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

Thesis

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

Thesis submitted for the degree of Doctor of Philosophy in Energy Research at the Open University, September 1984

Volume 2

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Nomenclature

Chapter 2

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

$t_m$  Total number of seconds in a month

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

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

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

$V$  Volume (m$^3$)

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

$(\bar{\tau a})$  Monthly average transmittance-absorptance product
**Nomenclature**

**Chapter 3**

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

**Chapter 4**

- **A**: Aperture area, or transparent frontal area of collector (m²)
- **Cₚ**: Specific heat of transfer fluid at constant pressure (J/kg°C)
- **Dₜₜ**: 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 (W/m²°C)
- **h₂**: Convective heat transfer coefficient, duct base to heat transfer fluid (W/m²°C)
- **hᵣ**: Radiative heat transfer coefficient (W/m²°C)
- **hₕ**: Wind heat transfer coefficient (W/m²°C)
- **H**: Duct height (m)
- **I**: Equivalent normal solar irradiance (W/m²)
- **k**: Thermal conductivity (W/m°C)
- **L**: Collector length (m)
- **m**: Mass flow rate of transfer fluid (Kg/s)
- **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)
- **Tₑ**: Exit fluid temperature (°C)
- **Tᵢ**: Inlet fluid temperature (°C)
- **Tₘ**: Mean fluid temperature (Tₑ + Tᵢ)/2 (°C)
- **Tₚ**: Average absorber temperature (°C)
- **Uᵦ**: Bottom loss heat transfer coefficient (W/m²°C)
- **Uₑ**: Edge loss heat transfer coefficient (W/m²°C)
- **Uₐ**: Collector overall heat transfer (loss) coefficient (W/m²°C)
\( U_t \)  Top loss heat transfer coefficient (Wm\(^{-2}\) °C\(^{-1}\))
\( V \)  Wind velocity (ms\(^{-1}\))
\( W \)  Collector width (m)
\( x \)  Insulation thickness (m)
\( \alpha \)  Absorptance of the collector absorber surface for solar radiation
\( \beta \)  Volume thermal expansion coefficient (K\(^{-1}\))
\( \epsilon_c \)  Cover emissivity
\( \epsilon_p \)  Absorber plate emissivity
\( \eta \)  Efficiency
\( \mu \)  Absolute (dynamic) coefficient of viscosity (Kg m\(^{-1}\) s\(^{-1}\))
\( \rho \)  Density (Kgm\(^{-3}\))
\( \tau \)  Transmittance of the solar collector
\( (\tau \alpha) \)  The product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance
\( \sigma \)  Stefan-Boltzmann constant
**Nomenclature**

**Chapter 5**

<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>A_C</td>
<td>Collector area (m²)</td>
</tr>
<tr>
<td>C_P</td>
<td>Volume heat capacity at constant pressure (JKg⁻¹°C⁻¹)</td>
</tr>
<tr>
<td>F'_P</td>
<td>Absorber plate (or collector) efficiency factor</td>
</tr>
<tr>
<td>F''_P</td>
<td>Collector flow factor</td>
</tr>
<tr>
<td>F_L</td>
<td>Correction factor for partial shading of the collector</td>
</tr>
<tr>
<td>F_2</td>
<td>Correction factor for variation of τ_α with the angle of incidence</td>
</tr>
<tr>
<td>F_3</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 (Wm⁻²°C⁻¹)</td>
</tr>
<tr>
<td>I</td>
<td>Equivalent normal solar irradiance (Wm⁻²)</td>
</tr>
<tr>
<td>I_b</td>
<td>Direct solar irradiance in plane of collector (Wm⁻²)</td>
</tr>
<tr>
<td>I_d</td>
<td>Diffuse solar irradiance in plane of collector (Wm⁻²)</td>
</tr>
<tr>
<td>I_m</td>
<td>Measured total solar irradiation incident upon the aperture plane of the collector (Wm⁻²)</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>(mce)</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 (Wm⁻²)</td>
</tr>
<tr>
<td>Qu</td>
<td>Energy per unit time, useful (W)</td>
</tr>
<tr>
<td>(Qu)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>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>T_{im}</td>
<td>Measured fluid inlet temperature (°C)</td>
</tr>
<tr>
<td>T_{m}</td>
<td>Mean fluid temperature ((T_e + T_i)/2) (°C)</td>
</tr>
<tr>
<td>T_p</td>
<td>Absorber plate temperature (°C)</td>
</tr>
<tr>
<td>T_{p}</td>
<td>Mean absorber temperature (°C)</td>
</tr>
<tr>
<td>T_{sky}</td>
<td>Equivalent black body sky temperature (°C)</td>
</tr>
<tr>
<td>T^*</td>
<td>Reduced temperature ((T_i - T_a)/I) ((m^2 , °C , w^{-1}))</td>
</tr>
<tr>
<td>U_L</td>
<td>Collector overall heat transfer (loss) coefficient ((Wm^{-2} , °C^{-1}))</td>
</tr>
<tr>
<td>V</td>
<td>Wind velocity ((ms^{-1}))</td>
</tr>
<tr>
<td>\eta</td>
<td>Efficiency</td>
</tr>
<tr>
<td>\tau_{a}</td>
<td>Product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance.</td>
</tr>
<tr>
<td>\tau_c</td>
<td>Collector time constant under flow conditions (s)</td>
</tr>
<tr>
<td>\tau_d</td>
<td>Cut off time (s)</td>
</tr>
<tr>
<td>(\tau_a)_e</td>
<td>Effective transmittance absorptance product</td>
</tr>
<tr>
<td>(\tau a)_a</td>
<td>Product of the absorptance and transmittance for normal irradiance</td>
</tr>
<tr>
<td>\Delta T^*</td>
<td>Time increment</td>
</tr>
<tr>
<td>\theta</td>
<td>Angle of incidence; degrees from normal</td>
</tr>
</tbody>
</table>
Nomenclature
Chapter 6

FR Collector heat removal factor
hp-c Convection coefficient between absorber plate and cover (Wm\(^{-2}\cdot{\text{C}}^{-1}\))
h_{rp-c} Radiation coefficient between absorber plate and cover (Wm\(^{-2}\cdot{\text{C}}^{-1}\))
h_{rc-a} Radiation coefficient from the cover to sky (Wm\(^{-2}\cdot{\text{C}}^{-1}\))
h_{w} Wind heat transfer coefficient. (Wm\(^{-2}\cdot{\text{C}}^{-1}\))
I Equivalent normal solar irradiance (Wm\(^{-2}\))
I_{th} Threshold solar irradiance (Wm\(^{-2}\))
T_{a} Ambient air temperature (°C)
T_{i} Inlet fluid temperature (°C)
U Collector heat loss coefficient P'U_{L} (Wm\(^{-2}\cdot{\text{C}}^{-1}\))
U_{L} Collector overall heat transfer (loss) coefficient (Wm\(^{-2}\cdot{\text{C}}^{-1}\))
\epsilon_{t} Thermal emissivity
\eta Efficiency steady state
\bar{\eta} Daily averaged efficiency
\eta_{o} Zero loss collector efficiency, P'(\alpha\tau)_{o}
\tau_{s} Solar transmissivity
(\tau\alpha) Product of the absorptance and transmittance for normal irradiance
Nomenclature

Chapter 7

\( A \) Aspect ratio or area of main heater  
\( a \) Accommodation coefficient  
\( \bar{c} \) Average velocity of molecules (\( \text{ms}^{-1} \))  
\( c_p \) Specific heat at constant pressure (\( \text{J Kg}^{-1} \cdot \text{C}^{-1} \))  
\( c_v \) Specific heat at constant volume (\( \text{J Kg}^{-1} \cdot \text{C}^{-1} \))  
\( d \) Molecular diameter (m)  
\( D_h \) Hydraulic diameter (m)  
\( g \) Acceleration of gravity (\( \text{ms}^{-2} \))  
\( Gr \) Grashof number  
\( h \) Combined heat transfer coefficient from absorber to cover (\( \text{Wm}^{-2} \cdot \text{C}^{-1} \))  
\( h' \) Heat transfer coefficient of material of known conductivity (\( \text{Wm}^{-2} \cdot \text{C}^{-1} \))  
\( h_b \) Heat transfer coefficient for flow across panel wall (\( \text{Wm}^{-2} \cdot \text{C}^{-1} \))  
\( h_c \) Heat transfer coefficient for flow across the inside of the panel due to convection and conduction (\( \text{Wm}^{-2} \cdot \text{C}^{-1} \))  
\( h_p \) Heat transfer coefficient for flow across panel (\( \text{Wm}^{-2} \cdot \text{C}^{-1} \))  
\( h_r \) Heat transfer coefficient for flow across the inside of the panel due to radiation (\( \text{Wm}^{-2} \cdot \text{C}^{-1} \))  
\( h_s \) Heat transfer coefficient for flow across standard insulation (\( \text{Wm}^{-2} \cdot \text{C}^{-1} \))  
\( k \) Thermal conductivity (\( \text{Wm}^{-1} \cdot \text{C}^{-1} \))  
\( L \) Linear dimension (m)  
\( m \) Wall molecule mass (Kg)  
\( m' \) Gas molecule mass (Kg)  
\( M \) Mass of one mole (kg mol\(^{-1}\))  
\( N_A \) Avogadro's number  
\( Nu \) Nusselt number  
\( p \) Gas pressure (\( \text{Nm}^{-2} \))  
\( P_c \) Critical pressure when \( Ra_a = Ra_c \)  
\( Pr \) Prandtl number  
\( q \) Power dissipated in central heater (W)
Q Energy per unit time, rate of heat supply to main heater (W)
Qp Rate of heat supply to panel from main heater (W)
r Specific gas constant (R/M)
R Gas constant
Ra Rayleigh number
Rac Critical Rayleigh number, for Ra < Rac no convection, Nu = 1
Re Reynolds number
s Absorber plate to cover separation (m)
t Panel wall thickness (m)
T Average of plate and cover temperature (°C)
T1 Inside panel temperature nearest to cold plate (°C)
T2 Inside panel temperature nearest to main heater (°C)
Tg Guard ring temperature (°C)
Ti Temperature of main heater, also fluid inlet temperature (°C)
T0 Temperature of cold plates (°C)
α Thermal diffusivity (m² s⁻¹)
β Thermal volume expansion coefficient (= 1/T for a perfect gas), (K⁻¹)
γ \(\frac{c_p}{c_v}\)
Δθ Hot plate temperature unbalance (Tᵢ - Tₙ), (°C)
ΔT Temperature difference across panel (°C)
ε₁ Emissivity of surface at temperature T₁ (°C)
ε₂ Emissivity of surface at temperature T₂ (°C)
μ Viscosity (Pa s)
ν Kinematic viscosity (μ/ρ) (Pa s m³Kg⁻¹)
ρ Density (Kg m⁻³)
σ Stefan-Boltzmann constant (Wm⁻² K⁻⁴)
λ Mean free path (m)
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TABLE 2.1 Energy input by fuel and sector in Petajoules for U.K. low grade heat needs (\(\leq 80^\circ\text{C}\)) for 1976 and 2025 as predicted by Leach [1]

<table>
<thead>
<tr>
<th>Sector</th>
<th>Fuel</th>
<th>Total 1976</th>
<th>Total 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solid</td>
<td>Liquid</td>
<td>Gas</td>
</tr>
<tr>
<td>Industry Space and Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>1976</td>
<td>0.8</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Engineering and other metal</td>
<td>1976</td>
<td>17.2</td>
<td>71.4</td>
</tr>
<tr>
<td>trades</td>
<td>2025</td>
<td>32.8</td>
<td>14.1</td>
</tr>
<tr>
<td>Chemical &amp; Allied Trades</td>
<td>1976</td>
<td>0.8</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Food, Drink &amp; Tobacco</td>
<td>1976</td>
<td>3.2</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>7.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Textiles, Leather &amp; Clothing</td>
<td>1976</td>
<td>5.1</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>7.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Paper, Printing &amp; Stationary</td>
<td>1976</td>
<td>1.9</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Building Materials</td>
<td>1976</td>
<td>0.9</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Other trades</td>
<td>1976</td>
<td>7.8</td>
<td>61.2</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>19.5</td>
<td>14.2</td>
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</table>

Process

<table>
<thead>
<tr>
<th>Processes</th>
<th>Total 1976</th>
<th>Total 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural</td>
<td>1976 0.9</td>
<td>22.1</td>
</tr>
<tr>
<td>Heating &amp; Drying</td>
<td>2025 -</td>
<td>16.1</td>
</tr>
<tr>
<td>Domestic Space</td>
<td></td>
<td>995</td>
</tr>
<tr>
<td></td>
<td></td>
<td>320</td>
</tr>
<tr>
<td>Commercial Space</td>
<td></td>
<td>375</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2323</td>
<td>1430</td>
</tr>
<tr>
<td>Substance</td>
<td>Comments</td>
<td>Density $\rho$/Kg m$^{-3}$</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Chabazitic tuff</td>
<td>Common beolite in Italy</td>
<td>1.4</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Iron shot</td>
<td></td>
<td>7.86</td>
</tr>
<tr>
<td>Scrap Iron</td>
<td>Zero voids (at 30% void $\rho C_p$ = 2.8)</td>
<td>7.90</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td>7.9</td>
</tr>
<tr>
<td>Magnetite, Fe$_2$O$_3$</td>
<td>Zero voids (at 30% void $\rho C_p$ = 2.7)</td>
<td>5.16</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td></td>
<td>5.20</td>
</tr>
<tr>
<td>Wet earth</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>Water and salt (brine)</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>Scrap Aluminium</td>
<td>Zero voids (30% void $\rho C_p$ = 1.8)</td>
<td>2.74</td>
</tr>
<tr>
<td>Therminol 55 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td></td>
</tr>
<tr>
<td>Caloria HT43 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td></td>
</tr>
<tr>
<td>Oils</td>
<td>Cracking occurs at high temp.</td>
<td>1.0</td>
</tr>
<tr>
<td>MgCO$_3$·6H$_2$O</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>MgCO$_3$</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Concrete</td>
<td>Zero voids (30% void $\rho C_p$ = 1.7)</td>
<td>2.25</td>
</tr>
<tr>
<td>Stone</td>
<td>Zero voids (30% void $\rho C_p$ = 1.7)</td>
<td>2.74</td>
</tr>
<tr>
<td>Material</td>
<td>Density</td>
<td>Porosity</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.74</td>
<td>0.92</td>
</tr>
<tr>
<td>Marble</td>
<td>2.70</td>
<td>0.75</td>
</tr>
<tr>
<td>Granite</td>
<td>2.70</td>
<td>0.796</td>
</tr>
<tr>
<td>Sulphur Liquid</td>
<td>2.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Rock</td>
<td>2.5</td>
<td>0.84</td>
</tr>
<tr>
<td>Concrete Cost (1980)</td>
<td>2.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Brick</td>
<td>2.23</td>
<td>0.84</td>
</tr>
<tr>
<td>Paraffin Oil</td>
<td>0.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Olive Oil</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Silica (SiO₂)</td>
<td>2.7</td>
<td>0.84</td>
</tr>
<tr>
<td>Pebbles</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Basalt</td>
<td>3.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Sulphur</td>
<td>2.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.95</td>
<td>0.963</td>
</tr>
<tr>
<td>Mitec</td>
<td>Molten salt</td>
<td>1.55</td>
</tr>
<tr>
<td>Sodium (1980)</td>
<td>Molten salt</td>
<td>1.55</td>
</tr>
<tr>
<td>Dry earth</td>
<td>1.26</td>
<td>0.8</td>
</tr>
<tr>
<td>Store</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>--------------------------</td>
<td></td>
</tr>
<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 m$^3$</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>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>2,900 m$^2$</td>
</tr>
<tr>
<td>heat transfer factor ($F_R$)</td>
<td>0.9</td>
</tr>
<tr>
<td>overall heat loss coefficient</td>
<td>1.0 Wm$^{-2}$°C$^{-1}$</td>
</tr>
<tr>
<td>optical efficiency averaged over useful incident angles ($\tau_a$)</td>
<td>0.8</td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>100</td>
<td>Concrete sections</td>
</tr>
<tr>
<td>500</td>
<td>Insulation</td>
</tr>
<tr>
<td>1200</td>
<td>Glass fibre</td>
</tr>
<tr>
<td>155</td>
<td>Collector</td>
</tr>
<tr>
<td>2420</td>
<td>Foundation</td>
</tr>
<tr>
<td>69</td>
<td>Base</td>
</tr>
<tr>
<td>118</td>
<td>Preparation and site</td>
</tr>
</tbody>
</table>

This is the average value from several references. Refer to chapter 2 for 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>
<th></th>
<th>Prometheus</th>
<th>Gas</th>
<th>Electricity (Economy 7)</th>
</tr>
</thead>
<tbody>
<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/£ \text{ yr}^{-1} )</td>
<td>18</td>
<td>117</td>
<td>146</td>
</tr>
<tr>
<td>( R_h/£ \text{ yr}^{-1} )</td>
<td>11</td>
<td>24</td>
<td>0</td>
</tr>
</tbody>
</table>

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

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

\[
PVC_h \quad i=0 \quad f=0.02 \quad 7500 \quad 11700 \quad 12500
\]
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>
</thead>
<tbody>
<tr>
<td>Collector type</td>
<td>Flat plate</td>
<td>Evacuated</td>
<td>Concentrating</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>selective</td>
<td>tube</td>
<td>collector</td>
<td>performance</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>50-30</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>
</tbody>
</table>

[ ] Chapter 2 reference numbers
<table>
<thead>
<tr>
<th>Store temperature rise/(°C)</th>
<th>Cost/£1982 per Kwh recovered energy seasonal storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel tank</td>
<td>80</td>
</tr>
<tr>
<td>Pit storage</td>
<td>50</td>
</tr>
<tr>
<td>Rock cavern</td>
<td>70</td>
</tr>
<tr>
<td>Storage in clay</td>
<td>12</td>
</tr>
<tr>
<td>Multiple well systems in rock</td>
<td>50</td>
</tr>
<tr>
<td>Aquifers</td>
<td>15</td>
</tr>
<tr>
<td>Prometheus (pebble bed, using data from Table 2.6)</td>
<td>100</td>
</tr>
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</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>Lamboho, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>56</td>
<td>100</td>
<td></td>
<td>27 000</td>
</tr>
<tr>
<td>Inglestad, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td></td>
<td>19 320</td>
</tr>
<tr>
<td>Studsvik, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>400</td>
<td>93</td>
<td></td>
<td>5 150</td>
</tr>
<tr>
<td>Lyckebo, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>500</td>
<td>100</td>
<td></td>
<td>10 500</td>
</tr>
<tr>
<td>Arizona, USA</td>
<td>Design Study</td>
<td>Water</td>
<td>250</td>
<td>100</td>
<td></td>
<td>3 012</td>
</tr>
<tr>
<td>Northampton, USA</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>10 000</td>
<td>100</td>
<td></td>
<td>6 000</td>
</tr>
<tr>
<td>Sussex, UK</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>100</td>
<td>100</td>
<td></td>
<td>10 000</td>
</tr>
<tr>
<td>City University, London, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>100</td>
<td>78</td>
<td></td>
<td>4 000</td>
</tr>
<tr>
<td>ERR, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>300</td>
<td>100</td>
<td></td>
<td>2 416</td>
</tr>
<tr>
<td>PCL, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>50</td>
<td>100</td>
<td></td>
<td>5 480</td>
</tr>
</tbody>
</table>
### TABLE 3.1 Thermal Characteristics of Basic Type AO House

<table>
<thead>
<tr>
<th>Component</th>
<th>Variable</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></td>
<td>88.5</td>
<td>1.0</td>
<td>88.5</td>
</tr>
<tr>
<td>Roof</td>
<td></td>
<td>48.6</td>
<td>0.6</td>
<td>29.2</td>
</tr>
<tr>
<td>Floor</td>
<td></td>
<td>48.6</td>
<td>0.5</td>
<td>24.3</td>
</tr>
<tr>
<td>Window</td>
<td></td>
<td>15.0</td>
<td>5.5</td>
<td>82.5</td>
</tr>
<tr>
<td>Total fabric specific loss</td>
<td></td>
<td></td>
<td></td>
<td>224W°C⁻¹</td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td></td>
<td></td>
<td>80W°C⁻¹</td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td></td>
<td></td>
<td>304W°C⁻¹</td>
</tr>
</tbody>
</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</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°C⁻¹)</td>
<td>Net annual space and water heating demand (GJ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A0</td>
<td>Basic (1975 Building Regs.)</td>
<td>304</td>
<td>46.4</td>
<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 (Wm⁻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>192 W°C⁻¹</td>
<td></td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td>68 W°C⁻¹</td>
<td></td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td>260 W°C⁻¹</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3.5 Thermal Characteristics of existing houses with different levels of retrofitted insulation.

<table>
<thead>
<tr>
<th>House type</th>
<th>Insulation level</th>
<th>Total house specific loss ($W^0C^{-1}$)</th>
<th>Net annual space water heating demand (GJ)</th>
</tr>
</thead>
<tbody>
<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>
<tr>
<td>Date</td>
<td>Activity</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>Conference</td>
<td>The conference started with a keynote speech and featured several workshops.</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>Workshop</td>
<td>Participants engaged in hands-on activities and discussions.</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>Presentation</td>
<td>A presentation was given on the latest research findings in the field.</td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td>Panel</td>
<td>A panel discussion on emerging trends and future directions was held.</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.1** Art collector, test faciliities and installed systems in the United Kingdom.
### Table 5.2(a) Results of steady state testing on D.C. Hall collector

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date</th>
<th>Time of test</th>
<th>Air mass flow rate</th>
<th>Air temp. at inlet</th>
<th>Air temp. at outlet</th>
<th>Air temp. increase ($T_e - T_i$)</th>
<th>Ambient Temp.</th>
<th>Total irradiance in plate of collector ($I_m$)</th>
<th>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>
</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>
</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>
</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>
</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>
</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>
</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>
</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>
</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>
</tr>
<tr>
<td>Day/Month/Year</td>
<td>Hrs</td>
<td>Lmin</td>
<td>Outlet Temp</td>
<td>Ambient Temp</td>
<td>Increase</td>
<td>Total Energetic Efficiency</td>
<td>Collector Eff.</td>
<td>Wind</td>
<td>Absorber Temp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-----</td>
<td>------</td>
<td>-------------</td>
<td>--------------</td>
<td>----------</td>
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<td>--------------</td>
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<td>---------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>19/6/83</td>
<td>122-130</td>
<td>83.5</td>
<td>26.8</td>
<td>44.6</td>
<td>17.8</td>
<td>25.8</td>
<td>8.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>19/6/83</td>
<td>19/6/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>15/06/83</td>
<td>122-130</td>
<td>83.5</td>
<td>26.8</td>
<td>44.6</td>
<td>17.8</td>
<td>25.8</td>
<td>8.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
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</tr>
<tr>
<td>9</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>16/6/83</td>
<td>15/06/83</td>
<td>145-139</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
<td>101.0</td>
<td>21.4</td>
<td>8.14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Table 5.2(b) shows the results of steady state testing of structured polycarbonate collector.

Date: Test Date
Time of Air Mass Flow Area at Initial
Air Temp.: Ambient Temp.
Air Temp. Increase: Temp. in Plate of Collector
Efficiency: Eff. in Plate of Collector
Collector Eff.: Efficiency of Collector
Wind Absorber Temp.: Temperature of Absorber
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 absorbance</td>
<td>0.95 at θ = 0 falling slightly as θ increases</td>
</tr>
<tr>
<td>Emissivity of upper surface of the plate (diffuse)</td>
<td>0.10</td>
</tr>
<tr>
<td>Emissivity of duct surface (diffuse)</td>
<td>0.91</td>
</tr>
<tr>
<td>Emissivity of cover (diffuse)</td>
<td>0.85</td>
</tr>
<tr>
<td>Cover polycarbonate thickness</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>0.06 kg s⁻¹</td>
</tr>
<tr>
<td>Thickness of plate and of duct-back</td>
<td></td>
</tr>
<tr>
<td>DY1</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>DY2</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>DY3</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>DY4</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>DY5</td>
<td>5.0 mm</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>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>τ_C/(min)</td>
<td>-</td>
<td>2.8</td>
<td>9.7</td>
</tr>
<tr>
<td>( F_{R'U_L} / (\text{Wm}^{-2} \text{K}^{-1}) )</td>
<td>2.83*</td>
<td>2.768</td>
<td>2.604</td>
</tr>
<tr>
<td>( F_{R'Ta} )</td>
<td>0.683</td>
<td>0.585</td>
<td>0.569</td>
</tr>
<tr>
<td>( K_{FRTa} )</td>
<td>0.683</td>
<td>0.706</td>
<td>0.686</td>
</tr>
<tr>
<td>( \hat{o} F_{R'U_L} )</td>
<td>-</td>
<td>0.012</td>
<td>0.036</td>
</tr>
<tr>
<td>( \hat{o} F_{R'Ta} )</td>
<td>0.0008</td>
<td>0.0025</td>
<td></td>
</tr>
</tbody>
</table>

\( K = \text{correction factor for equivalent normal direct radiation} = \frac{(\tau_0)_{\text{direct}}}{(\tau_0)_{\text{diffuse}}} = \frac{0.830}{0.688} = 1.206 \)

* = at low fluid inlet temperatures
<table>
<thead>
<tr>
<th>n</th>
<th>F_R[10^x], k_n</th>
<th>cF_R[10^x], k_n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.437808115123</td>
<td>0.17945235996</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>n</th>
<th>F_R[10^x], k_n</th>
<th>cF_R[10^x], k_n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.437808115123</td>
<td>0.17945235996</td>
</tr>
</tbody>
</table>

**F** = 0.513943004957  
**U** = 7.8966850935

**DATA SETS ACCEPTED FOR ANALYSIS 80**

**n/P** = 0.34370021325  
**T** = 0.023

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<th>T*</th>
<th><strong>n</strong>/P*</th>
</tr>
</thead>
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<td></td>
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<tr>
<td>0.43936890309</td>
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**POINTS ON THERMAL PERFORMANCE CHARACTERISTIC 80**

**FROM LEAST SQUARES FITS EACH WAY**

**MINIMUM ETA0** = 0.325431187816  
**MAXIMUM ETA0** = 0.714184616622

**U** = 7.33893217894  
**U** = 13.9416808148
### Table 5.8

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

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\overline{T_p}/k$</th>
<th>$\overline{T_b}/k$</th>
<th>$T_m/k$</th>
<th>$F_{RUL}$ (Wm$^{-2}$ C$^{-1}$)</th>
<th>$\eta$</th>
<th>$F_{ave UL}$ (Wm$^{-2}$ C$^{-1}$)</th>
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<td>303</td>
<td>332.73</td>
<td>333.01</td>
<td>322.1</td>
<td>317.86</td>
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<td>.645</td>
<td>3.111</td>
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<td>364.98</td>
<td>365.28</td>
<td>357.16</td>
<td>354.00</td>
<td>2.902</td>
<td>.476</td>
<td>3.230</td>
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<tr>
<td>383</td>
<td>396.47</td>
<td>396.94</td>
<td>391.47</td>
<td>389.73</td>
<td>3.044</td>
<td>.293</td>
<td>3.362</td>
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<tr>
<td>423</td>
<td>427.23</td>
<td>428.06</td>
<td>425.00</td>
<td>425.11</td>
<td>3.185</td>
<td>.095</td>
<td>3.503</td>
</tr>
<tr>
<td>433</td>
<td>435.13</td>
<td>435.94</td>
<td>433.57</td>
<td>434.06</td>
<td>3.226</td>
<td>.037</td>
<td>3.564</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, $T_a = 293k$, $T_{wind} = 1m s^{-1}$, $T_{sky} = 273k$

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\overline{T_p}/k$</th>
<th>$\overline{T_b}/k$</th>
<th>$T_m/k$</th>
<th>Energy lost per unit time per unit area (W m$^{-2}$)</th>
<th>$F_{RUL}$ (Wm$^{-2}$ C$^{-1}$)</th>
<th>$F_{ave UL}$ (Wm$^{-2}$ C$^{-1}$)</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td>343</td>
<td>333.32</td>
<td>333.79</td>
<td>336.20</td>
<td>338.16</td>
<td>146.66</td>
<td>2.932</td>
<td>3.247</td>
</tr>
<tr>
<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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<tr>
<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>3.439</td>
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<td>*303</td>
<td>301.62</td>
<td>301.71</td>
<td>302.03</td>
<td>302.31</td>
<td>20.98</td>
<td>2.098</td>
<td>2.035</td>
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<tr>
<td>*433</td>
<td>405.92</td>
<td>407.78</td>
<td>413.13</td>
<td>419.46</td>
<td>410.30</td>
<td>2.93</td>
<td>3.245</td>
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</table>

* $T_{sky} = 293k$
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<tr>
<th></th>
<th>7.11</th>
<th>7.17</th>
<th>7.31</th>
<th>7.37</th>
<th>7.48</th>
<th>7.77</th>
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</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>28</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>q (W/m²)</td>
<td>0.541</td>
<td>0.457</td>
<td>0.557</td>
<td>0.520</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind (°C)</td>
<td>10</td>
<td>6</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Test method</td>
<td>P  U</td>
<td>P  U</td>
<td>P  U</td>
<td>P  U</td>
<td>P  U</td>
<td>P  U</td>
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</tbody>
</table>

### Summary of Collector Testing Results

**Table 5.10**
<table>
<thead>
<tr>
<th>Material</th>
<th>Reflective index (n)</th>
<th>Solar Transmittance (0.2-4.0 μm) %</th>
<th>Infrared Transmittance (3.0-500 μm) %</th>
<th>Expansion Coefficient (°C⁻¹)</th>
<th>Temperature Limits (°C)</th>
<th>Weather-ability (comments)</th>
<th>Chemical Resistance (comments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lexan (Polycarbonate)</td>
<td>1.586</td>
<td>125 mil</td>
<td>125 mil</td>
<td>7.98 x 10⁻⁵</td>
<td>120-130</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Plexiglass (Acrylic)</td>
<td>1.49</td>
<td>125 mil</td>
<td>125 mil</td>
<td>8.29 x 10⁻⁵</td>
<td>80-90</td>
<td>Average</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>
</tr>
<tr>
<td>Tedlar P.V.F. (fluorocarbon)</td>
<td>1.46</td>
<td>4 mil</td>
<td>4 mil</td>
<td>5.95 x 10⁻⁵</td>
<td>110-170</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mylar (Polyester)</td>
<td>1.64-1.67</td>
<td>5 mil</td>
<td>5 mil</td>
<td>2.00 x 10⁻⁵</td>
<td>150-200</td>
<td>Poor</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunlite (Fibre glass)</td>
<td>1.54</td>
<td>25 mil</td>
<td>25 mil</td>
<td>2.98 x 10⁻⁵</td>
<td>95-100</td>
<td>Fair to good</td>
<td>Good</td>
</tr>
<tr>
<td>Float glass (Glass)</td>
<td>1.518</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.21 x 10⁻⁶</td>
<td>230</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Temper glass (Glass)</td>
<td>1.518</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.21 x 10⁻⁶</td>
<td>230-250</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear limesheet glass (Low iron glass)</td>
<td>1.51</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.64 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear lime temper glass (Low iron glass)</td>
<td>1.51</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.64 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunlite white crystal glass (0.01% iron glass)</td>
<td>1.50</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.00 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
</tbody>
</table>

Source: Gary, H.P. 'Treatise on solar energy' Vol.1, A Wiley Interscience Publication, Chichester, 1982
<table>
<thead>
<tr>
<th>Selective paint</th>
<th>Most/least reflective coating</th>
<th>Supporting coating/surface</th>
<th>Reflective coating/surface</th>
<th>Supporting coating/surface</th>
<th>Reflective coating/surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>0.30</td>
<td>0.93</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
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<td>0.07</td>
<td>0.07</td>
<td>0.15</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
</tr>
<tr>
<td>0.06</td>
<td>0.06</td>
<td>0.23</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>0.35</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
</tr>
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<td>0.04</td>
<td>0.04</td>
<td>0.45</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
</tr>
<tr>
<td>0.03</td>
<td>0.03</td>
<td>0.55</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
</tr>
<tr>
<td>0.02</td>
<td>0.02</td>
<td>0.65</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
</tr>
<tr>
<td>0.01</td>
<td>0.01</td>
<td>0.75</td>
<td>Supporting coating/surface</td>
<td>Reflective coating/surface</td>
<td>Supporting coating/surface</td>
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**Source:** Heat 14, Cardiff University
### TABLE 6.3 Key to collector variable features, used to obtain Figure 6.19

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

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

<table>
<thead>
<tr>
<th>Air Flow in the Rear-duct:</th>
<th>Stagnation ((M = 0))</th>
<th>All TI</th>
<th>M = 0.0600 kg s(^{-1})</th>
<th>PON irrelevant</th>
<th>(\text{PON} = 128W)</th>
<th>(\text{PON} = 124W)</th>
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</thead>
<tbody>
<tr>
<td>Flow 0</td>
<td></td>
<td>TI = 303 K</td>
<td>M = 0.0600 kg s(^{-1})</td>
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<td></td>
</tr>
<tr>
<td>Flow 1</td>
<td></td>
<td>TI = 323 K</td>
<td>M = 0.0562 kg s(^{-1})</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Flow 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>
### TABLE 7.1 Some typical thermal accommodation coefficients

<table>
<thead>
<tr>
<th>Gas</th>
<th>Surface</th>
<th>Surface condition (absorbed gas)</th>
<th>Temp. (°C)</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Bronze</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.88 - 0.95</td>
</tr>
<tr>
<td></td>
<td>Cast Iron</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.87 - 0.96</td>
</tr>
<tr>
<td></td>
<td>Aluminium</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.87 - 0.97</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>Indeterminate</td>
<td>32</td>
<td>0.624</td>
</tr>
<tr>
<td></td>
<td>Pt</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>Indeterminate</td>
<td>-170</td>
<td>0.38</td>
</tr>
<tr>
<td>N₂</td>
<td>Pt. Bright</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Pt. Black</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Pt Saturated</td>
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<td>0.74</td>
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<tr>
<td></td>
<td>W</td>
<td>CO₂</td>
<td>32</td>
<td>0.990</td>
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<td></td>
<td>Pt</td>
<td>CO₂</td>
<td>30</td>
<td>0.76</td>
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<td>Pt. Bright</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.32</td>
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<td>Pt. Black</td>
<td>Indeterminate</td>
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<td>0.74</td>
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<td></td>
<td>W, flashed</td>
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<td>W, not flashed</td>
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<td>-30</td>
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<td>W Clean</td>
<td></td>
<td>-190</td>
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<tr>
<td></td>
<td>W K on H₂</td>
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<td>0.22</td>
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<th>$Q/(\text{Wm}^{-2})$</th>
<th>$T_f/°C$</th>
<th>$h_f/(\text{Wm}^{-2}°C^{-1})$</th>
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<td>0.547</td>
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<td>13.57</td>
<td>48.83</td>
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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. ST. KURIAN 1979, ENERGY CONSUMPTION 'EUROPEAN YEARBOOK 1983'.
FIGURE 1.1(b) HISTOGRAM OF ENERGY CONSUMPTION PER CAPITA FOR DIFFERENT PHYSICAL QUALITY OF LIFE INDEX (PQLI) FOR THE PEOPLE OF THE WORLD. THE PERCENTAGES SHOWN IN EACH BAR ARE THE PERCENTAGES WITHIN THAT RANGE OF PQLI.
FIGURE 2.1 UK LOW GRADE HEAT, FUEL CONSUMPTION AND END USE.

FIGURE 2.2 DOMESTIC SPACE AND HOT WATER DEMAND.
**Figure 2.3**
DISTRIBUTION OF ANNUAL GAS CONSUMPTION FOR 90 SIMILAR HOUSES IN MILTON KEYNES, FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS', PICKUP, G.A.C.7]

**Figure 2.4**
WEEKLY CONSUMPTION OF HOT WATER FOR ONE HOUSEHOLD, FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS', PICKUP, G.A.C.7]
Total No of dwellings: 87
Overall mean weekly consumption: 0.841 m³/week
Standard deviation: 0.351 m³/week

Contribution due to
OAPs flats
(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 [9]

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SOLAR m=0
SOLAR m=2
BLACKBODY AT 40°C

**FIGURE 2.6** SOLAR AND THERMAL RADIATION SPECTRAL DISTRIBUTIONS. AIR MASS m=0 IS FOR EXTRA-TERRESTRIAL RADIATION, m=2 IS A TYPICAL CITY DISTRIBUTION.
**Figure 2.7**
Annual variation of mean daily totals of direct and diffuse insolation on a horizontal surface.

**Figure 2.8**
Average global solar radiation on a horizontal surface.
FIGURE 2.9  DEMONSTRATION PROJECT IN STUDSVIK. [26]


**Figure 2.11** Seasonal Heat Storage and a Central Short Term Storage Reservoir (CST) Constructed for TNO Delft [35]

One-Family Houses (Small Scale)

- With heat storage in preferably soft ground or clay solid rock

Apartment Building (Intense Populated Areas) (Large Scale)

- With heat storage in
  - Preferably solid rock
  - Most types of ground

**Figure 2.12** Different Applications for 'Sunstore' [37], Seasonal Storage in the Ground
FIGURE 2.13 PLAN OF PROMETHEUS RETROFITTED TO SUPPLY 83 HOUSES WITH ALL THEIR SPACE HEATING AND HOT WATER.

FIGURE 2.14 COLLECTOR MOUNTED ON TOP OF STORE, PART OF PROMETHEUS DESIGN.
PROTOTYPE OF A PROMETHEUS TYPE SOLAR AIR-COLLECTOR/HEAT STORE, INSTALLED AT THE OPEN UNIVERSITY, MILTON KEYNES, UK.

FIGURE 2.15 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.
**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 ventilation (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 A0 house

Figure 3.2  Net space heating demand for Type A0, A5 and A11 3 bedroom end of terrace house.
**Figure 3.3**

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

**Figure 3.4**

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

**Figure 3.6** Comparison of predicted solar energy supply for a house using the F-chart method with the measured solar supply for the Milton Keynes solar house.
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. \( \dot{q} \)

**McARDLES**

\[ \dot{q} = 5.7 + 3.5V \]

**WATMUFF**

\[ \dot{q} = 2.8 + 3.0V \]

**LLOYD**

\[ \dot{q} = 0.15 \cdot \frac{R_{th}^{1/6} \cdot T_r}{L+W} \] for \( T_r = 10^\circ C, T_s = 15^\circ C, L = 1m, W = 1m \).

**SPARROW**

\[ \dot{q} = \frac{k \cdot 2 \cdot 8 \cdot 8 \cdot R_{th}^{1/6} \cdot T_r}{L+W} \] for \( T_r = 10^\circ C, T_s = 15^\circ C, L = 1m, W = 1m \).

**GREEN**

\[ \dot{q} = \left( h_0 + h_s \frac{L}{W} \right)^{1/2} \] for \( A = 1.4m^2, 45^\circ \) inclination.

**KIND**

\[ \dot{q} = \frac{W \cdot h_0^{1/2} \cdot L}{W + h_s} \] for collector length 2.4m, width 1.2m, height 4.5m, \( T_r = 25^\circ C \).

**FIGURE 4.7 CORRELATIONS FOR WIND HEAT LOSS COEFFICIENT**
ENVIRONMENTAL PARAMETERS

COLLECTOR CONFIGURATION

COLLECTOR VARIABLES

INITIAL ESTIMATE OF

CALCULATE $R_e$ (equivalent) FROM EQUATION 4.25

$N_u$ 4.23
$h_1 ... 4.22
$h_1$ 4.27
$U_b$ 4.4

$V_e$
$U_L$ 4.3
$F'$ 4.20
$F_R$ 4.19
$Q_1$ 4.18

$\eta = \frac{Q_u}{A_1}$

CALCULATE NEW ABSORBER TEMPERATURE

$T_{new} = T_i + \left[ \frac{Q_u}{A_1} (1 - F_R) \right]$

AND NEW FLUID TEMPERATURE

$T_{new} = T_i + \left[ \frac{Q_u}{A_1} (1 - F_R / F) \right]$ $U_L / F_R$

CALCULATE AVERAGE TEMPERATURE BETWEEN COVER AND ABSORBER

CALCULATE $\overline{B}$ AND $\overline{F}$ FOR GAP BETWEEN COVER AND ABSORBER

$T_{ave}$ SEE CHAPTER 7

$hr_{ic}$ Eqn 4.7
$hr_{ia}$ 4.8
$hr_{oa}$ 4.13
$U_e$ 4.6

CALCULATE NEW COVER TEMPERATURE

$T_{cover} = \frac{T_e - U_e (T_p - T_e)}{h_v + h_c}$

FIGURE 4.8 FLOW DIAGRAM OF 'EFFIC2' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A FRESH DUCT AIR HEATING COLLECTOR
FLOW DIAGRAM OF 'EFFIC' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A TYPICAL HEATING COLLECTOR

INPUT
ENVIRONMENTAL PARAMETERS
I, V, T_a

COLLECTOR CONFIGURATION
(PD) e_1, e_2, k, H, A, L, W, D
U_e, x

COLLECTOR VARIABLES
T_c, m

INITIAL ESTIMATE OF
T_f, T_m

CALCULATE
R_c, L.E. EQUATION 4.25
N_h 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_f 4.20
F_r 4.19
Q_u 4.18

\( \eta = \frac{Q_u}{A I} \)

CALCULATE NEW ABSORBER TEMPERATURE
\( T_f = T_c + (Q_u/AI)(1-F_r) \)

IS
\( [T_{f_{end}} - T_f] > 0.01 \)

NO
\( T_f = T_{f_{end}} \)

YES

OUTPUT
z, T_f, U_e, U_L, U_e, F_r, F_f, Q_u

FIGURE 4.9
FIGURE 4.10 RESPONSE OF ZERO AND LONG TIME CONSTANT COLLECTOR TO CHANGING INSULATION
**Figure 4.11** Nodal configuration of a flat plate, rear-duct air heating, solar collector as 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 WEL 1966-1975)
SECTION X-X

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.'
PRESSURE TAP (2.0mm D)
COPPER TUBE (52.4mm D)

ORIFICE PLATE

Corner sharp to within a radius of 0.015 mm
100 (±0.05) mm
3.5 to 4.0° uniform to within 10°

Flat to ±0.05 mm
Smoth to ±0.01 mm
to within 0.5° parallel to upper face.

70 ± 0.1 mm dia.

**Figure 5.8** ORIFICE PLATE AND ITS LOCATION FOR MEASURING MASS FLOW RATE
**Figure 5.9** ASHRAE Standard 93-77 testing configuration for a solar collector when the transfer fluid is air.

**Figure 5.10** Open University air collector testing configuration.
Figure 5.11: Response of structured polycarbonate collector to a step change in insulation from 750 W/m² to zero with a fluid flow rate of 72 kg/h⁻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 peri-flow orifice plate for air at 20°C.
FIGURE 5.20 PRESSURE DISTRIBUTION WITHIN COLLECTOR TEST CONFIGURATION WITH AND WITHOUT FLUID FLOW

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

**Figure 5.23** Steady State Efficiency Curve for Structured Polycarbonate Collector Tested Outdoors
FIGURE 5.24  UNCORRECTED EFFICIENCY CURVE WITH VARIATION OF WIND SPEED BETWEEN 0-4 m/s. SOURCE: [25].

FIGURE 5.25  EFFICIENCY CURVE CORRECTED FOR VARIATION IN WIND SPEED USING A NORMALIZING FUNCTION. SOURCE: [25].
FIGURE 5.26 VARIATION OF MASS FLOW RATE CAUSED BY CHANGE IN WIND SPEED
FIGURE 5.27 ROUND ROBIN TESTING OF LIQUID FLAT PLATE COLLECTORS. THE COMBINED EFFECT OF METEOROLOGICAL EXTREMES AND MEASUREMENT UNCERTAINTY. SOURCE: TAYLOR [28]

FIGURE 5.28 MEASURED DEPENDENCY OF $F(CO_2)$ ON THE DIFFUSE FRACTION FOR A SINGLE-GLAZED FLAT-PLATE COLLECTOR. SOURCE: FOROSKI [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 $F_{el}$, $F_{el}(0,t)$, and $\Delta F_{el}$ 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 INSULATION 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.U. VALUES IN 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 (Manohar, 1982). 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, Transmittance of Polycarbonate and Reflectance of Maxglo.
**Figure 5.44**  
Intensity distribution across collector during indoor testing in W/m², average intensity 2.11 W/m², standard deviation ± 0.4 W/m².

**Figure 5.45**  
Wing generator.
**Figure 5.46** Variation of wind speed (m.s\(^{-1}\)) 5 mm above collector surface

Measured heat loss with collector operating under stagnation and assuming \((\rho c_k) = 0.32\) plotted against average air velocity parallel to collector plane and measured 5 mm above collector plane.

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

FIGURE 5.49  EFFICIENCY CURVE OF D.C. HALL COLLECTOR WITH NON-SELECTIVE ABSORBER (NEKTOL). 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  Steady State and Efficiency Curve Plotted Against Mean Absorber Plate Temperature ($T_p$) for Simulated Collector.
FIGURE 5.53  STEADY STATE AND ZERO TESTING EFFICIENCY CURVE PLOTTED AGAINST MEAN FLUID TEMPERATURE ($T_m$) FOR SIMULATED COLLECTOR.
Figure 5.54: Collector temperature profile for model collector under steady state and zero testing conditions for the same fluid inlet temperature (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** $F_{wL}$ versus mean fluid temperature for collector by 1 under zero testing and abusive steady state testing.
FIGURE 5.58 EFFICIENCY CURVES FOR D.C. HALL COLLECTOR USING DIFFERENT TEST METHODS
Figure 5.51 Efficiency curve for structured polycarbonate collector under different test conditions.

Figure 5.60 Top loss coefficient versus absorber temperature for P&O Sham type collector (Maxorb absorber).
Figure 5.6  Steady state efficiency of solar collector (black chrome) measured during operation and indoor testing. Source: Taylor, P.J. 'Performance of selecting and non-selective solar thermal absorbers in a working installation,' Solar World Congress ed by S.v. Szondy, 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 (April-November).
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. I. STRONG, VOL 2, PP 1149-1153.
Figure 6.8  Efficiency curves for different methods of heat loss reduction.

**Figure 6.10** Efficiency curve of advanced flat plate collector with xenon between the absorber and cover at a pressure of 1 torr.

**Figure 6.11** Efficiency versus mass flow rate for structured polycarbonate collector. $I_{in} = 211\, W/m^2$, $T_a = 28^\circ C$, $T_{in} > T_a$, $I_c = T_a$ 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 compound 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 45° south facing slope.
FIGURE 6.16
ANNUAL ENERGY COLLECTED VERSUS COLLECTOR TEMPERATURE, COMPARISON OF FIVE TYPES OF COLLECTOR. SOURCE [33].

FIGURE 6.17
INTEGRATED GLOBAL AND DIFFUSE SOLAR RADIATION FROM MARCH TO OCTOBER AS A FUNCTION OF THE GLOBAL INTENSITY. SOURCE [35] FOR SWEDEN.
Figure 6. Simulated ambient conditions. For further details see text in Appendix C.

Wind = 1.0 m s⁻¹

TK = TA - 20, clear skies

TK = TA - 10, overcast skies
Figure 6.14  Steady-state efficiency ($\eta$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\bar{\eta}$ are for a variety of simulated conditions (see Table 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) SÜD/TAD1, flow 2  
(viii) SÜD/TAD2, flow 3  
(ix) SÜD/TAD1, flow 2  
(x) SÜD3/TAD1, flow 3  
(xi) SÜD/TAD1, flow 2.
**Figure 6.20** 'FMC' air heating solar collector developed by G.E. [42]

**Figure 6.21** Incident angle modifier for the FMC 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 CONDUCTION.
**Figure 7.2**

Plot of $h_c$ versus plate separation $s$ for $T_{air} = 150^\circ C$, $T_{wall} = 325^\circ C$ with various plate inclinations.

**Figure 7.8**

$h_c$ versus tilt angle to the horizontal for air and $T_{wall}$ for various absorber temperatures ($T_a$) with cover temp $= 10^\circ C$. 
Figure 7.9
HEAT TRANSFER COEFFICIENT VARIATION WITH ABSORBER TEMPERATURE
FOR CONVECTION AND RADIATION.
Figure 7.10  True and predicted heat loss between two parallel plates 5 x 5 cm
Cover temperature 10 °C
**Figure 7.11** Effective Rayleigh number versus molecular weight for different gases, at atmospheric pressure between two parallel plates, separation 5 mm, cold plate temperature 10°C, hot plate 30°C.
FIGURE 7.12  Heat transfer coefficient for gases of different molecular weight. For $S = 5 \text{ cm}$, cold plate temperature $10^\circ \text{C}$, hot plate temperature $30^\circ \text{C}$. 
FIGURE 7.13  COST VS HEAT TRANSFER COEFFICIENT FOR DIFFERENT GASES.

$S = 5 \text{ cm}$, 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, \( s = 5 \text{ cm}, T = 293 \text{ K}, T_2 = 823 \text{ K} \) FOR CURVE 1, 273 K FOR CURVE 2 AND 473 K 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: NOHOTRA, A AND GARG, H.P.
1 "MINIMIZING CONVECTIVE HEAT LOSS". SOLAR ENERGY VOL.25, NO.6, P523.

**FIGURE 7.17** REFLECTED SOLAR RAYS FOR A MULTI COVER SOLAR COLLECTOR.
FIGURE 7.19  HEAT TRANSFER COEFFICIENT $h_c$ DUE TO NATURAL CONVECTION FOR AIR AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL FLAT PLATES SPACING $5\text{ cm}$, $T_i = 283.0^\circ\text{K}$, WITH A HONEYCOMB AND 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 $s = 5.0$ cm, cold plate temperature $T_c = 10^\circ C$. 
Figure 7.22  Heat transfer coefficients for several collector configurations

$s = 5$ cm, $T_e = 10^4$
Figure 7.23  Guard Ring Heater

Figure 7.24  Guard Ring Unbalance versus Measured Heat Transfer across a 5cm Thick Styrofoam EP 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, $s = 5\text{ in}$, various temperature difference.
FIGURE 7.29 THEORETICAL AND MEASURED HEAT TRANSFER $h_c$ FOR AIR AND ARGON
Figure 7.30 Theoretical heat transfer across structured polycarbonate of various thicknesses, both radiation and convection, assuming flat convection and a measured emissivity of 0.72.
PLATE 2.1  PROTO PROMETHEUS - 1. COLLECTOR  2. STORE TOP INSULATION
AND COLLECTOR Rear INSULATION  3. FAN MOTOR  4. MONITORING
EQUIPMENT  6. SPACE FOR INSULATION
PLATE 2.2  PROTO PROMETHEUS STORAGE TANK FILLED WITH PEBBLES.
PLATE 5.1

SOLAR SIMULATOR TESTING A STRUCTURED POLYCARBONATE COLLECTOR.
17, STRUCTURED POLYCARBONATE COLLECTOR, 16, WIND GENERATOR.
19, COOL RAY LAMPS.
PLATE 5.2  INDOOR COLLECTOR TEST FACILITY.
7. DATA LOGGER, 8. STRUCTURED POLYCARBONATE COLLECTOR,
9. PRESSURE TAPS, 10. SITE OF ORIFICE PLATE.
PLATE 7.1  VIEW OF HEATED OIL FILM FROM AN INFRARED CAMERA. THE BROUGHT THE SPOT THE HOTTER THE SPOT.
PLATE 7.2
GUARDED HOT PLATE THERMAL CONDUCTIVITY RIG
11. INSULATED GUARD RING AND TEST CELL, 12. GAS CYLINDER
13. WATER COOLER, 14. HEATER POWER SUPPLY
APPENDIX A

SUNSTORE: Computer model of interseasonal store and sample output.
10 REM **************************** SUNSTORE *****************************
20 REM
30 SHORT DEMAND(12)
40 SHORT SOL(12,24)
50 ASSIGN 1 TO "SUN DATA"
60 READ 1, SOL
70 SHORT TEM(12,24)
80 ASSIGN 2 TO "TEM DATA"
90 READ 2, TEM
100 DIM MONTHS(12)(3)
110 ASSIGN 3 TO "MONTH"
120 READ 3, MONTHS
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  "00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000}
1100 PRINT "Tso= Original Store Temp. at the beginning of month (C)"
1110 PRINT "Ta = Ambient Temp. Averaged over periods of collector operation (C)"
1120 PRINT "It = Time Period of Collector Operation (Ms)"
1130 PRINT "It = Total Radiation which is above Threshold (Mj/m2)"
1140 PRINT "qn = Normalized Net Heat to Storage =qt-1-Im/s (Mj/m2)"
1150 PRINT "T = Useful Heat Collected- qn*Im (Mj/m2)"
1160 PRINT "Im = Normalized Total Monthly Load (Mj/m2)"
1180 PRINT "It = Normalized Total Monthly Storage Tank Losses (Mj/m2)"
1200 PRINT ""
1) ITH = Threshold Level (Collector will only operate above this minimum)
2) Tso = Original Store Temperature at the beginning of month
3) Ta = Ambient Temperature
4) tP = Time Period of Collector Operation (Ms)
5) It = Total Irradiation which is above Threshold (MJ/m2)
6) qN = Normalized Net Heat to Storage = qT-1m-1s (MJ/m2)
7) tS = Store Temperature at the end of the month (°C)
8) qT = Useful Heat Collected = qN×tP (MJ/m2)
9) lS = Normalized Total Monthly Load (MJ/m2)
10) lM = Normalized Total Monthly Storage Tank Losses (MJ/m2)
11) qAUX = Auxiliary Heat - is + (MJ/m2)

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% of energy supplied by solar system = 69.0%
% of solar energy collected above threshold = 42.0%
% of solar energy collected = 41.5%

Total auxiliary energy for system = 129360.7849 MJ (~35943.551803 KWh)

Solar energy demand of house per annum = 41.69 GJ (11580.555556 KWh)
APPENDIX B

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.
PROGRAM TOPAIR

20 REM erner: Calculate the top loss coefficient for a single glass tank.
30 LEO
40 For i=0 To 20
50 T0=10+185! 33.13
60 T1=10! Ambient temp (C)
70 WIND=1! Wind speed (ms-1)
80 FOR j=0 To 99
90 E=0.95! Absorber emissivity
100 ECD=B! Cover plate emissivity
110 S=5! Plate separation (cm)
120 G=9.812! Acceleration due to gravity (ms-2) at LONDON
130 K=0.257! Thermal conductivity of gas at Tave (W=m-K)
140 B=0! Tilt angle (Horizontal)
150 CP=1007! Heat capacity of air (J/KgK)
155 CP=1007! Heat capacity of gas between cover and absorber(K)
160 S=5/100! Convert to meters
170 L=1
180 W=2+W/1
200 REM

210 TC=TA+(TP-TA)/2! Guess the cover temp
220 T1=273.15+TC! Convert to Kelvin
230 TA=273.15+TA! Convert to Kelvin
240 TC=273.15+TC! Convert to Kelvin
250 TP=273.15+TC! Convert to Kelvin
260 T2=TP! Convert to Kelvin
270 DT=2-T1! Temp difference Delta T
280 Tave=(T1+DT/2! Average gas temperature
290 DEN=352.91/Tave
300 k=Tave-.000076+.003446
310 VIS=Tave+(.00000466+.00004635)
320 VOL=1/Tave! Thermal volume expansion coefficient only holds for perfect gas
330 VIS=DEN! Kinematic viscosity
340 Gr=G*VOL*(3*DT/21)*GRASHOF NUMBER
350 Pr=CPV/S
360 Ra=Gr*Pr! Rayleigh No
370 REM ! Calculate Nusselt number
380 Ni=1-1708/(Gr*Cos(B))/5830*(1/13-1)
390 IF Ni<0 THEN Ni=0! Take only positive terms
400 N2=(N1*180)/5830! Nusselt No
410 IF Ni<0 THEN Ni=0! Take only positive terms
420 N1=1.4487*(1-BIN(1.881)*1.6*1708/(Gr*Cos(B)))+N2! Nusselt No
430 h=N2! Heat transfer coefficient
440 h=r*(.0000000567*(Tp+2+Tc)*2)*/(Tp+Tc)/(1/EP+1/EC-1)! Rad from plate to cover
450 M=9.0000000567*Ec(Tc+2+Ta)*2*Tc+Ta)! Rad cover to sky
470 DTW=TC-TA
480 Tave=W/1+Tave
490 DEN=352.91/Tave
500 W=2+W/1
510 VIS=DEN+(.00000466+.00004635)
REM             EFFIC
REM              THIS PROGRAM CALCULATES THE STEADY STATE EFFICIENCY OF A TOP DUCT
REM AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
REM p237 Figure 6.1.2. (d)
REM INPUT VARIABLE DATA
REM FOR J=0 TO 10
REM M=1.44*10^5  MASS FLOW RATE (kg/hr)
REM Ta=16.2     AMBIENT TEMP (C)
REM Ti=  IN FLUID TEMPERATURE (C) IF THIS CHANGES ALSO CHANGE Ti
REM T2=20.4     ABSORBER TEMPERATURE (C) IF THIS CHANGES ALSO CHANGE Ti
REM Wind=5      SPEED (m/s)
REM I=236       INTENSITY OF SOLAR RAD (W/m2)
REM E=0.8       TRANSMISSIVITY & ABSORPTIVITY OF COVER AND ABSORBER
REM E2=0.95     EMISIVITY OF ABSORBER
REM H=0.034     CONDUCTIVITY OF REAR INSULATION (W/m/C)
REM Ti=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 S=1        PLATE SEPARATION IN CM
REM D=1        FIN SEPARATION IN CM
REM
240 DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ?????
245 IF Y=0 THEN GOTO 470
250 INPUT A$ 
260 IF A$="N" THEN GOTO 470
270 PRINTER IS 701
280 PRINT "COLLECTOR INITIAL PARAMETERS ARE 
290 PRINT USING 930  "MASS FLOW RATE, M, kg/hr" 
300 PRINT USING 930  "AMBIENT TEMP., Ta,°C" 
310 PRINT USING 930  "INLET FLUID TEMP., Tin,°C" 
320 PRINT USING 930  "ABSORBER TEMP., T2,°C" 
330 PRINT USING 930  "SPEED, WIND, m/s" 
340 PRINT USING 930  "SOLAR RADIATION, I, W/m2" 
350 PRINT USING 930  "TRANSMISSIVITY & ABSORPTIVITY, Ta" 
360 PRINT USING 930  "EMISIVITY OF COVER, E1" 
370 PRINT USING 930  "EMISIVITY OF ABSORBER, E2" 
380 PRINT USING 930  "INSULATION CONDUCTIVITY, K1, W/m/C" 
390 PRINT USING 930  "INSULATION THICKNESS, T1, m" 
400 PRINT USING 930  "COLLECTOR AREA, A, m2" 
410 PRINT USING 930  "COLLECTOR LENGTH, L, m" 
420 PRINT USING 930  "COLLECTOR WIDTH, W, m" 
430 PRINT USING 930  "PLATE SEPARATION, S, cm" 
440 PRINT USING 930  "FIN SEPARATION, D, cm" 
450 PRINT " 
460 PRINT INPUT IS 1 
470 REM              INPUT CONSTANT DATA 
480 STE=0.00000000567  STEFAN-BOLZMANN CONSTANT (W/m2K4) 
490 VIS=.0000188     VISCOSITY OF AIR IN DUCT (N-s/m2) 
500 K=.0241        THERMAL CONDUCTIVITY OF AIR IN DUCT (W/mK) 
510 C=1000         HEAT CAPACITY OF AIR AT CONSTANT PRESSURE (J/kg°C) 
520 REM              INPUT VARIABLE DATA 
530 Ti=11275.15    HELVIN
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

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<th>Symbol</th>
<th>Definition</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 - absorbtance 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>
TT
TK
TO
Jo
W
WIND
M, J, D, D1, D2, D3

air inlet temperature
sky temperature
air outlet temperature
overall U-value of the collector
width of collector
wind speed
various subscripts (see text)

\( \eta \)
\( \bar{\eta} \)
\( \theta \)
steady-state thermal efficiency of the collector
daily averaged thermal efficiency of the collector
angle between collector normal and solar beam

1 INTRODUCTION

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

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

2 THE COLLECTOR MODEL

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

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

5.1 The collectors

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

Table 1 Collector configurations, and rear-duct air flow

| 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 cover | Polycarbonate, thickness 2.00 mm |

Plate absorptance 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° south-facing

Thickness of plate and of duct-back

| | 0.2 mm | 0.5 mm | 1.0 mm | 2.0 mm | 5.0 mm |
| DY1 | | | | |
| DY2 | | | | |
| DY3 | | | | |
| DY4 | | | | |
| DY5 | | | | |

Collector time-constant (flow 1)

| | 85 s | 170 s | 300 s | 580 s | 1400 s |
| Flow 1 | | | | | |
| Flow 2 | | | | | |
| Flow 3 | | | | | |

Air flow in the rear-duct

| Flow | Stagnation (M=0) |  |
| Flow 0 | | |
| Flow 1 | \( \text{all } T_I = 303 \text{ K } M = 0.0600 \text{ kg s}^{-1} \text{ (PON, irrelevant)} \) | |
| Flow 2 | \( T_I = 303 \text{ K } M = 0.0600 \text{ kg s}^{-1} \text{ PON = 128 W} \) | |
| Flow 3 | \( T_I = 323 \text{ K } M = 0.0562 \text{ kg s}^{-1} \text{ PON = 124 W} \) | |

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 \( M = 0.0600 \text{ kg s}^{-1} \) and \( T_I = 303 \text{ K} \) (flow 2 in Table 1) this power is 6.4 W. The corresponding pressure drop across the duct is 12 mm water gauge. If it is
assumed that the circulation fan gives a constant volumetric flow rate then at
other values of \( T_I \) the value of \( M \) will be different from 0.0600 kg s\(^{-1}\) at
\( T_I = 323 \) K, \( M = 0.0562 \) 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 \( \eta \)
\( \eta = \frac{F_R (f(\theta) - U_L (T_I - T_A)/S)}{S f(\theta) \cdot S} \) (1)

where \( f(\theta) \) is such that

\[ S f(\theta) = S \] (2)

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

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

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

3.3 Daily-averaged efficiency

The collector configurations DY1 to DY5 were run under conditions flow 2 and flow 3 for a variety of simulated days 21 June (J), 21 March (M), 21 December (D). The simulated conditions of insolation and weather on these days are shown in Figure 3. The ambient temperature 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 insulations, the prefix SO denoting the clear sky irradiance normal to the beam, and the prefix SI 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 η is never being wrongly evaluated.

In order to plot η 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), (vii), (xi). The increase in η 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 η 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
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 \( T_O \) 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 \( T_O \) 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 \( T_O \). 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 \((T_I-T_A)/S\) in non-steady insolation, and that this is largely because of the diurnal variation, rather than because of more rapid fluctuations in insolation. Peak temperatures can also be significantly larger at low thermal capacitance, particularly when there are rapid fluctuations in insolation.

REFERENCES


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


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

(i) $SUJ/TAJ$, flow 2  (ii) $SOM/TAM$, flow 2  (iii) $SOD/TAD1$, flow 2  
(iv) $SOM/TAM$, flow 3  (v) $SJM/TAM$, flow 2  (vi) $SOD/TAD1$, flow 3  
(vii) $SJD1/TAD1$, flow 2  (viii) $SOD/TAD2$, flow 3  (ix) $SJD2/TAD1$, 
flow 2  (x) $SJD3/TAD1$, flow 2  (xi) $SJD/TAD1$, flow 2.
Figure 3  Simulated ambient conditions. For further details see text.
APPENDIX D

TRANS: Computer programme for analysing collector data under transient conditions.
214  
940 NEXT K
950 NEXT K
960 ZE=SOR (ZE=YY/(NF-NC))
970 PRINT "ETAD=";E;"+/";I;E
980 U=X(NC)
990 PRINT "FU=";U;"+/";I;E
1000 PRINT "TABLE F.4"
1010 FOR K=1 TO NF
1020 C(K)=X(NC)/E
1030 PRINT K,C(K)
1035 NEXT K
1040 F=-(U/(HLOG (1-U/H)))
1050 PRINT "F=";F
1060 E=E/F
1070 U=U-F
1080 PRINT "ETAD=";E;"=";U
1090 PRINT "DATA SETS ACCEPTED FOR ANALYSIS";NF
1100 REM READ DATA TO GENERATE THERMAL PERFORMANCE CURVE
1110 ASSIGN# 1 TO "TRANID700"
1120 NF=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 1460
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
1410 X(NC)=0
1420 FOR K=1 TO NK
1430 E=E+X(K)*C(K)
1440 X(NC)=X(NC)+T(K)
1450 NEXT K
1460 Y=V/(FRE)
1470 X(NC)=X(NC)/"**"E
1480 PRINT Y,X(NC)
1490 REM CALC LEAST SOR TO THERMAL PERFORMANCE
1500 SX=SX+X(NC)
1510 SY=SY+Y
1520 SY=SY+X(NC)*X(NC)
1530 SY=SY+Y*Y
1540 SX=SY+X(NC)*Y
1550 NF=NF+1
1560 GOTO 1220
1570 DNP=NF
1580 PRINT "POINTS ON THERMAL PERFORMANCE CHARACTERISTIC";NF
1590 PRINT "FROM LEAST SQUARES FITS EACH WAY"
1600 E=(SY*SX-SX*SY)/(DNP*DNP*SY)
1610 U=(SX*SY-DNP*DNP*SY)/(DNP*DNP*SY)
1620 PRINT "MINIMUM ETAO=";E;"=";U
1630 E=(SY*SY-SX*SY)/(DNP*DNP*SY)
1640 U=(SY*SY-DNP*DNP*SY)/(DNP*DNP*SY)
1650 PRINT "MAXIMUM ETAO=";E;"=";U
1660 STOP
1670 END