR A FLAT PLATE COLLECTOR, $s = 5\text{ cm}$, $T_i = 293\text{K}$, $T_2 = 323\text{K}$ 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: MODOTA, A AND GARG, H.P.
'MINIMIZING CONVECTIVE HEAT LOSSES.' SOLAR ENERGY VOL. 25, NO. 6, P 523.

FIGURE 7.17 REFLECTED SOLAR RAYS FOR A MULTI COVER SOLAR COLLECTOR.
FIGURE 7.18 A SOLAR RAY AND CUT-AWAY DIAGRAM OF A HEXAGONAL HONEYCOMB COLLECTOR. SOURCE: HOLLANDS K.G.T. "ADVANCED NON-CONCENTRATING SOLAR COLLECTORS" SOLAR ENERGY CONVERSION ED BY A.E. DIXON AND J.D. LESLIE. PERGAMON PRESS 1979
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, $T_i = 283$ K, WITH A HONEYCOMB PAD WITH SLATS ASPECT RATIO $5$
Figure 7.20  Thermal Conductivity versus Rayleigh Number for various gases $T_1 = 10^\circ C$, $T_2 = 30^\circ C$, $S = 5$ cm.
Figure 7.21 Rayleigh Number Versus Temperature for Argon and Air at Atmospheric Pressure Between Two Parallel Flat Plates spacing s = 5 cm, Cold Plate Temperature $T_c = 10^\circ C$.
Figure 7.22 Heat Transfer Coefficients for Several Collector Configurations

- Convection and Conduction, Air, Atmospheric Pressure, Tilt Angle θ = 0°
- Convection and Conduction, Air, Atmospheric Pressure, Tilt Angle θ = 60°
- Convection and Conduction, Argon, Atmospheric Pressure, Tilt Angle θ = 0°
- Convection and Conduction, Air, Honeycomb, Tilt Angle (60°)
- Radiation, Maxorb Absorber (ε = 0.99) and Iron Glass Cover (ε = 0.99)
- Conduction Only, Air at 4 × 10^3 Pa
- Conduction Only, Argon at 3 × 10^3 Pa

s = 5 cm, T = 10°C
Figure 7.23: Guard Ring Heater

Figure 7.24: Guard Ring Unbalance versus Measured Heat Transfer Across a 5 cm Thick Styrofoam & Sample
FIGURE 7.25 ACRYLIC 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 in. and various temperature differences.
FIGURE 7.29 THEORETICAL AND MEASURED HEAT TRANSFER \( h \) 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 EMISSIVITY OF 0.72.
PLATE 2.1

PROTO PROMETHEUS - 1. COLLECTOR, 2. STORE TOP INSULATION AND COLLECTOR ARR. INSULATION, 3. FAN MOTOR 4...5. MONITORING EQUIPMENT. 6. SPACE FOR INSULATION.
PLATE 2.2 PROTO PROMETHEUS STORAGE TANK FILLED WITH PEBBLES.
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 DATA "NO DATA" !
30 SHORT DEMAND(12) !
40 SHORT SOL(12,24) !
50 ASSIGN 1 TO "SUN DATA" !
60 READ# 1 SOL(1) ! read average solar rad for each hour !
each month
70 SHORT TEMP(12,24)
80 ASSIGN 2 TO "TEM DATA" !
90 READ# 1 TEM(1) !
100 DIM MONTH(12)(13)
110 ASSIGN 3 TO "MONTH" !
120 READ# 3 MONTH(1)
130 SHORT DAYS(12) !
140 ASSIGN 4 TO "DAYS" !
150 READ# 4 DAYS() !
160 PRINT USING 200
170 TOTSUN=0 !
180 PRINT "TOTSUN=total annual solar radiation" !
190 PRINT "!******************************************" !
200 IMAGE /////"***** SOLAR RADIATION AT KEW DISTRIBUTION OF HOURLY GLOBAL IRRIGATION ****"//
210 PRINT USING 220
220 IMAGE "******** ON A HORIZONTAL SURFACE IN MJ/m2 ***********"**********"//
230 FOR M=1 TO 12 !
240 PRINT TAB (6&M):MONTH(M) !
250 NEXT M
260 FOR H=1 TO 24 !
270 FOR M=1 TO 12 !
280 PRINT TAB (M6):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 F=0.9 ! HEAT TRANSFER FACTOR
360 c=.837 ! SPECIFIC HEAT OF STORE MATERIAL (kJ/KgC)
370 MET="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" ! 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 THICK=.6 ! THICKNESS OF INSULATING MATERIAL (m)
470 Ta=1.1 ! OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES
480 YEARS=1 ! NUMBER OF YEARS PROGRAM TO RUN DO NOT USE MORE THAN 1 IF gaUX=0
490 Tg=10 ! TEMPERATURE OF GROUND SURROUNDING STORE (C)
500 TS=30 ! MINIMUM STORAGE TEMPERATURE (C)
510 REM **************************** DATA ****************************
1000 REM ******************************************
1010 PRINT TAB(10);"MONTHS(T)=";DEM(D);" HEATING DEMAND-MONTHS:";DEH(D);" HEATING DEMAND-MM:
1020 TOTD=(DEH+DEM)/12:PRINT STR$(TOTD);" TOTAL ANNUAL HEATING DEMAND:";
1030 DEM=D/(TOTD*12):PRINT STR$(DEM);" HEATING DEMAND PER M2 OF COLLECTOR:";
1050 PRINT TAB(10);"DAY=MONTH/31; HOUSE PER ANNUM =";TODT;" GJ/M2;";
1060 PRINT "IFICATION"
1070 PRINT USING 1080
1080 IMAGE ///
1090 IMAGE /* [] */
1100 IMAGE /* [] */
1110 IMAGE /* [] */
1120 PRINT "I/M = THRESHOLD LEVEL (COLLECTOR WILL OPERATE ABOVE THIS INTERVAL) (W/M2)"
1130 PRINT "Tao = Original Store Temperature at the beginning of month (C)"
1140 PRINT "Ta = Ambient Temperature Averaged over periods of collector operation (C)"
1150 PRINT "Tf = Time Period of Collector Operation (M)"
1160 PRINT "T = Total Radiation which is above Threshold (MJ/M2)"
1170 PRINT "qN = Normalized Net Heat to Storage =qT-1m-1s (MJ/M2)"
1180 PRINT "qT = Useful Heat Collected = qN+1m (MJ/M2)"
1190 PRINT "qM = Normalized Monthly Load (MJ/M2)"
1200 PRINT "qS = Normalized Monthly Storage Load (MJ/M2)"
1210 PRINT M ITH Tso Ta tT It qN ts tT iN qaux
1220 PRINT
1230 FOR I=1 TO 12
1240 TI=0
1250 TSO=0
1260 TEMP=0
1270 FOR J=1 TO 24
1280 ITHM;TET=I(T-1(J,1))
1290 IF ITHM;I(T-1(J,1))<0.05 THEN GOTO 1330
1300 IF TEMP=I(J,1) THEN GOTO 1340
1310 TEMP=I(J,1)
1320 TEMP+1TEMP=I(J,1)
1330 NEXT J
1340 IF TEMP=I(J,1) THEN GOTO 1360
1350 TEMP=I(J,1)
1360 TEMP=I(J,1)+36000000
1370 TEMP=I(J,1)+36000000
1380 IF TEMP=I(J,1) THEN GOTO 1770
1390 IF TEMP=I(J,1) THEN GOTO 1770
1400 IF TEMP=I(J,1) THEN GOTO 1770
1410 IF TEMP=I(J,1) THEN GOTO 1770
1420 IF TEMP=I(J,1) THEN GOTO 1770
1430 IF TEMP=I(J,1) THEN GOTO 1770
1440 IF TEMP=I(J,1) THEN GOTO 1770
1450 IF TEMP=I(J,1) THEN GOTO 1770
1460 IF TEMP=I(J,1) THEN GOTO 1770
1470 IF TEMP=I(J,1) THEN GOTO 1770
1480 IF TEMP=I(J,1) THEN GOTO 1770
1490 IF TEMP=I(J,1) THEN GOTO 1770
1500 IF TEMP=I(J,1) THEN GOTO 1770
1510 IF TEMP=I(J,1) THEN GOTO 1770
1520 IF TEMP=I(J,1) THEN GOTO 1770
1530 IF TEMP=I(J,1) THEN GOTO 1770
1540 IF TEMP=I(J,1) THEN GOTO 1770
1550 IF TEMP=I(J,1) THEN GOTO 1770
1560 IF TEMP=I(J,1) THEN GOTO 1770
1570 IF TEMP=I(J,1) THEN GOTO 1770
1580 IF TEMP=I(J,1) THEN GOTO 1770
1590 IF TEMP=I(J,1) THEN GOTO 1770
1600 IF TEMP=I(J,1) THEN GOTO 1770
1610 IF TEMP=I(J,1) THEN GOTO 1770
1620 IF TEMP=I(J,1) THEN GOTO 1770
1630 IF TEMP=I(J,1) THEN GOTO 1770
1640 IF TEMP=I(J,1) THEN GOTO 1770
1650 IF TEMP=I(J,1) THEN GOTO 1770
1660 IF TEMP=I(J,1) THEN GOTO 1770
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1760 IF TEMP=I(J,1) THEN GOTO 1770
1770 IF TEMP=I(J,1) THEN GOTO 1770
1780 IF TEMP=I(J,1) THEN GOTO 1770
1790 IF TEMP=I(J,1) THEN GOTO 1770
1800 IF TEMP=I(J,1) THEN GOTO 1770
1810 IF TEMP=I(J,1) THEN GOTO 1770
1820 IF TEMP=I(J,1) THEN GOTO 1770
1830 IF TEMP=I(J,1) THEN GOTO 1770
1840 IF TEMP=I(J,1) THEN GOTO 1770
1850 IF TEMP=I(J,1) THEN GOTO 1770
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1870 IF TEMP=I(J,1) THEN GOTO 1770
1880 IF TEMP=I(J,1) THEN GOTO 1770
1890 IF TEMP=I(J,1) THEN GOTO 1770
1900 IF TEMP=I(J,1) THEN GOTO 1770
1910 IF TEMP=I(J,1) THEN GOTO 1770
1920 IF TEMP=I(J,1) THEN GOTO 1770
1930 IF TEMP=I(J,1) THEN GOTO 1770
1940 IF TEMP=I(J,1) THEN GOTO 1770
1950 IF TEMP=I(J,1) THEN GOTO 1770
1960 IF TEMP=I(J,1) THEN GOTO 1770
1970 IF TEMP=I(J,1) THEN GOTO 1770
1980 IF TEMP=I(J,1) THEN GOTO 1770
1990 IF TEMP=I(J,1) THEN GOTO 1770
2000 IF TEMP=I(J,1) THEN GOTO 1770
2010 DATA 7550,6490,5560,3120,980,770,770,770,1790,5270,7450
2020 END
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**Note:**
- Daily Radiation is the total solar radiation received on a horizontal surface.
- Daily Solar Gain is the total gain of energy from the sun.
- Daily Heat Loss is the total heat loss from the system.
- Net Daily Gain is the difference between the daily solar gain and daily heat loss.
- Monthly Solar Gain and Heat Loss are the cumulative totals for a month.
- Net Monthly Gain is the difference between the monthly solar gain and monthly heat loss.
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 **************************** PROGRAM TDPAIR ****************************
25 LECTOR SEE DUFFIE & BECKMAN P204
30 REM
40 ' 50 FOR I=0 TO 20
50 TP=10+I*5: ABSORBER TEMP
60 TA=10 : Ambient temp (C)
70 WIND=1: Wind speed (ms-1)
80 EP=0.95: Absorber emissivity
90 ECD=0: Cover plate emissivity
100 S=5: Plate separation (cm)
120 G=9.812: Acceleration due to gravity (ms-2) at LONDON
130 K=0.0257: Thermal conductivity of gas at Tave (Wm-2K-1)
140 B=0: Inclination angle=0(Horizontal)
150 CP=1007: Heat capacity of air (J/KgK)
155 EP=1007: Heat capacity of GAS BETWEEN COVER AND ABSORBERKgK
160 S=S/100: CONVERT TO METERS
170 L=1
180 K=W=190 SW=21.4W/(L+W)
200 REM **************************** THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFE
210 TC=TA+(TP-2T)/2: guess the cover temp
220 Ti=273.15+TC: CONVERT TO KELVIN
230 TA=273.15+TA: CONVERT TO KELVIN
240 TC=273.15+TC: CONVERT TO KELVIN
250 TP=TP+273.15: CONVERT TO KELVIN
260 Ti=Ti: CONVERT TO KELVIN
270 DT2-T1: TEMP DIFFERENCE DELTA T
280 Tave=(T1+DT2)/2: AVERAGE GAS TEMPERATURE
290 DEN=352.91/Tave
300 k=Tave/.0000076+.0034406
310 VIS=Tave*.0000046+.000006451
320 VOL=1/Tave: THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFE
330 V=VIS/DEN: KINEMATIC VISCOSITY
340 Gr=G*VOL*SW/3DWT/VW/2: GRASHOF NUMBER
350 Pr=CP/WVIS/K
360 Ra=Gr*Pr: RAYLEIGH No
370 REM **************************** CALCULATE NUSLNT NUMBER ****************************
380 N1=1-170B/(Ra*COS(B)): N1=170B/(Ra*COS(B))=N1: NUSLNT No
390 IF N1<0 THEN N1=0: TAKE ONLY POSITIVE TERMS
400 N2=(Ra*COS(B)/5830)/(1.83-1)
410 IF N2<0 THEN N2=0: TAKE ONLY POSITIVE TERMS
420 Nu=1.44*N1*(1-SINT*(1.83-1.6170B/(Ra*COS(B))))+N2: NUSLNT No
430 h=K/SINU: HEAT TRANSFER COEFFICIENT
440 hr=0.0000000567*(TP*2+TC2)*(TP+TC1)/(1/EP+1/EC-1): RAD FROM PLATE TO COVER000 PRINT
450 hsky=0.0000000567*EC2*TC2*TA: RAD COVER TO SKY
470 DWT=TC-TA
480 Tave=TA+DWT/2
490 DENH=352.91/Tave
500 KWH=Tave#*.0000076+.0034406
510 VISW=Tave#*.0000046+.000006451
```
REM **************************************** EFFIC ************************************************
REM REM This program calculates the steady state efficiency of a top duct.
REM REM AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
REM p237 Figure 6.12.1 (d)
REM REM **************************************** INPUT VARIABLE DATA ****************************************
REM IF J=0 TO 10
REM M=1.4310 1 MASS FLOW RATE (kg/hr)
REM Ta=16.2 AMBIENT TEMP (°C)
REM Ti=Ta IN FLUID TEMPERATURE (°C)
REM T2=20.4 ABSORBER TEMPERATURE (°C) IF THIS CHANGES ALSO CHANGE Ti
REM Ti=(T2-TA)/2+Ta
REM W=5. WIND SPEED (m/s)
REM L=1.236 INTENSITY OF SOLAR RAD (W/m2)
REM E=0.8 TRANSMISSIVITY & ABSORBTIVITY OF COVER AND ABSORBER
REM E2=0.95 EMISSIVITY OF ABSORBER
REM L=0.344 CONDUCTIVITY OF REAR INSULATION (W/m°C)
REM L=0.075 INSULATION THICKNESS (m)
REM A=1 COLLECTOR AREA (m2)
REM L=2. COLLECTOR LENGTH IN METERS
REM W=1. WIDTH OF COLLECTOR IN METERS
REM D=1. PLATE SEPARATION IN CM
REM R=1. FIN SEPARATION IN CM
REM DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
REM IF Y=1 THEN GOTO 470
REM IF A=# THEN GOTO 470
REM PRINTER IS 701
REM PRINT USING 930 "MASS FLOW RATE, M, Kg/hr"
REM PRINT USING 930 "AMBIENT TEMP, TA, °C"
REM PRINT USING 930 "INLET TEMPERATURE, Ti, °C"
REM PRINT USING 930 "WIND SPEED, WIND, m/s"
REM PRINT USING 930 "SOLAR RADIATION, I, W/m2"
REM PRINT USING 930 "TRANSMISSIVITY & ABSORBTIVITY, E"
REM PRINT USING 930 "EMISSIVITY OF COVER, E1"
REM PRINT USING 930 "EMISSIVITY OF ABSORBER, E2"
REM PRINT USING 930 "INSULATION CONDUCTIVITY, K, W/m°C"
REM PRINT USING 930 "INSULATION THICKNESS, T, m"
REM PRINT USING 930 "COLLECTOR AREA, A, m2"
REM PRINT USING 930 "COLLECTOR LENGTH, L, m"
REM PRINT USING 930 "COLLECTOR WIDTH, W, m"
REM PRINT USING 930 "PLATE SEPARATION, S, cm"
REM PRINT USING 930 "FIN SEPARATION, D, cm"
REM PRINT USING 930 "EFFICIENCY"
APPENDIX C

THE EFFECT OF THERMAL CAPACITANCES ON THE PERFORMANCE OF SOLAR COLLECTORS

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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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY1-5</td>
<td>plate and duct-back thicknesses (5)</td>
</tr>
<tr>
<td>f(θ)</td>
<td>transmittance - absorptance function of the collector</td>
</tr>
<tr>
<td>FR</td>
<td>collector heat-removal factor</td>
</tr>
<tr>
<td>HPA(I)</td>
<td>heat-transfer coefficient plate (or duct-back) to air in the I'th segment of the duct</td>
</tr>
<tr>
<td>M</td>
<td>duct air flow rate</td>
</tr>
<tr>
<td>NI</td>
<td>number of duct segments</td>
</tr>
<tr>
<td>PON</td>
<td>threshold power for switch on of air flow</td>
</tr>
<tr>
<td>S</td>
<td>irradiance in cover plane</td>
</tr>
<tr>
<td>S0</td>
<td>solar beam irradiance</td>
</tr>
<tr>
<td>S1</td>
<td>diffuse irradiance on a horizontal surface</td>
</tr>
<tr>
<td>SP</td>
<td>irradiance absorbed by plate</td>
</tr>
<tr>
<td>TA</td>
<td>ambient temperature</td>
</tr>
</tbody>
</table>
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.

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

| Collector length (along flow) | 4.00 m |
| Collector width (W) | 1.00 m |
| Cover to plate spacing | 0.05 m |
| Rear duct gap | 0.01 m |
| Back insulation | Dry glass fibre, thickness 0.10 m |
| Edge insulation | Dry glass fibre, thickness 0.05 m |
| Material of plate and duct-back | Polycarbonate, thickness 2.00 mm |
| Cover | 2.00 mm |
| Plate absorbtance | 0.95 at $\theta=0$, falling slightly as $\theta$ increases |
| Emissivity of upper surface of the plate (diffuse) | 0.10 |
| Emissivity of duct surfaces (diffuse) | 0.91 |
| Emissivity of the cover (diffuse) | 0.85 |
| Thermal properties of air at 283 K for ambient air, at 303 K elsewhere |
| Latitude | 52°N |
| Collector tilt (to horizontal) | 35° |
| Collector orientation | South-facing |
| Thickness of plate and of duct-back | Collector time-constant (flow 1) |
| DY1 | 0.2 mm |
| DY2 | 0.5 mm |
| DY3 | 1.0 mm |
| DY4 | 2.0 mm |
| DY5 | 5.0 mm |
| Air flow in the rear-duct |
| Flow 0 | Stagnation (M=0) |
| Flow 1 | All TI $M = 0.0600$ kg s$^{-1}$ (PON, irrelevant) |
| Flow 2 | TI = 303 K $M = 0.0600$ kg s$^{-1}$ PON = 128 W |
| Flow 3 | TI = 323 K $M = 0.0562$ kg s$^{-1}$ PON = 124 W |

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 gage. If it is
assumed that the circulation fan gives a constant volumetric flow rate then at other values of TI the value of \( M \) will be different from 0.0600 kg s\(^{-1}\) at \( T_1 = 323 \text{ K} \), \( M = 0.0562 \text{ kg s}^{-1} \) (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 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 m x 1 m collector, and not for the whole array. These values of PON correspond to an air temperature rise of between 2 K and 3 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)

\[
\eta = \frac{F_R \cdot f(\theta) - U_L \cdot (T_1 - T_A)}{S}
\]

(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, \( T_A = 293 \text{ K} \), \( T_K = 273 \text{ K} \), \( \text{WIND} = 1.0 \text{ m s}^{-1} \), \( M = 0.0600 \text{ kg s}^{-1} \). These values lie within the ASHRAE specifications for steady-state collector testing (6).

In order to obtain the efficiency curve the value of TI 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 \( F_R \cdot f(\theta) \) (equation (1)). The program yields a value of 0.830 for \( f(\theta) \), and therefore \( F_R \) is 0.823. The slope gives \( -F_R \cdot U_L \), and at low values of \((T_1-T_A)/S\) this is \(-2.83 \text{ W m}^{-2} \text{ K}^{-1}\), giving a value of \( U_L \) of 3.44 W m\(^{-2}\) K\(^{-1}\). The value of \( F_R \cdot U_L \) increases as TI 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 \( \frac{f(\theta)}{S} \), \( F_R \) 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 TA varies sinusoidally through the day (Figure 3(a)) with an amplitude of 5 K. Note that there are two temperature curves for 21 December, TAD1 and TAD2. 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 insolations, 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 TA, and in overcast conditions it is 10 K below TA. 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

\[ \eta = \frac{\text{total energy extracted by the air flow in the day/integration of } S}{\text{over the day.}} \]  

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 \( \eta \) is never being wrongly evaluated.

In order to plot \( \bar{\eta} \) on Figure 2 it is necessary to re-define the abscissa (TI-TA)/S. TI is constant (303 K or 323 K), and for TA 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 (TI-TA)/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), (viii), (xi). The increase in \( \bar{\eta} \) 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 (TI-TA)/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 TA and TK do not make an appreciable contribution to the spread of \( \bar{\eta} \) with thermal capacitance on the scale of Figure 2.

The advantage of low mass could, in principle, be more marked under intermittent insolation. S1D1-S1D3 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
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 \( \bar{\eta} \) differ from those of \( \eta \). 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 \( \eta \) in Figure 2 the value of \( \theta \) is always zero, thus raising \( f(\theta) \), 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 \( \bar{\eta} \), 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 \( \bar{\eta} \) 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.

- nodes in airflow
- other nodes

Cover

Duct segment

Plate

Duct-base

Air flow

Back-insulation

Nodes in airflow

Other nodes
Figure 2 Steady-state efficiency ($\eta$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\eta$ are for a variety of simulated conditions (see Table 1 and Figure 3).

(i) $SOJ/TAJ$, flow 2  (ii) $SOM/TAM$, flow 2  (iii) $SOD/TAD1$, flow 2

(iv) $SOM/TAM$, flow 3  (v) $SIM/TAM$, flow 2  (vi) $SOD/TAD1$, flow 3

(vii) $SID1/TAD1$, flow 2  (viii) $SOD/TAD2$, flow 3  (ix) $SID2/TAD1$, flow 2

(x) $SID3/TAD1$, flow 2  (xi) $SID/TAD1$, flow 2.
Figure 3  Simulated ambient conditions. For further details see text.
APPENDIX D

TRANS: Computer program for analysing collector data under transient conditions.
940 NEXT K
950 NEXT K
960 ZE=SOR (ZE\*YY/(NF-NC))
970 PRINT "ETAO=";E,"+/";2E
980 U=X(NC)
990 PRINT "FU=";U,"-/";2(U)
1000 PRINT "TABLE F.4"
1010 FOR K=1 TO NK
1020 C(K)*X(K)/E
1030 PRINT K,C(K)
1035 NEXT K
1040 F=U/(1-HLOG (1-U/H))
1050 PRINT "F=";F
1060 E=E/F
1070 U=U-F
1080 PRINT "ETAO=";E,"U=";U
1090 PRINT "DATA SETS ACCEPTED FOR ANALYSIS";NP
1100 REM READ DATA TO GENERATE THERMAL PERFORMANCE CURVE
1110 ASSIGN# 1 TO "TRANSD7000"
1120 NP=0
1130 READ# 1 ; I,X(NK),Y,T(NK)
1135 IF I=0 AND X(NK)=0 THEN GOTO 1570
1140 I=I+1
1150 FOR K=2 TO NK
1160 L=NE-K+1
1170 READ# 1 ; I,X(L),Y,T(L)
1175 IF I=0 AND X(L)=0 THEN GOTO 1570
1180 IF I#1 THEN GOTO 1130
1190 II=II+1
1200 NEXT K
1210 GOTO 1400
1220 FOR K=2 TO NK
1230 L=NE-K+2
1240 X(L)=X(L-1)
1250 T(L)=T(L-1)
1260 NEXT K
1270 READ# 1 ; I,X(I),Y,T(I)
1275 IF I=0 AND X(I)=0 THEN GOTO 1570
1280 IF I#1 THEN GOTO 1150
1290 II=II+1
1300 E=0
1310 X(NC)=0
1320 FOR K=1 TO NK
1330 E=E+X(K)*C(K)
1340 X(NC)=X(NC)+T(K)
1350 NEXT K
1360 Y=Y/(FRE)
1370 X(NC)=X(NC)^N/"N^N/E"
1380 PRINT Y,X(NC)
1390 REM CALC LEAST SOR TO THERMAL PERFORMANCE
1400 SX=SX+X(NC)
1410 SY=SY+Y
1420 SY=SY-X(NC)*X(NC)
1430 SY=SY+Y
1440 SY=SY+X(NC)*X(NC)
1450 NP=NP+1
1540 NF-IF+1
1550 NF=NF
1560 GOTO 1260
1570 DNF=NF
1580 PRINT "POINTS ON THERMAL PERFORMANCE CHARACTERISTIC";NP
1590 PRINT "FROM LEAST SQUARES FITS EACH WAY"
1600 E=(SX*SY-SX*SY)/(DNF*SY-SX*SY)
1610 U=(SN*SN-DNF*SY)/((DNF*SN*SN)
1620 PRINT "MINIMUM ETAO=";E,"U=";U
1630 E=(SN*SY-SX*SY)/(DNF*SN*SY)
1640 U=(SN*SN-DNF*SY)/((DNF*SN*SY)
1650 PRINT "MAXIMUM ETAO=";E,"U=";U
1655 NEXT NK
1660 STOP
1670 END