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

Thesis

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B.Sc. (Hons) Brunel

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

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**Nomenclature**

**Chapter 2**

- $A_c$: Collector area (m$^2$)
- $A_s$: Storage tank surface area (m$^2$)
- $c$: Appropriate specific heat (J 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)
- $MC$: Storage heat capacity (J °C$^{-1}$)
- $N$: Lifetime of hardware (years)
- $n$: Number of years
- $PV_{ch}$: 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)
ΔT  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 (m³)
ρ    Density (kg m⁻³)
(τα) 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 ($^\circ C$)
$T_{\text{ref}}$ An empirically derived reference temperature ($100^\circ C$)
$t_m$ Total number of seconds in a month
$U_L$ Collector overall loss coefficient ($Wm^{-2} ^\circ C^{-1}$)
$(\tau \alpha)$ Monthly average transmittance-absorptance product
### Nomenclature

#### Chapter 4

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aperture area, or transparent frontal area of collector (m²)</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific heat of transfer fluid at constant pressure (Jkg⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>Dh</td>
<td>Characteristic length (m)</td>
</tr>
<tr>
<td>F'</td>
<td>Absorber plate (or collector) efficiency factor</td>
</tr>
<tr>
<td>FR</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration of gravity (ms⁻²)</td>
</tr>
<tr>
<td>h₁</td>
<td>Convective heat transfer coefficient, duct top to heat transfer fluid (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>h₂</td>
<td>Convective heat transfer coefficient, duct base to heat transfer fluid (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hₗ</td>
<td>Radiative heat transfer coefficient (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hw</td>
<td>Wind heat transfer coefficient (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>H</td>
<td>Duct height (m)</td>
</tr>
<tr>
<td>I</td>
<td>Equivalent normal solar irradiance (Wm⁻²)</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity (Wm⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>L</td>
<td>Collector length (m)</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate of transfer fluid (Kg s⁻¹)</td>
</tr>
<tr>
<td>Nu</td>
<td>Nussult number</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>Qu</td>
<td>Energy per unit time, useful (W)</td>
</tr>
<tr>
<td>Ra</td>
<td>Rayleigh number</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>T₁</td>
<td>Duct top, temperature (°C)</td>
</tr>
<tr>
<td>T₂</td>
<td>Duct base, temperature (°C)</td>
</tr>
<tr>
<td>Ta</td>
<td>Ambient air-temperature (°C)</td>
</tr>
<tr>
<td>Tc</td>
<td>Cover temperature (°C)</td>
</tr>
<tr>
<td>Te</td>
<td>Exit fluid temperature (°C)</td>
</tr>
<tr>
<td>Ti</td>
<td>Inlet fluid temperature (°C)</td>
</tr>
<tr>
<td>Tm</td>
<td>Mean fluid temperature (Te + Ti)/2 (°C)</td>
</tr>
<tr>
<td>Tp</td>
<td>Average absorber temperature (°C)</td>
</tr>
<tr>
<td>Ub</td>
<td>Bottom loss heat transfer coefficient (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>Ue</td>
<td>Edge loss heat transfer coefficient (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>UL</td>
<td>Collector overall heat transfer (loss) coefficient (Wm⁻² °C⁻¹)</td>
</tr>
</tbody>
</table>
\( U_t \)  \hspace{1cm} \text{Top loss heat transfer coefficient (Wm}^{-2} \cdot \text{C}^{-1})

\( V \)  \hspace{1cm} \text{Wind velocity (ms}^{-1})

\( W \)  \hspace{1cm} \text{Collector width (m)}

\( x \)  \hspace{1cm} \text{Insulation thickness (m)}

\( \alpha \)  \hspace{1cm} \text{Absorptance of the collector absorber surface for solar radiation}

\( \beta \)  \hspace{1cm} \text{Volume thermal expansion coefficient (K}^{-1})

\( \varepsilon_c \)  \hspace{1cm} \text{Cover emissivity}

\( \varepsilon_p \)  \hspace{1cm} \text{Absorber plate emissivity}

\( \eta \)  \hspace{1cm} \text{Efficiency}

\( \mu \)  \hspace{1cm} \text{Absolute (dynamic) coefficient of viscosity (Kg m}^{-1} \cdot \text{s}^{-1})

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

\( \tau \)  \hspace{1cm} \text{Transmittance of the solar collector}

\( (\tau \alpha) \)  \hspace{1cm} \text{The product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance}

\( \sigma \)  \hspace{1cm} \text{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 ((m^2))</td>
</tr>
<tr>
<td>(A_C)</td>
<td>Collector area ((m^2))</td>
</tr>
<tr>
<td>(c_p)</td>
<td>Volume heat capacity at constant pressure ((J/Kg^{-1}\cdot {\degree}C^{-1}))</td>
</tr>
<tr>
<td>(P')</td>
<td>Absorber plate (or collector) efficiency factor</td>
</tr>
<tr>
<td>(P'')</td>
<td>Collector flow factor</td>
</tr>
<tr>
<td>(P_1)</td>
<td>Correction factor for partial shading of the collector</td>
</tr>
<tr>
<td>(P_2)</td>
<td>Correction factor for variation of (\tau_a) with the angle of incidence</td>
</tr>
<tr>
<td>(P_3)</td>
<td>Correction factor for variation in optical properties from normal for diffuse irradiance</td>
</tr>
<tr>
<td>(P_R)</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>(h_w)</td>
<td>Wind heat transfer coefficient ((Wm^{-2}\cdot {\degree}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 \cdot s^{-1}))</td>
</tr>
<tr>
<td>(m_t)</td>
<td>Mass flow rate of leak ((Kg \cdot s^{-1}))</td>
</tr>
<tr>
<td>(M)</td>
<td>Fluid capacity of collector ((Kg))</td>
</tr>
<tr>
<td>((mc)_e)</td>
<td>Effective heat capacity of collector ((J \cdot {\degree}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 ((\degree C))</td>
</tr>
<tr>
<td>(T_b)</td>
<td>Average back plate temperature ((\degree C))</td>
</tr>
<tr>
<td>(T_e)</td>
<td>Exit fluid temperature ((\degree C))</td>
</tr>
<tr>
<td>(T_f)</td>
<td>Average temperature of the fluid in the collector ((\degree C))</td>
</tr>
<tr>
<td>(T_i)</td>
<td>Inlet fluid temperature ((\degree 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 ($^\circ$C)</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Mean fluid temperature ($T_e + T_i$)/2 ($^\circ$C)</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Absorber plate temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Mean absorber temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T_{sky}$</td>
<td>Equivalent black body sky temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T^*$</td>
<td>Reduced temperature ($T_i - T_a$)/I ($m^2$ $^\circ$C w$^{-1}$)</td>
</tr>
<tr>
<td>$U_L$</td>
<td>Collector overall heat transfer (loss) coefficient ($Wm^{-2}$ $^\circ$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>$\tau_\alpha$</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>$(\tau_\alpha)_e$</td>
<td>Effective transmittance absorptance product</td>
</tr>
<tr>
<td>$(\tau_\alpha)_s$</td>
<td>Product of the absorptance and transmittance for normal irradiance</td>
</tr>
<tr>
<td>$\Delta T^*$</td>
<td>Time increment</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of incidence; degrees from normal</td>
</tr>
</tbody>
</table>
### Nomenclature

#### Chapter 6

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_R$</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>$h_{p-c}$</td>
<td>Convection coefficient between absorber plate and cover (Wm$^{-2}$°C$^{-1}$)</td>
</tr>
<tr>
<td>$hrp-c$</td>
<td>Radiation coefficient between absorber plate and cover (Wm$^{-2}$°C$^{-1}$)</td>
</tr>
<tr>
<td>$h_{rc-a}$</td>
<td>Radiation coefficient from the cover to sky (Wm$^{-2}$°C$^{-1}$)</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>$I_{th}$</td>
<td>Threshold solar irradiance (Wm$^{-2}$)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient air temperature (°C)</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Inlet fluid temperature (°C)</td>
</tr>
<tr>
<td>$U$</td>
<td>Collector heat loss coefficient $P'U_L$ (Wm$^{-2}$°C$^{-1}$)</td>
</tr>
<tr>
<td>$U_L$</td>
<td>Collector overall heat transfer (loss) coefficient (Wm$^{-2}$°C$^{-1}$)</td>
</tr>
<tr>
<td>$\epsilon_t$</td>
<td>Thermal emissivity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency steady state</td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
<td>Daily averaged efficiency</td>
</tr>
<tr>
<td>$\eta_o$</td>
<td>Zero loss collector efficiency, $P'(\alpha \tau)$</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Solar transmissivity</td>
</tr>
<tr>
<td>$(\tau \alpha)$</td>
<td>Product of the absorptance and transmittance for normal irradiance</td>
</tr>
</tbody>
</table>
Nomenclature

Chapter 7

A Aspect ratio or area of main heater
a Accommodation coefficient
\( \bar{c} \) Average velocity of molecules (ms\(^{-1}\))
\( c_p \) Specific heat at constant pressure (J Kg\(^{-1}\) °C\(^{-1}\))
\( c_v \) Specific heat at constant volume (J Kg\(^{-1}\) °C\(^{-1}\))
d Molecular diameter (m)
\( D_h \) Hydraulic diameter (m)
g Acceleration of gravity (ms\(^{-2}\))
Gr Grashof number
h Combined heat transfer coefficient from absorber to cover (Wm\(^{-2}\) °C\(^{-1}\))
\( h' \) Heat transfer coefficient of material of known conductivity (Wm\(^{-2}\) °C\(^{-1}\))
\( h_b \) Heat transfer coefficient for flow across panel wall (Wm\(^{-2}\) °C\(^{-1}\))
\( h_c \) Heat transfer coefficient for flow across the inside of the panel due to convection and conduction (Wm\(^{-2}\) °C\(^{-1}\))
\( h_p \) Heat transfer coefficient for flow across panel (Wm\(^{-2}\) °C\(^{-1}\))
\( h_r \) Heat transfer coefficient for flow across the inside of the panel due to radiation (Wm\(^{-2}\) °C\(^{-1}\))
\( h_s \) Heat transfer coefficient for flow across standard insulation (Wm\(^{-2}\) °C\(^{-1}\))
k Thermal conductivity (Wm\(^{-1}\) °C\(^{-1}\))
L Linear dimension (m)
m Wall molecule mass (Kg)
m' Gas molecule mass (Kg)
M Mass of one mole (kg mol\(^{-1}\))
\( N_A \) Avogadro's number
Nu Nusselt number
p Gas pressure (Nm\(^{-2}\))
\( P_c \) Critical pressure when \( R_a = R_{ac} \)
Pr Prandtl number
q Power dissipated in central heater (W)
\( Q \) Energy per unit time, rate of heat supply to main heater (W)
\( Q_p \) Rate of heat supply to panel from main heater (W)
\( r \) Specific gas constant (R/M)
\( R \) Gas constant
\( Ra \) Rayleigh number
\( Ra_C \) Critical Rayleigh number, for \( Ra < Ra_C \) no convection, \( Nu = 1 \)
\( Re \) Reynolds number
\( s \) Absorber plate to cover separation (m)
\( t \) Panel wall thickness (m)
\( T \) Average of plate and cover temperature (°C)
\( T_1 \) Inside panel temperature nearest to cold plate (°C)
\( T_2 \) Inside panel temperature nearest to main heater (°C)
\( T_g \) Guard ring temperature (°C)
\( T_i \) Temperature of main heater, also fluid inlet temperature (°C)
\( T_o \) Temperature of cold plates (°C)
\( \alpha \) Thermal diffusivity (m² s⁻¹)
\( \beta \) Thermal volume expansion coefficient (= 1/T for a perfect gas), (K⁻¹)
\( \gamma \) c_p/c_v
\( \Delta \theta \) Hot plate temperature unbalance (\( T_i - T_g \)), (°C)
\( \Delta T \) Temperature difference across panel (°C)
\( \epsilon_1 \) Emissivity of surface at temperature \( T_1 \) (°C)
\( \epsilon_2 \) Emissivity of surface at temperature \( T_2 \) (°C)
\( \mu \) Viscosity (Pa s)
\( \nu \) Kinematic viscosity (\( \mu/\rho \)) (Pa s m³Kg⁻¹)
\( \rho \) Density (Kg m⁻³)
\( \sigma \) Stefan-Boltzmann constant (Wm⁻² K⁻⁴)
\( \lambda \) 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 (≤80°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></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space and Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron &amp; Steel 1976</td>
<td>-</td>
<td>4.9</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Engineering and other metal 1976</td>
<td>17.2</td>
<td>71.4</td>
<td>40.1</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>32.8</td>
<td>14.1</td>
</tr>
<tr>
<td>Chemical &amp; Allied Trades 1976</td>
<td>0.8</td>
<td>4.2</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Food, Drink &amp; Tobacco 1976</td>
<td>3.2</td>
<td>18.1</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>7.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Textiles, Leather &amp; Clothing 1976</td>
<td>5.1</td>
<td>21.3</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>7.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Paper, Printing &amp; Stationary 1976</td>
<td>1.9</td>
<td>5.4</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Building Materials 1976</td>
<td>0.9</td>
<td>4.6</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Other trades 1976</td>
<td>7.8</td>
<td>61.2</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>19.5</td>
<td>14.2</td>
</tr>
<tr>
<td>Process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural 1976</td>
<td>0.9</td>
<td>22.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>-</td>
<td>16.1</td>
</tr>
<tr>
<td>Domestic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substance</td>
<td>Comments</td>
<td>Density $\rho$/Kg m$^{-3}$ $\times 10^3$</td>
<td>Specific heat capacity $C_p$/JK$^{-1}$ Kg$^{-1}$$\times 10^3$</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------------------------------</td>
<td>------------------------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Chabazitic tuff</td>
<td>Common beolite in Italy</td>
<td>1.4</td>
<td>1.09</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>1.0</td>
<td>4.19</td>
</tr>
<tr>
<td>Iron shot</td>
<td></td>
<td>7.86</td>
<td>0.54</td>
</tr>
<tr>
<td>Scrap Iron</td>
<td>Zero voids</td>
<td>7.90</td>
<td>0.53</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td>7.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Magnetite, Fe$_2$O$_3$</td>
<td>Zero voids</td>
<td>5.16</td>
<td>0.75</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td></td>
<td>5.20</td>
<td>0.75</td>
</tr>
<tr>
<td>Wet earth</td>
<td></td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>Water and salt (brine)</td>
<td></td>
<td>1.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Alumina (Al$_2$ O$_3$)</td>
<td></td>
<td>4.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Scrap Aluminium</td>
<td>Zero voids</td>
<td>2.74</td>
<td>0.963</td>
</tr>
<tr>
<td>Therminol 55 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td>2.4</td>
<td>-18</td>
</tr>
<tr>
<td>Caloria HT43 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td>2.3</td>
<td>-10</td>
</tr>
<tr>
<td>Oils</td>
<td>Cracking occurs at high temp.</td>
<td>1.0</td>
<td>2.51</td>
</tr>
<tr>
<td>MgCO$_3$·6H$_2$O</td>
<td></td>
<td>1.7</td>
<td>1.60</td>
</tr>
<tr>
<td>MgCO$_3$</td>
<td></td>
<td>3.0</td>
<td>0.84</td>
</tr>
<tr>
<td>Concrete</td>
<td>Zero voids</td>
<td>2.25</td>
<td>1.13</td>
</tr>
<tr>
<td>Stone</td>
<td>Zero voids</td>
<td>2.74</td>
<td>0.88</td>
</tr>
<tr>
<td>Material</td>
<td>Density</td>
<td>Viscosity</td>
<td>Cost (1980) £25/m³</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------</td>
<td>-----------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.74</td>
<td>0.92</td>
<td>2.26</td>
</tr>
<tr>
<td>Marble</td>
<td>2.70</td>
<td>0.75</td>
<td>2.39</td>
</tr>
<tr>
<td>Granite</td>
<td>2.70</td>
<td>0.796</td>
<td>2.12</td>
</tr>
<tr>
<td>Sulphur Liquid</td>
<td>2.1</td>
<td>1.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Rock</td>
<td>2.5</td>
<td>0.84</td>
<td>2.09</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.4</td>
<td>0.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Brick</td>
<td>2.23</td>
<td>0.84</td>
<td>1.9</td>
</tr>
<tr>
<td>Paraffin Oil</td>
<td>0.8</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Olive Oil</td>
<td>0.9</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Silica (Si O₂)</td>
<td>2.7</td>
<td>0.84</td>
<td>2.3</td>
</tr>
<tr>
<td>Pebbles</td>
<td>3.0</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Basalt</td>
<td>3.2</td>
<td>0.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Sulphur</td>
<td>rhombic</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Sodium</td>
<td>2.1</td>
<td>0.7</td>
<td>2.9</td>
</tr>
<tr>
<td>Mitec</td>
<td></td>
<td></td>
<td>1.55</td>
</tr>
<tr>
<td>Draw salt</td>
<td></td>
<td></td>
<td>1.55</td>
</tr>
<tr>
<td>Dry earth</td>
<td>1.26</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>
TABLE 2.3 Basic Prometheus configuration to heat 100 houses

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

<table>
<thead>
<tr>
<th>Collector</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>heat transfer factor (F_R)</td>
<td>overall heat loss coefficient</td>
<td>optical efficiency averaged over useful incident angles (τα)</td>
<td></td>
</tr>
<tr>
<td>2,900 m²</td>
<td>0.9</td>
<td>1.0 Wm⁻²°C⁻¹</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
<td>Quantity</td>
<td>Unit</td>
<td>Energy Intensity</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>----------</td>
<td>------</td>
<td>-----------------</td>
</tr>
<tr>
<td>1800</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
<tr>
<td>500</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
<tr>
<td>444</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
<tr>
<td>1200</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
<tr>
<td>175</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
<tr>
<td>2120</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
<tr>
<td>103</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
<tr>
<td>118</td>
<td>Concrete sections</td>
<td>1.5</td>
<td>m³</td>
<td>760</td>
</tr>
</tbody>
</table>

Note: The energy input cost is calculated from the energy intensity and the quantity. The cost per unit is also calculated accordingly.
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>

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

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

\[
i=0 \quad f=0.02 \quad 7500\quad 11700\quad 12500
\]
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>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flat plate selective</td>
<td>Evacuated tube collector</td>
<td>Concentrating collector</td>
<td>High performance evacuated</td>
<td></td>
</tr>
<tr>
<td>Collector area /m²</td>
<td>2100</td>
<td>4600</td>
<td>14000</td>
<td>2800</td>
<td></td>
</tr>
<tr>
<td>Storage volume /m³</td>
<td>7500</td>
<td>17700</td>
<td>38500</td>
<td>11200</td>
<td></td>
</tr>
<tr>
<td>Insulation thickness/m</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Operating temperature of store/°C</td>
<td>72-42</td>
<td>95-60</td>
<td>70-30</td>
<td>130-30</td>
<td></td>
</tr>
<tr>
<td>Number of houses heated by system</td>
<td>50</td>
<td>300</td>
<td>400</td>
<td>100</td>
<td></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>
<td></td>
</tr>
<tr>
<td>Cost of collectors £1980/m²</td>
<td>60</td>
<td>64</td>
<td>64</td>
<td>72</td>
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<tr>
<td>Cost of store £1980/m³</td>
<td>16</td>
<td>11</td>
<td>10</td>
<td>26</td>
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<tr>
<td>Collector area/Storage volume (m²/m³)</td>
<td>0.28</td>
<td>0.26</td>
<td>0.36</td>
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<tr>
<td>Total system capital cost £1980</td>
<td>322900</td>
<td>659000</td>
<td>1740000</td>
<td>570000</td>
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<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>
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<tr>
<td>Storage volume required for type A5 house /m³</td>
<td>127</td>
<td>65</td>
<td>49</td>
<td>112</td>
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<tr>
<td>Cost per A5 house/£1980</td>
<td>5480</td>
<td>2416</td>
<td>2215</td>
<td>5700</td>
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[ ] Chapter 2 reference numbers
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<th>Store type</th>
<th>Temperature Rise (°C)</th>
<th>Cost/£1982 per KWh for recovered energy seasonal storage</th>
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<td>Steel tank</td>
<td>80</td>
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<td>Pit storage</td>
<td>50</td>
<td>0.19 - 0.30</td>
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<td>Rock cavern</td>
<td>70</td>
<td>0.11 - 0.21</td>
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<tr>
<td>Storage in clay</td>
<td>12</td>
<td>0.07 - 0.13</td>
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<tr>
<td>Multiple well systems in rock</td>
<td>50</td>
<td>0.07 - 0.12</td>
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<tr>
<td>Aquifers</td>
<td>15</td>
<td>0.025 - 0.08</td>
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<td>Prometheus (pebble bed, using data from Table 2.6)</td>
<td>100</td>
<td>0.43</td>
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<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>
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<td>Lambohov, Sweden</td>
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<td>Inglestad, Sweden</td>
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<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td>19 320</td>
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<td>Water</td>
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<td>5 150</td>
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<td>6 000</td>
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<td>10 000</td>
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<td>City University, London, UK</td>
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<td>4 000</td>
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TABLE 3.1 Thermal Characteristics of Basic Type AO House

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<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (Wm⁻²°C⁻¹)</th>
<th>UA (W°C⁻¹)</th>
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<td>88.5</td>
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<td>48.6</td>
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<td>29.2</td>
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<tr>
<td>Floor</td>
<td>48.6</td>
<td>0.5</td>
<td>24.3</td>
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<td>Window</td>
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<td>82.5</td>
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<tr>
<td>Total fabric specifics loss</td>
<td></td>
<td>224W°C⁻¹</td>
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<tr>
<td>Ventilation specific loss</td>
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<td>80W°C⁻¹</td>
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<tr>
<td>Total house specific loss</td>
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<td>304W°C⁻¹</td>
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<td>Month</td>
<td>Days in month</td>
<td>Solar radiation on a South-facing vertical surface (KWh/m²/month)</td>
<td>Solar radiation on a South-facing surface 30° to horizontal (KWh/m²/month)</td>
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<td>31</td>
<td>84</td>
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<td>95</td>
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<td>Nov</td>
<td>30</td>
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<tr>
<td>Dec</td>
<td>31</td>
<td>25</td>
<td>22</td>
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<tr>
<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss (W(^{\circ})C(^{-1}))</td>
<td>Net annual space and water heating demand (GJ)</td>
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<tr>
<td>------------</td>
<td>------------------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------------------</td>
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<tr>
<td>A0</td>
<td>Basic (1975 Building Regs.)</td>
<td>304</td>
<td>46.4</td>
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<tr>
<td>A1</td>
<td>A0 + orientate house north-south</td>
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<tr>
<td>A2</td>
<td>A1 + 50 mm loft insulation (100 mm total)</td>
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<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
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<tr>
<td>A4</td>
<td>A3 + 50 mm loft insulation (150 mm total)</td>
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<td>A4 + extra layer of glazing (i.e. double)</td>
<td>213</td>
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<tr>
<td>A6</td>
<td>A5 + cavity increased to 100 mm</td>
<td>186</td>
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<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
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<td>A8</td>
<td>A7 + all windows on south side</td>
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<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
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<td>A9 + extra layer of glazing (i.e. triple)</td>
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<td>A10 + cavity increased to 200 mm</td>
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<td>Component</td>
<td>Area A (m²)</td>
<td>U-value (Wm⁻²°C⁻¹)</td>
<td>UA (W°C⁻¹)</td>
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<tr>
<td>Wall</td>
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<td>Floor</td>
<td>41.2</td>
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<td>Window</td>
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<tr>
<td>Total fabric specific loss</td>
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<td>192 W°C⁻¹</td>
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<td>Ventilation specific loss</td>
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<td>68 W°C⁻¹</td>
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<td>Total house specific loss</td>
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<td></td>
<td>260 W°C⁻¹</td>
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<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss (W°C⁻¹)</td>
<td>Net annual space heating demand (GJ)</td>
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<td>------------------</td>
<td>-----------------------------------</td>
<td>----------------------------------</td>
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<tr>
<td>B0 Basic (average UK housing stock)</td>
<td>260</td>
<td>34.9</td>
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<tr>
<td>B1 B0 + 50 mm of loft insulation (100 mm total)</td>
<td>249</td>
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<tr>
<td>B2 B1 + fibre-fill cavity (50 mm)</td>
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<td>B3 B2 + 50 mm of loft insulation (150 mm total)</td>
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<td>B4 B3 + extra layer of glazing (i.e. double)</td>
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<td>B5 B4 + extra layer of glazing (i.e. triple)</td>
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<td>B6 B5 + 100 mm external wall insulation</td>
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<td>Table 4.4: Art Collector, Test Facilities and Installed Systems in the United Kingdom</td>
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**TABLE 5.1** Data collected during steady state testing of the D.C. Hall collector

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**COLUMN INDEX**

1. **Time (hrs : min)**
2. Mass flow rate (kg hr⁻¹)
3. Total insulation (kcal °C⁻¹)
4. Air temperature rise passing through collector (Tᵥ - Tᵥ°) (°C⁻¹)
5. Ambient air temperature (°C)
6. Inlet air temperature (°C)
7. Outlet air temperature (°C)
8. Absorber temperature (°C)
9. Wind speed (ms⁻¹)
10. Efficiency (°C)
11. (Tᵥ° - Tᵥ°) / Tᵥ°
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<th>Test No.</th>
<th>Date</th>
<th>Time of test</th>
<th>Air mass flow rate</th>
<th>Air temp. at inlet</th>
<th>Air temp. at outlet</th>
<th>Air temp. increase ((T_e - T_i))</th>
<th>Ambient Temp.</th>
<th>Total irradiance in plate of collector (I_m)</th>
<th>(\frac{(T_e - T_a)}{I_m})</th>
<th>Collector efficiency</th>
<th>Wind speed</th>
<th>Absorber Temp.</th>
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<td>25/6/83</td>
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<td>10.3</td>
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<td>1123-1132</td>
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<td>16.7</td>
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**Note:** Results of steady state testing of structured polycarbonate collector

**Table 5.2:**
TABLE 5.3 Collector configuration modelled for transient analysis by RRDCT.

<table>
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<tr>
<th>Collector length (along flow)</th>
<th>4.00 m</th>
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<tbody>
<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 $\theta = 0$ falling slightly as $\theta$ 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>DY1 0.2 mm, DY2 0.5 mm, DY3 1.0 mm, DY4 2.0 mm, DY5 5.0 mm</td>
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</table>

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

<table>
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<tr>
<th></th>
<th>Steady state</th>
<th>Transient 0.5mm (DY2)</th>
<th>Transient 2mm (DY4)</th>
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<td>$\Delta t/(min)$</td>
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<tr>
<td>$N$</td>
<td>-</td>
<td>6</td>
<td>5</td>
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<tr>
<td>$\tau /{(min)}$</td>
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<td>2.8</td>
<td>9.7</td>
</tr>
<tr>
<td>$F_{RUL}/(\text{Wm}^{-2} \text{K}^{-1})$</td>
<td>2.83*</td>
<td>2.768</td>
<td>2.604</td>
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<tr>
<td>$F_{R \alpha}$</td>
<td>0.683</td>
<td>0.585</td>
<td>0.569</td>
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<tr>
<td>$KF_{R \alpha}$</td>
<td>0.683</td>
<td>0.706</td>
<td>0.686</td>
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<tr>
<td>$\sigma F_{RUL}$</td>
<td>-</td>
<td>0.012</td>
<td>0.036</td>
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<tr>
<td>$\sigma F_{R \alpha}$</td>
<td>0.0003</td>
<td>0.0025</td>
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</tr>
</tbody>
</table>

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

$* = \text{at low fluid inlet temperatures}$
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**Table 5.5**: Transient test data for SP collector input to TPA.
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POINTS ON THERMAL PERFORMANCE CHARACTERISTIC 80 FROM LEAST SQUARES FITS EACH Way MINIMUM ETA= .225453187816 U= 7.33893217894 MAXIMUM ETA= .714186416622 U= 13.9618680148
### TABLE 5.8
Temperature distribution within DY1 collector (0.2mm thick plate and duct back) during ASHRAE steady state testing, $T_a = 293k$, $I = 700\text{w} \cdot \text{m}^{-2}$, Wind = $1\text{m} \cdot \text{s}^{-1}$, $T_{sky} = 273k$

<table>
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<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\bar{T}_p/k$</th>
<th>$\bar{T}_b/k$</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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</thead>
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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 = $1\text{m} \cdot \text{s}^{-1}$, $T_{sky} = 273k$

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<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\bar{T}_p/k$</th>
<th>$\bar{T}_b/k$</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>
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<td>*303</td>
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<td>301.71</td>
<td>302.03</td>
<td>302.31</td>
<td>20.98</td>
<td>2.098</td>
<td>2.035</td>
</tr>
<tr>
<td>*433</td>
<td>405.92</td>
<td>407.78</td>
<td>413.13</td>
<td>419.46</td>
<td>410.30</td>
<td>2.93</td>
<td>3.245</td>
</tr>
</tbody>
</table>

* $T_{sky} = 293k$
<table>
<thead>
<tr>
<th>T / °C</th>
<th>Q / W</th>
<th>η / %</th>
<th>D.C. Hall Collector</th>
<th>D.C. Hall Collector</th>
<th>D.C. Hall Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>4.5</td>
<td>0.5</td>
<td>2.5</td>
<td>4.0</td>
<td>5.1</td>
</tr>
<tr>
<td>1.0</td>
<td>4.0</td>
<td>0.5</td>
<td>2.0</td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>0.5</td>
<td>3.5</td>
<td>0.5</td>
<td>1.5</td>
<td>3.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Note:**
- **T**: Temperature in °C
- **Q**: Heat flux density in W/m²
- **η**: Efficiency
- **D.C. Hall Collector**: Measurement results for D.C. Hall Collector

**Table 5.10**
Summary of collector testing results
<table>
<thead>
<tr>
<th>Material</th>
<th>Reflective index (n)</th>
<th>Solar (0.2-4.0μm) %</th>
<th>Infrared (3.0-500μm) %</th>
<th>Expansion coefficient (°C⁻¹)</th>
<th>Temperature Limits (°C)</th>
<th>Weatherability (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>
</tr>
<tr>
<td>Teflon F.F.P. (Fluorocarbon)</td>
<td>1.343</td>
<td>5 mil</td>
<td>5 mil</td>
<td>12.55 x 10⁻⁵</td>
<td>200-220</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Tedlar P.V.F. (fluorocarbon)</td>
<td>1.46</td>
<td>4 mil</td>
<td>4 mil</td>
<td>5.95 x 10⁻⁵</td>
<td>110-170</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mylar (Polyester)</td>
<td>1.64-1.67</td>
<td>5 mil</td>
<td>5 mil</td>
<td>2.00 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>Sunade white crystal glass (0.01% iron glass)</td>
<td>1.50</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.00 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
</tbody>
</table>

Source: Gary, H.P. 'Treatise on solar energy' Vol.1, A Wiley Interscience Publication, Chichester, 1982
<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Current (mA)</th>
<th>Resistance (ohms)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>10</td>
<td>50</td>
<td>Copper</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
<td>25</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>1500</td>
<td>30</td>
<td>15</td>
<td>Aluminum</td>
</tr>
<tr>
<td>2000</td>
<td>40</td>
<td>10</td>
<td>Black Oxide</td>
</tr>
<tr>
<td>2500</td>
<td>50</td>
<td>5</td>
<td>Black Chrome</td>
</tr>
</tbody>
</table>

Table 6.2: Table 6.2: Optical properties of selective absorber surface coatings.
### TABLE 6.3 Key to collector variable features, used to obtain Figure 6.19

<table>
<thead>
<tr>
<th>cover material: cover 1</th>
<th>plate glass, thickness 6.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>cover 2</td>
<td>polycarbonate, thickness 2.0 mm</td>
</tr>
<tr>
<td>thickness of the plate and of the 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>
<tr>
<td>air flow in the rear-duct:</td>
<td></td>
</tr>
<tr>
<td>flow 0</td>
<td>stagnation ( (M = 0) )</td>
</tr>
<tr>
<td>flow 1</td>
<td>all TI ( M = 0.0600 ) kg s(^{-1}) (PON irrelevant)</td>
</tr>
<tr>
<td>flow 2</td>
<td>TI = 303 K ( M = 0.0600 ) kg s(^{-1}) PON = 128W</td>
</tr>
<tr>
<td>flow 3</td>
<td>TI = 323 K ( M = 0.0562 ) kg s(^{-1}) PON = 124W</td>
</tr>
</tbody>
</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>N₂</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>
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<tr>
<td></td>
<td>Glass</td>
<td>Indeterminate</td>
<td>-170</td>
<td>0.38</td>
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<tr>
<td>O₂</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>
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<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Pt</td>
<td>Saturated</td>
<td>30</td>
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</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>W</td>
<td></td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td>Pt</td>
<td>Saturated</td>
<td>30</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>H₂</td>
<td>W</td>
<td></td>
<td>0.32</td>
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<tr>
<td></td>
<td>Pt.Bright</td>
<td>Indeterminate</td>
<td></td>
<td>0.74</td>
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<td>Pt.Black</td>
<td>Indeterminate</td>
<td></td>
<td>0.22</td>
</tr>
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<td>Glass</td>
<td>Saturated</td>
<td>25</td>
<td>0.29</td>
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<tr>
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<td>Glass</td>
<td>Indeterminate</td>
<td>-170</td>
<td>1.0</td>
</tr>
<tr>
<td>He</td>
<td>W, flashed</td>
<td>Indeterminate</td>
<td>20</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>W, not flashed</td>
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<td>W</td>
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<td>W</td>
<td>Clean</td>
<td>-30</td>
<td>0.0153</td>
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<td></td>
<td>W</td>
<td>Clean</td>
<td>-190</td>
<td>0.0151</td>
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<tr>
<td></td>
<td>W</td>
<td>K on H₂</td>
<td>25</td>
<td>0.106</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>H₂ on K</td>
<td>25</td>
<td>0.096</td>
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<tr>
<td></td>
<td>W</td>
<td>O on K</td>
<td>25</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>K on O</td>
<td>25</td>
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<td>W</td>
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<td>H₂</td>
<td>-22</td>
<td>0.17</td>
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<td>W</td>
<td>N₂</td>
<td>-194</td>
<td>0.32</td>
</tr>
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<td>Pt</td>
<td>Saturated</td>
<td>30</td>
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</tr>
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<td>K</td>
<td>Clean</td>
<td>25</td>
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<td>Na</td>
<td>Clean</td>
<td>25</td>
<td>0.19</td>
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<td>Glass</td>
<td>Indeterminate</td>
<td>25</td>
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<td>W</td>
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<td>0.272</td>
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<td>0.294</td>
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<td>Clean</td>
<td>-196</td>
<td>0.549</td>
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<td>Pt</td>
<td>Saturated</td>
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<td>0.89</td>
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<td>W</td>
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<td>0.498</td>
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<td>Clean</td>
<td>-196</td>
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<td>0.773</td>
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<td>-30</td>
<td>0.804</td>
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<td></td>
<td>W</td>
<td>Clean</td>
<td>-183</td>
<td>0.942</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Condition</th>
<th>( T_s )/°C</th>
<th>( T_i )/°C</th>
<th>( h_P ) /( \text{Wm}^{-2} \text{OC}^{-1} )</th>
<th>( Q_A ) /( \text{Wm}^{-2} )</th>
<th>( T_f )/°C</th>
<th>( h_R ) /( \text{Wm}^{-2} \text{OC}^{-1} )</th>
<th>( h_C ) /( \text{Wm}^{-2} \text{OC}^{-1} )</th>
<th>( \Delta T )/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air at atmospheric pressure</td>
<td>10</td>
<td>14</td>
<td>0.798</td>
<td>3.19</td>
<td>10.16</td>
<td>13.84</td>
<td>0.163</td>
<td>0.704</td>
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<tr>
<td></td>
<td>10.1</td>
<td>20.7</td>
<td>1.910</td>
<td>20.05</td>
<td>11.10</td>
<td>19.70</td>
<td>0.168</td>
<td>2.193</td>
</tr>
<tr>
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<td>10.1</td>
<td>21.3</td>
<td>1.725</td>
<td>19.32</td>
<td>11.07</td>
<td>20.33</td>
<td>0.169</td>
<td>1.915</td>
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<td>33.3</td>
<td>2.195</td>
<td>50.05</td>
<td>13.00</td>
<td>30.80</td>
<td>0.180</td>
<td>2.632</td>
</tr>
<tr>
<td>Air, ( p = 82 ) torr</td>
<td>10.35</td>
<td>37.9</td>
<td>1.60</td>
<td>44.08</td>
<td>12.55</td>
<td>35.70</td>
<td>0.185</td>
<td>1.720</td>
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<tr>
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<td>10.35</td>
<td>38.8</td>
<td>1.621</td>
<td>46.12</td>
<td>12.66</td>
<td>36.49</td>
<td>0.185</td>
<td>1.750</td>
</tr>
<tr>
<td>Air, ( p = 81 ) torr</td>
<td>10.3</td>
<td>43</td>
<td>1.567</td>
<td>51.24</td>
<td>12.86</td>
<td>40.44</td>
<td>0.189</td>
<td>1.669</td>
</tr>
<tr>
<td>Air, ( p = 71 ) torr</td>
<td>10.2</td>
<td>24.9</td>
<td>0.925</td>
<td>13.60</td>
<td>10.88</td>
<td>24.22</td>
<td>0.172</td>
<td>0.847</td>
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<tr>
<td>Freon/Air</td>
<td>10.3</td>
<td>22.1</td>
<td>1.685</td>
<td>19.88</td>
<td>11.29</td>
<td>21.11</td>
<td>0.170</td>
<td>1.856</td>
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<tr>
<td>Carbon Tet/Air</td>
<td>10.1</td>
<td>17.8</td>
<td>1.635</td>
<td>12.59</td>
<td>10.73</td>
<td>17.17</td>
<td>0.166</td>
<td>1.789</td>
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<td>10.1</td>
<td>17.9</td>
<td>1.645</td>
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<td>10.74</td>
<td>17.26</td>
<td>0.166</td>
<td>1.803</td>
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<td>10.4</td>
<td>27.9</td>
<td>1.986</td>
<td>34.75</td>
<td>12.14</td>
<td>26.16</td>
<td>0.175</td>
<td>2.303</td>
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<td>10.5</td>
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<td>12.66</td>
<td>29.14</td>
<td>0.178</td>
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<td>34.9</td>
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<td>59.80</td>
<td>13.59</td>
<td>33.91</td>
<td>0.182</td>
<td>3.082</td>
</tr>
<tr>
<td></td>
<td>10.6</td>
<td>36.7</td>
<td>2.245</td>
<td>58.59</td>
<td>13.53</td>
<td>33.77</td>
<td>0.183</td>
<td>2.712</td>
</tr>
<tr>
<td>Air ( p = 0.3 ) torr</td>
<td>10.2</td>
<td>16.6</td>
<td>0.547</td>
<td>3.504</td>
<td>10.38</td>
<td>16.42</td>
<td>0.165</td>
<td>0.414</td>
</tr>
<tr>
<td>Air ( p = 0.35 ) torr</td>
<td>10.9</td>
<td>45.7</td>
<td>1.135</td>
<td>39.51</td>
<td>12.87</td>
<td>43.72</td>
<td>0.193</td>
<td>1.088</td>
</tr>
<tr>
<td>Air ( p = 16 ) torr and changing</td>
<td>11.2</td>
<td>51.2</td>
<td>1.186</td>
<td>47.46</td>
<td>13.57</td>
<td>48.83</td>
<td>0.198</td>
<td>1.148</td>
</tr>
</tbody>
</table>
FIGURE 1.1b  Histogram of energy consumption per capita for different physical quality of life index (PQI) for the people of the world. The percentages shown in each bar are the percentages within that range of PQI.
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 m$^3$/week
Standard deviation: 0.351 m$^3$/week

Contribution due to OAPs flats
(1 or 2 occupants)

Dwelling mean weekly hot water consumption m$^3$

**FIGURE 2.5** MEAN WEEKLY HOT WATER CONSUMPTION FOR 87: VARIOUS SITES. FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS' BY G. A. PICKUP [7]

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

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


FIGURE 2.10

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

ONE-FAMILY HOUSES (SMALL SCALE)

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 2.19 PROTO-PROMETHEUS TEMPERATURE DISTRIBUTION (WITH FAN ON), ON 22ND SEPTEMBER 1981 AT 14:25 h.
Figure 2.19 Frequency distribution of pebble smallest dimension.
FIGURE 2.20 FREQUENCY DISTRIBUTION OF PEBBLE LARGEST DIMENSION
**Figure 2.21**  Proto-Prometheus store temperature, from 22nd September 1981 to 2nd October 1981 under stagnation (fan off).

**Figure 2.22** Energy demand for a 3-bedroom house built to R75 building regulations (type A) with solar heating supplied by a basic type Prometheus.
Figure 2.23  Effect of changing the collector overall heat loss coefficient on the % of annual energy supplied by Prometheus to a Type A1 house.

Figure 2.24  Effect of changing the collector area on the % of annual energy supplied by Prometheus to a Type A1 house.
FIGURE 2.25  THE EFFECT OF CHANGING THE STORAGE TANK INSULATION THICKNESS ON THE % OF SOLAR ENERGY SUPPLIED BY PROMETHEUS TO A TYPE 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 2.8 m² OF COLLECTOR PER HOUSE) FOR A TYPE A 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.
Insulation measures
- Standard solar system with short term storage
- Interseasonal solar system

**Figure 3.3**
Useful energy saved and extra cost for various insulation options and solar systems installed while constructing a basic Type A0 house.

**Figure 3.4**
Energy demand for a 3-bedroom terrace built to 1975 building regulations and energy supplied by 4, 12 and 24 m² of solar collector.
**Figure 3.5** Energy demand for a well insulated 3 bedroom house, and energy supplied by 4, 12, and 24 m² of solar collector.

**Figure 3.6** Comparison of predicted solar energy supply for a house using the E-chart method with the measured solar supply for the Milton Keynes solar house.
**Figure 3.7** – Useful energy saved and extra costs for various insulation options and solar systems retrofitted to an existing Type B0 house.
**FIGURE 4.1** NONPOROUS ABSORBER-TYPE AIR HEATERS.

**FIGURE 4.2** POROUS ABSORBER-TYPE AIR HEATERS.
Figure 4.3 Hybrid Photovoltaic and Air Heating Solar Collector

Figure 4.4 Collector Heat Losses
FIGURE 4.5  REAR DUCT COLLECTOR CONFIGURATION

FIGURE 4.6  TOP DUCT COLLECTOR CONFIGURATION
The curves correspond to the following relations:

**H.C. Northam**

\[ h_w = 5.7 + 3.9v \]

**Watmuff**

\[ h_w = 2.8 + 3.0v \]

**Lloyd**

\[ h_w = \frac{0.15 \times R^{0.46} \times k}{\left[ \frac{2.1uw}{L+u} \right] + k} \] for \( T_a = 10^\circ C, T_e = 15^\circ C, L = 1m, W = 1m. \)

**Sparrow**

\[ h_w = \frac{k \times 0.86 \times R^{0.46} \times T_e}{\left[ \frac{2.1uw}{L+u} \right] + k} \] for \( T_a = 10^\circ C, T_e = 15^\circ C, L = 6m, W = 1m. \)

**Green**

\[ h_w = \left( h_{10} + h_{25} \right)^{0.8} \] for \( A = 1.4m^2, 45^\circ \) inclination

**KIND**

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

**Figure 4.7** Correlations for wind heat loss coefficient
FIGURE 4.8 FLOW DIAGRAM OF 'EFFICZ' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A PARABOLIC AIR HEATING COLLECTOR.
FIGURE 4.9  FLOW DIAGRAM OF 'EFFIC' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A TOT DUCT AIR-WING COLLECTOR
Figure 4.10 Response of Zero and Long Time Constant Collector to Changing Insolation
FIGURE 4.11 NODAL CONFIGURATION OF A FLAT PLATE, REAR DUCT AIR HEATING, SOLAR COLLECTOR AS USED IN 'RREADCT'.

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 WM 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 $= 20 \text{ cm}^{-1}$)

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

Figure 5.7  Solar transmittance of structured polycarbonate versus incident angle. Source: H.L. Redfoot et al., "Glazing solar collectors with acrylic and double walled polycarbonate plastics"
FIGURE 5.8 ORIFICE PLATE AND ITS LOCATION FOR MEASURING MASS FLOW RATE
FIGURE 5.9  ASHRAE STANDARD 93-77 TESTING CONFIGURATION FOR A SOLAR COLLECTOR WHEN THE TRANSFER FLUID IS AIR.

FIGURE 5.10  OPEN UNIVERSITY AIR COLLECTOR TESTING CONFIGURATION.
Figure 5.11: Response of structured polycarbonate collector to a step change in insolation from 750 W/m² to zero with a fluid flow rate of 7.2 kg/hr.

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 at 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 $m = 0.5 \text{ kg/hr}$.

Figure 5.19  Calibration curve for pitot flow orifice plate for air at 20°C.
FIGURE 5.20 PRESSURE DISTRIBUTION WITHIN COLLECTOR TEST CONFIGURATION WITH AND WITHOUT FLUID FLOW

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

FIGURE 5.21 SAMPLE OUTPUT OF D.C. WALL COLLECTOR TO TESTING OUTDOORS NOT UNDER STOPLY 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 TRANIENT EFFICIENCY CURVE FOR 0.5 mm ABSORBER PLATE
**Figure 5.30** Transient diffuse radiation

**Figure 5.31** Fluid outlet temperature under transient conditions.

**Figure 5.32** Integrated response of collector over 1 and 2 minutes to transient radiation.
FIGURE 5.33. THE VARIATION IN $F_{uL}$, $F_{m}(N)$, AND $\delta F_{uL}$ WITH THE NUMBER OF INCREMENTS USED IN THE TRANSIENT ANALYSIS.
FIGURE 5.33 COLLECTOR RESPONSE FUNCTIONS FOR OPTIMUM VALUES OF $N$.

FIGURE 5.35 CALCULATED COLLECTOR TIME CONSTANTS FOR DIFFERENT COLLECTOR CONFIGURATIONS. SEE TABLE 5.3.
FIGURE 5.36  EFFICIENCY CURVE GENERATED FROM TRANSIENT TESTING RESULTS
OF THE SP COLLECTOR AND PROCESSED BY 'TRANS' FOR N=1.
UNCORRECTED FOR ANGLE OF INCIDENCE OF RADIATION.

FIGURE 5.37  TRANSIENT INSOLATION DURING TESTING OF SP COLLECTOR
ON 17/6/83, CONTINUED ON NEXT PAGE.
FIGURE 5.37 CONTINUED. TRANSIENT INSOLATION DURING TESTING OF 3P COLLECTOR ON 14/6/83 - 15/6/83.
Figure 5.30 Standard error in $F_{UL}$ versus $N$, the number of previous time steps influencing the collector's present performance under transient conditions for the structured polycarbonate collector.

Figure 5.31 Efficiency curve for outdoor transient testing of structured polycarbonate collector. Data generated from 'TRANS' for N=7, uncorrected for angle of incidence of radiation.
FIGURE 5.40 COLLECTOR RESPONSE FUNCTION FOR S.P. COLLECTOR N=7.

FIGURE 5.41 EFFICIENCY CURVE FOR OUTDOOR TRANSIENT TESTING OF D.C. HALL COLLECTOR (MANUS ABBEY). 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 Maxorb.
**FIGURE 5.44** INTENSITY DISTRIBUTION ACROSS COLLECTOR DURING INDOOR TESTING IN Wm⁻², AVERAGE INTENSITY 2.11 Wm⁻², STANDARD DEVIATION ± 0.4 Wm⁻².

**FIGURE 5.45** WING GENERATOR.
Figure 5.46 Variation of Wind Speed (m/s), 5mm Above Collector Surface

Figure 5.47 Measured and Predicted Heat Loss $U$ for D.C. Wall Collector (Non-Selective) with Varying Wind Speed Indoors.
Figure 5.48  Efficiency curve of structured polycarbonate collector measured indoors and outdoors.

Figure 5.49  Efficiency curve of D.C. Hall collector with non-selective absorber (Nextel). Indoor measurements and computer predictions.
**Figure 5.50** Redesigned Indoor Collector Test Facility

**Figure 5.51** Steady State and Zero Testing Efficiency Curves
Figure 5.52: Steady State and Efficiency Curve Plotted Against Mean Absorber Plate Temperature ($T_p$) for Simulated Collector.

ASHRAE STEADY STATE

ZERO TESTING $T_{sky} = T_{a} - 20$

$T_{sky} = T_{a}$

$$\left(\frac{T_p - T_a}{I}\right) / \left(\text{°C} \cdot \text{W}^{-1}\right)$$
Figure 5.53: Steady state and zero testing efficiency curve plotted against mean fluid temperature ($T_m$) for simulated collector.
Figure 5.54. Collector temperature profile for model collector under steady state and zero testing conditions for the same fluid inlet temperature (30°C).

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

Figure 5.57: \( \frac{F_{w L}}{U} \) versus mean fluid temperature for collector dyi under zero testing and a large steady state testing.
Figure 5.58 Efficiency curves for D.C. Hall collector using different test methods.
FIGURE 5.59  EFFICIENCY CURVE FOR STRUCTURED POLYCARBONATE COLLECTOR
UNDER DIFFERENT TEST CONDITIONS

FIGURE 5.60  TOP LOSS COEFFICIENT VERSUS ABSORBER TEMPERATURE FOR P.D. CHALL
TYPE COLLECTOR (HARROWS ABSORBER)
Figure 5.61: Steady-state efficiency of solar collector (black chrome) measured during operation and indoor testing, source: Taylor, P.J. "Performance of Selective and Non-Selective Solar Thermal Absorbers in a Working Installation," Solar World Congress edited 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 6.5
Maximum improvement to flat plate collector performance by increasing $\tau$ and $\alpha$. 

$\frac{T_i - T_a}{T} = \frac{1}{\alpha}$

$\tau$ and $\alpha$. 

$\frac{T_i - T_a}{T} = \frac{1}{\alpha}$
FIGURE 6.6  REFLECTANCE OF SOLAR COLLECTOR COATINGS

FIGURE 6.7  STEADY STATE EFFICIENCY OF SOLAR COLLECTOR MEASURED DURING OPERATION AND INDOOR TESTING. SOURCE: TAYLOR, T. J., "PERFORMANCE OF SELECTIVE AND NON-SELECTIVE SOLAR THERMAL ABSORBERS IN A WORKING INSTALLATION," SOLAR WORLD CONGRESS ED. BY S. N. SEKODA, VOL. 2, PP 1149-1153.
**Figure 6.8**
Efficiency curves for different methods of heat loss reduction.

**Figure 6.9**
FIGURE 6.10  
EFFICIENCY CURVE OF ADVANCED FLAT PLATE COLLECTOR WITH XENON
BETWEEN THE ABSORBER AND COVER AT A PRESSURE OF 1 TORR.
[27]
**FIGURE 6.12** 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 PVT SEPARATIONS (z) AND TWO LEVELS OF INCIDENT INSOLATION.
Figure 6.14 Efficiency curve for a combined parabolic concentrator compared with a flat plate collector. Source: Argonne National Laboratory Tech Report.

Figure 6.15 Global and diffuse insulation 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.
(a) 

(b) 

(c) 

(d) 

\[ WIND = 1.0 \, \text{m s}^{-1} \]

TK = TA - 20, clear skies

TK = TA - 10, overcast skies

Figure 6.18 Simulated ambient conditions. For further details see text in Appendix C.
Figure 6.14  Steady-state efficiency ($\eta$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\bar{\eta}$ are for a variety of simulated conditions (see Table 1 and Figure 3). *1

(i) S\textsuperscript{OJ}/T\textsuperscript{AJ}, flow 2  
(ii) S\textsuperscript{OM}/T\textsuperscript{AM}, flow 2  
(iii) S\textsuperscript{OD}/T\textsuperscript{AD1}, flow 2  
(iv) S\textsuperscript{OM}/T\textsuperscript{AM}, flow 3  
(v) S\textsuperscript{1M}/T\textsuperscript{1AM}, flow 2  
(vi) S\textsuperscript{OD}/T\textsuperscript{AD1}, flow 3  
(vii) S\textsuperscript{1D1}/T\textsuperscript{AD1}, flow 2  
(viii) S\textsuperscript{OD}/T\textsuperscript{AD2}, flow 3  
(ix) S\textsuperscript{1D2}/T\textsuperscript{AD1}, flow 2  
(x) S\textsuperscript{1D3}/T\textsuperscript{AD1}, flow 2  
(xi) S\textsuperscript{1D}/T\textsuperscript{AD1}, flow 2.
FIGURE 6.20  'FMTC' AIR HEATING SOLAR COLLECTOR DEVELOPED BY G.E. [4.2]

Figure 6.22  Instantaneous efficiencies of the FMC collector and a single glazed flat plate collector and their variation with insolation. [42]
FIGURE 7.1  THERMAL CONDUCTIVITY OF VARIOUS GASES AT 20°C VERSUS MOLECULAR WEIGHT.

FIGURE 7.2  CELLULAR CONVECTION FOR A LIQUID. FOR GASES, DUE TO THEIR DIFFERENT TEMPERATURE VISCOSITY RELATIONSHIP, THE GAS FALLS IN THE CENTRE OF THE CELL.
**FIGURE 7.3**  OBSERVATION OF CELLULAR CONVECTION

**FIGURE 7.4**  BASE FLOW BETWEEN INCLINED PLATES
Figure 7.5  Local heat transfer coefficient between two inclined plates (see Figure 7.6). Source: Normand C. and Pomery Y. 'Convective instability: A physicist's approach', Journal of Modern Physics, vol. 49, no. 3, July 1977.

Figure 7.6  Schematic depicting effect of gap spacing on conductance
\[ h \] versus tilt angle to the horizontal for air and emission for various absorber temperatures \( T_a \) with cover temp = 10°C. 

\[ \text{Figure 7.8} \]
\( h_r \) heat transfer due to radiation between a non-selective absorber \((\varepsilon = 0.9)\) and a glass cover \((\varepsilon = 0.9)\)

\( h_c \) heat transfer due to convection and conduction in air at atmospheric pressure

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

**Figure 7.9** Heat Transfer Coefficient Variation with Absorber Temperature for Convection and Radiation.
FIGURE 7.10 TRUE AND PREDICTED HEAT LOSS BETWEEN TWO PARALLEL PLATES 5 x 5 cm
COVER TEMPERATURE 10 °C
FIGURE 7.11  EFFECTIVE RAYLEIGH NUMBER VERSUS MOLECULAR WEIGHT FOR DIFFERENT GASES, AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL PLATES, SEPARATION D = 0.00m, COLD PLATE TEMPERATURE 10°C, HOT PLATE 30°C
**FIGURE 7.12**

Heat transfer coefficient for gases of different molecular weight, for $S = 5$ cm, cold plate temperature $10^\circ C$, hot plate temperature $30^\circ C$. 

Symbols used: $O_3$, $H_2$, $C_2H_6$, $O_2$, $N_2$, $CO$, $H_2O$, $NO$, $CO_2$, $SO_2$, $CHO$, $Cl_2$, $Ar$, $Kr$, $Xe$. 

Molecular weight (g mol$^{-1}$)
Figure 7.13: Cost versus 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, $s = 5 \text{ cm}$, $T = 293 \text{ K}$, $T_i = 323 \text{ K}$ 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: Hulotra A and Garg, H. P., 'Minimizing convective heat loss'. Solar Energy, Vol. 25, No. 6, pp. 523.

**Figure 7.17** Reflected solar rays for a multi cover solar collector.
FIGURE 7.18  A SOLAR RAY AND CUT-AWAY DIAGRAM OF A HEXAGONAL HONEYCOMB COLLECTOR. SOURCE: HOLLANDS, K.G.T. 'ADVANCED NON-CONCENTRATING SOLAR COLLECTORS' SOLAR ENERGY CONVERSION EDITED BY A.E. DIXON AND J.D. LESLIE, PERGAMON PRESS 1979
FIGURE 7.19 HEAT TRANSFER COEFFICIENT $h_c$ DUE TO NATURAL CONVECTION FOR AIR AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL FLAT PLATES SPACING 5 cm, $T_s = 293 K$, WITH A HONEYCOMB AND WITH SLATS Aspect Ratio 5
Figure 7.21
Rayleigh number versus temperature for argon and air at atmospheric pressure between two parallel flat plates spacing $s = 5$ cm, cold plate temperature $T_c = 10^\circ$C.
Figure 7.22 Heat transfer coefficients for several collector configurations

- Convection and conduction, air, atmospheric pressure, tilt angle $\theta = 0^\circ$
- Convection and conduction, air, atmospheric pressure, tilt angle $\theta = 60^\circ$
- Convection and conduction, argon, atmospheric pressure, tilt angle $\theta = 0^\circ$
- Convection and conduction, air, honeycomb, tilt angle (60°)
- Radiation, maxorb absorber ($E_s=0.9$)ậu iron glass cover ($E_s=0.98$)
- Convection only, air at $4\times10^3\text{ Pa}$
- Convection only, argon at $3\times10^3\text{ Pa}$
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, $s = 5\text{ cm}$, VARIOUS TEMPERATURE DIFFERENCES
Figure 7.29 Theoretical and Measured Heat Transfer $h_c$ for Air and Argon

EXPERIMENTAL POINTS

- Argon
- Air
- Argon with helium

HOT PLATE TEMPERATURE, $T_\alpha / ^\circ C$

CONDUCTION AND CONVECTION HEAT TRANSFER COEFFICIENT, $h_c / [W/m^2 K]$
FIGURE 7.30 THEORETICAL HEAT TRANSFER ACROSS STRUCTURED POLYCARBONATE OF VARIOUS THICKNESSES. BOTH RADIATION AND CONVECTION, ASSUMING FLAT CONVECTION AND A MEASURED EMISIVITY OF 0.72.
PLATE 2.1
Proto Prometheus: 1, Collector. 2, Store Top Insulation and Collector Rear Insulation. 3, Fan Motor. 4, Monitoring Equipment. 5, Space for Insulation.
PLATE 2.2 PROTO PROMETHEUS STORAGE TANK FILLED WITH PEBBLES.
PLATE 5.1

SOLAR SIMULATOR TESTING A STRUCTURED POLYCARBONATE COLLECTOR.
17. STRUCTURED POLYCARBONATE COLLECTOR, 16. WIND GENERATOR,
14. COOLING RAY LAMPS.
PLATE 5.2 INDOOR COLLECTOR TEST FACILITY
7. DATA LOGGER, 8. STRUCTURED POLYCARBONATE COLLECTOR,
9. PRESSURE TAPS, 10. SITE OF ORIFICE PLATE
PLATE 7.1

VIEW OF HEATED OIL FILM FROM AN INFRARED CAMERA.
THE BRIGHTER THE SPOT THE HOTTER THE SPOT.
PLATE 7.2  GUARDED HOT PLATE THERMAL CONDUCTIVITY RIG
11. INSULATED GUARD RING AND TEST CELL, 12. GAS CYLINDER
13. WATER COOLER, 14. HEATER POWER SUPPLY
APPENDIX A

SUNSTORE: Computer model of interseasonal store and sample output.
10 REM ******************** SUNSTORE *******************
20 NUM = 200
30 SHORT DEMAND(12)
40 SHORT SOL(12,24)
50 ASSIGN 1 TO "SUN DATA"
60 READ# 1 SOL(),
   each month
70 SHORT TEM(12,24)
80 ASSIGN 2 TO "TEM DATA"
90 READ# 1 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=total annual solar radiation
180 PRINT "="
190 PRINT "" SUNSTORE "="
200 IMAGE //**** SOLAR RADIATION AT KEN DISTRIBUTION OF HOURSLY GLOBAL IRRADITION //****
210 PRINT USING 220
220 IMAGE "******** ON A HORIZONTAL SURFACE IN MJ/m2 **********" //****
230 FOR H=1 TO 12 :
240 PRINT TAB (6&M):MONTHS(M);;
250 NEXT M
260 FOR H=1 TO 24 :
270 FOR M=1 TO 12 :
280 PRINT TAB (M6)&:SOL(M, H);
290 TOTsun=TOSUN=SOL(M, H)&DAYS(M) ! calculate total annual solar radiation.
300 NEXT M
310 PRINT "" STORAGE = "" SOLAR RADIATION MJ/m2"
320 PRINT "" "" DATA INPUT"" ""************
330 REM ""********************
340 REM """" F1=.9 ! HEAT TRANSFER FACTOR
350 C=637 ! SPECIFIC HEAT OF STORE MATERIAL (KJ/KGC)
360 MET="PEBBLES" ! STORAGE MATERIAL
370 WIDTH=10! STORAGE WIDTH IN METERS
380 HEIGHT=4! STORAGE HEIGHT IN METERS
390 LENGTH=280! STORAGE LENGTH IN METERS
400 HOUSE=100! NUMBER OF HOUSES SURVED BY STORE
410 DENSITY=600! DENSITY OF STORAGE MATERIAL (Kg/m3)
420 K2=1! OVERALL COLLECTOR HEAT LOSS COEFFICIENT (W/m2)
430 COLAREA=2800! TOTAL AREA OF COLLECTORS SURVING STORE (m2)
440 COND=.036! THERMAL CONDUCTIVITY OF STORAGE INSULATING MATERIAL (W/m2C)
450 THICK=4.5 ! THICKNESS OF INSULATING MATERIAL (m)
460 OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES
470 T=10! TEMPERATURE OF GROUND SURROUNDING STORE (C)
480 Y=10! NUMBER OF YEARS PROGRAM TO RUN DO NOT USE MORE THAN 10 IF qaux>0
490 Ta=10! TEMPERATURE OF GROUND SURROUNDING STORE (C)
500 T50=30! MINIMUM STORAGE TEMPERATURE (C)
510 REM """" STORAGE = """" SOLAR RADIATION MJ/m2"
520 REM """"-----------------------
530 CALL I
540 NUI=1
550 T1=30
560 TOTAL=0
570 TOTD=0
580 qNUI=0
590 qTOTD=0
600 t1TOD=0
610 DTOD=0
620 qAUXTO=0
630 PLOTT IS 1
640 GRAPHALL
650 LIMIT 0,150,0,70
660 MSCALE 0,0
670 GRID 1,1,0,10,10
680 qTOT=0
690 NUI=0
700 EXTRAN=0
710 COUNT=0
720 qAUX=0
730 VOL=WIDTH*HEIGHT*LENGTH
740 VOLL=OL/HOUSE
750 Mass=VOLL/DENSITY/1000
760 m=mass(COLAREA/HOUSE)
770 AREASTOR=AREATO+HEIGHT*2*HEIGHT*LENGTH
780 AS=AREASTOR/AREATO
790 USCONDU/THICK
800 USCONDU/THICK
810 PRINT USING 800
820 IMAGE //"""" STORE """" //****
830 PRINT "STORE LENGTH:";LENGTH;"Meters;" Width=";WIDTH;"Meters", HEII="HEII
840 PRINT "VOLUME:";VOL;"m3"
850 PRINT "STORAGE MATERIAL;" METAL; " DENSITY=";DENSITY;"Kg/m3;" SPECIFI
860 PRINT "STORE INSULATION THICKNESS;" THICK=";THERMAL CONDUCTIVITY;" CONI
870 PRINT USING 880
880 IMAGE //"""" COLLECTOR """" //****
890 PRINT "TOTAL COLLECTOR AREA=";COLAREA;"m2"
900 PRINT "F1=HEAT TRANSFER FACTORE=Fr heat removal factor if st; has a good heat heatexchanger=";F1
910 PRINT "UL=OVERALL HEAT LOSS COEFFICIENT;" UL
920 PRINT "Ta=OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES;" Ta
930 PRINT USING 940
940 IMAGE //"""" HOUSE """" //****
950 PRINT "NUMBER OF HOUSES=";HOUSE
960 PRINT "THE MONTHLY HEATING LOAD FOR EACH HOUSE IS (heating and hot water)!
970 FOR K1=1 TO 12
980 REM """" STORE = """" SOLAR RADIATION MJ/m2"
990 REM """"-----------------------
1000 REM """" READER DEMAND( 12) READS MONTHLY DATA OF HEATING LOAD FOR EACH HOUSE(MJ)
**
195
1000 REM
1005 PRINT "SYSTEM OPERATION:"
1010 PRINT "Ta = Ambient Temperature Averaged over periods of collector operation (°C)"
1015 PRINT "Tt = Time Period of Collector Operation (Ms)"
1020 PRINT "Tn = Normalized Net Heat to Storage = qT-1-1x (M)/m2)"
1025 PRINT "qT = Useful Heat Collected = qN+1 (M)/m2)"
1030 PRINT "Tm = Normalized Total Monthly Load (M)/m2)"
1035 PRINT "i = Solar Radiation (J/m2)"
1040 PRINT "t = Time (s)"
1045 PRINT "qN = Net Heat to Storage (M)/m2)"
1050 PRINT "qT = Solar Radiation (J/m2)"
1055 PRINT "qUX = Auxiliary Heat (Kwh)"
1060 END

1210 M ITH Tso Ta Tt It qN ts4 qT im qUX
1220 PRINT

1230 FOR I=1 TO 12
1240 Tm=0
1250 TSOL=0
1260 TEMP=0
1270 FOR J=1 TO 24
1280 ITHUL=[Ta](TSOL-TEM(I),(J))
1290 IF ITH=0 THEN GOTO 1330
1300 IF ITH=0 THEN GOTO 1330
1310 IF ITH=0 THEN GOTO 1330
1320 IF ITH=0 THEN GOTO 1330
1330 NEXT J
1340 IF Tm=0 THEN GOTO 1360
1350 TEMP/TEMP/TIM
1360 TIM[=360000DAYS(1)]
1370 TSOL=TSOL+Tm
1380 IF Tm=0 AND COUNT=0 THEN GOTO 1770
1390 TEMP/TEMP/TIM
1400 TIM[=360000DAYS(1)]
1410 qT[=1+TSOL-ULS(1+TSO-TEMP)]]
1420 qN[=1+TSOL-ULS(1+TSO-TEMP)]]
1430 qUX[=1+TSOL-ULS(1+TSO-TEMP)]]
1440 IF Ts=350 THEN GOTO 1530
1450 IF Tm=0 THEN GOTO 1770
1460 IF Tm=0 THEN GOTO 1770
1470 IF Tm=0 THEN GOTO 1770
1480 IF Tm=0 THEN GOTO 1770
1490 IF Tm=0 THEN GOTO 1770
1500 IF Tm=0 THEN GOTO 1770
1510 IF Tm=0 THEN GOTO 1770
1520 GOTO 1540
1530 Tm=1+TSOL-ULS(1+TSO-TEMP)]]
1540 I=1+TSOL-ULS(1+TSO-TEMP)]]
1550 qN[=1+TSOL-ULS(1+TSO-TEMP)]]
1560 qUX[=1+TSOL-ULS(1+TSO-TEMP)]]
1570 qUX[=1+TSOL-ULS(1+TSO-TEMP)]]
1580 COUNT=0
1590 IF COUNT=0 THEN GOTO 1770
1600 IF COUNT=0 THEN GOTO 1770
1610 IF COUNT=0 THEN GOTO 1770
1620 IF COUNT=0 THEN GOTO 1770
1630 IF COUNT=0 THEN GOTO 1770
1640 IF COUNT=0 THEN GOTO 1770
1650 IF COUNT=0 THEN GOTO 1770
1660 IF COUNT=0 THEN GOTO 1770
1670 IF COUNT=0 THEN GOTO 1770
1680 IF COUNT=0 THEN GOTO 1770
1690 IF COUNT=0 THEN GOTO 1770
1700 IF COUNT=0 THEN GOTO 1770
1710 IF COUNT=0 THEN GOTO 1770
1720 IF COUNT=0 THEN GOTO 1770
1730 IF COUNT=0 THEN GOTO 1770
1740 IF COUNT=0 THEN GOTO 1770
1750 IF COUNT=0 THEN GOTO 1770
1760 IF COUNT=0 THEN GOTO 1770
1770 IF COUNT=0 THEN GOTO 1770
1780 IF COUNT=0 THEN GOTO 1770
1790 IF COUNT=0 THEN GOTO 1770
1800 IF COUNT=0 THEN GOTO 1770
1810 PRINT USING 1970: "TOTAL", qN, qUX, Tt, COUNT, COUNT, COUNT, COUNT
1820 PRINT
1830 SUN[=1-(qUX/TSOL-ULS(1+TSO-TEMP)]]
1840 PRINT USING 1980: "TOTAL", qN, qUX, Tt, COUNT, COUNT, COUNT, COUNT
1850 PRINT USING 1990: "TOTAL", qN, qUX, Tt, COUNT, COUNT, COUNT, COUNT
1860 PRINT USING 2000: "TOTAL", qN, qUX, Tt, COUNT, COUNT, COUNT, COUNT
1870 PRINT "TOTAL AUXILIARY ENERGY FOR SYSTEM:" -(qUX/TSOL-ULS(1+TSO-TEMP)]]
1880 PRINT "TOTAL AUXILIARY ENERGY PER HOUSE:" -(qUX/TSOL-ULS(1+TSO-TEMP)]]
1890 PRINT "TOTAL AUXILIARY ENERGY PER HOUSE:" -(qUX/TSOL-ULS(1+TSO-TEMP)]]
1900 PRINT
1910 PRINT "THE END"

average store temp during month storage loss if store at Temp current store at Temp liquid in is Temp store heat to storage
auxiliary heat to keep store at
annual rad when collector is on annual solar energy collected annual net heat collected annual useful heat collected annual store tank losses
annual auxiliary energy per m2. annual auxiliary energy per m2. count. no of months store stop prog when run for n years final store temp: initial store T from DEC to JAN
% solar rad col above threshold % solar energy collected
### SOLAR-RADIATION AT NEW DISTRIBUTION OF HOURLY-GLOBAL IRRADIATION

***ON A HORIZONTAL SURFACE IN MJ/m²***

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TOTAL ANNUAL SOLAR RADIATION = 3410.94 MJ/m²

### STORE

**STORE LENGTH** = 280 Meters  **WIDTH** = 10 Meters  **HEIGHT** = 4 Meter

**VOLUME** = 11200 m³

**STORAGE MATERIAL PEBBLES**

**DENSIY** = 1600 kg/m³  **SPECIFIC HEAT** = 0.877 KJ/kg°C

**STORE INSULATION THICKNESS** = 6 m  **THERMAL CONDUCTIVITY** = 0.056 W/m²K

### COLLECTOR

**TOTAL COLLECTOR AREA** = 2800 m²

**F1 = HEAT TRANSFER FACTOR** (equivalent to Fr heat removal factor if store has a good heat exchanger) = 0.9

**UL = OVERALL HEAT LOSS COEFFICIENT** = 1

**Tv = OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES** = 0.8

### HOUSE

**NUMBER OF HOUSES** = 100

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

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TOTAL = 462

1026.80 1488.93 390.2 **-462.**

**% 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** = 129390.6 7849 MJ **(-35943.3551803 KWH)**

**AUXILIARY ENERGY PER HOUSE** = 129390.6 7849 MJ **(-35943.3551803 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.
10
20 REM **************************** PROGRAM TDLAIR ***************
30 LET R  = 0.0004D0 + 0.000046351
40 LET T0 = T + DELT
50 FOR I=0 TO 20
60 T0(TP=185) ABSORBER TEMP
70 T0(TA=181) Ambient temp (C)
80 T0(WD=1) Wind speed (ms-1)
90 LET E  = 0.95 Absorber emissivity
100 LET EDP = 0.8 Cover plate emissivity
110 LET S = 1 Plate separation (cm)
120 LET g = 9.81 ACCELERATION DUE TO GRAVITY (m/s2) AT LONDON
130 LET K = 0.257 THERMAL CONDUCTIVITY OF GAS AT TAVE (W/m2C)
140 LET B = 1 Life angle (Horizontal)
150 LET CP = 1007 HEAT CAPACITY OF AIR (J/kgK)
155 LET CP = 1007 HEAT CAPACITY OF GAS BETWEEN COVER AND ABSORBER KG
160 LET S = 100 COVER TO METERS
170 LET L = 1
180 LET W = 1
190 LET 21LW/(L+W) = 0.000046351
200 REM **************************** THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFECT GAS
300 LET V = TAVE (V,0.00076,0.034406
310 LET VIS = TAVE (V,0.000046351,0.000046351
320 LET V = TAVE (V,0.000046351,0.000046351
330 LET V = VIS/DEN KINETIC VISCOSITY
340 LET Gr = Gr/VS3/DT(V/2) GRASHOF NUMBER
350 LET Pr = CP/VIS/K
360 LET R = Gr/Pr RAYLEIGH No
370 REM **************************** CALCULATE NUSSELT NUMBER
380 LET N = 1708 (Ra T expansivity) / 5830 (1/3-1)
390 LET N = 1708 (Ra T expansivity) / 5830 (1/3-1)
400 LET N = 1708 (Ra T expansivity) / 5830 (1/3-1)
410 LET N = 1708 (Ra T expansivity) / 5830 (1/3-1)
420 LET=1.444411 (1-SIN (1.8B)) / 1.6708 (Ra T expansivity) + N2 NUSSELT No
430 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
440 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
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660 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
670 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
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730 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
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800 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
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830 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
840 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
850 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
860 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
870 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
880 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
890 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
900 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
910 LET hkc/sINU = HEAT TRANSFER COEFFICIENT
920 END
10 REM *********************** EFFIC ********************
20 REM --- THIS PROGRAM CALCULATES THE STEADY STATE EFFICIENCY OF A TOP DUCT
30 REM AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
40 REM p.237 Figure 6.12.1 (d)
50 REM
51 PRINT "INPUT VARIABLE DATA"
52 PRINT "F = 0 TO 10"
53 PRINT "m = 1/4; j = 10 ; MASS FLOW RATE (kg/hr)
54 PRINT "Ta = 16.2 ; AMBIENT TEMP (C)
55 PRINT "Ti = 1 ; IN FLUID TEMPERATURE (C)
56 PRINT "T2 = 20.4 ; ABSORBER TEMPERATURE (C) IF THIS CHANGES ALSO CHANGE Ti"
57 PRINT "T1 = (T2-TA)/2+TA"
58 PRINT "WIND = 5 ; WIND SPEED (m/s)
59 PRINT "I = 236 ; INTENSITY OF SOLAR RAD (W/m2)
60 PRINT "Ta = 8 ; TRANSMISSIVITY & ABSORBIVITY OF COVER AND ABSORBER
61 PRINT "E = 0.85 ; EMISSIVITY OF ABSORBER
62 PRINT "K = 0.34 ; CONDUCTIVITY OF REAR INSULATION (W/mC)
63 PRINT "Ti = 0.075 ; INSULATION THICKNESS (m)
64 PRINT "A = 1 ; COLLECTOR AREA (m2)
65 PRINT "L = 2 ; COLLECTOR LENGTH IN METERS
66 PRINT "W = 1 ; WIDTH OF COLLECTOR IN METERS
67 PRINT "S = 1 ; PLATE SEPARATION IN CM
68 PRINT "D = 1 ; FIN SEPARATION IN CM
69 PRINT "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
70 IF J = Y THEN GOTO 470
71 IF A = "N" THEN GOTO 470
72 PRINT "COLLECTOR INITIAL PARAMETERS ARE"
73 PRINT "M = 1/4; j = 10 ; MASS FLOW RATE (kg/hr)
74 PRINT "Ta = 16.2 ; AMBIENT TEMP (C)
75 PRINT "Ti = 1 ; IN FLUID TEMPERATURE (C)
76 PRINT "T1 = (T2-TA)/2+TA"
77 PRINT "WIND = 5 ; WIND SPEED (m/s)
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81 PRINT "K = 0.34 ; CONDUCTIVITY OF REAR INSULATION (W/mC)
82 PRINT "Ti = 0.075 ; INSULATION THICKNESS (m)
83 PRINT "A = 1 ; COLLECTOR AREA (m2)
84 PRINT "L = 2 ; COLLECTOR LENGTH IN METERS
85 PRINT "W = 1 ; WIDTH OF COLLECTOR IN METERS
86 PRINT "S = 1 ; PLATE SEPARATION IN CM
87 PRINT "D = 1 ; FIN SEPARATION IN CM
88 PRINT "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
89 IF J = "Y" THEN GOTO 470
90 PRINT "COLLECTOR INITIAL PARAMETERS ARE"
91 PRINT "M = 1/4; j = 10 ; MASS FLOW RATE (kg/hr)
92 PRINT "Ta = 16.2 ; AMBIENT TEMP (C)
93 PRINT "Ti = 1 ; IN FLUID TEMPERATURE (C)
94 PRINT "T1 = (T2-TA)/2+TA"
95 PRINT "WIND = 5 ; WIND SPEED (m/s)
96 PRINT "I = 236 ; INTENSITY OF SOLAR RAD (W/m2)
97 PRINT "Ta = 8 ; TRANSMISSIVITY & ABSORBIVITY OF COVER AND ABSORBER
98 PRINT "E = 0.85 ; EMISSIVITY OF ABSORBER
99 PRINT "K = 0.34 ; CONDUCTIVITY OF REAR INSULATION (W/mC)
100 PRINT "Ti = 0.075 ; INSULATION THICKNESS (m)
101 PRINT "A = 1 ; COLLECTOR AREA (m2)
102 PRINT "L = 2 ; COLLECTOR LENGTH IN METERS
103 PRINT "W = 1 ; WIDTH OF COLLECTOR IN METERS
104 PRINT "S = 1 ; PLATE SEPARATION IN CM
105 PRINT "D = 1 ; FIN SEPARATION IN CM
106 PRINT "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
107 IF J = "Y" THEN GOTO 470
108 PRINT "COLLECTOR INITIAL PARAMETERS ARE"
109 PRINT "M = 1/4; j = 10 ; MASS FLOW RATE (kg/hr)
110 PRINT "Ta = 16.2 ; AMBIENT TEMP (C)
111 PRINT "Ti = 1 ; IN FLUID TEMPERATURE (C)
112 PRINT "T1 = (T2-TA)/2+TA"
113 PRINT "WIND = 5 ; WIND SPEED (m/s)
114 PRINT "I = 236 ; INTENSITY OF SOLAR RAD (W/m2)
115 PRINT "Ta = 8 ; TRANSMISSIVITY & ABSORBIVITY OF COVER AND ABSORBER
116 PRINT "E = 0.85 ; EMISSIVITY OF ABSORBER
117 PRINT "K = 0.34 ; CONDUCTIVITY OF REAR INSULATION (W/mC)
118 PRINT "Ti = 0.075 ; INSULATION THICKNESS (m)
119 PRINT "A = 1 ; COLLECTOR AREA (m2)
120 PRINT "L = 2 ; COLLECTOR LENGTH IN METERS
121 PRINT "W = 1 ; WIDTH OF COLLECTOR IN METERS
122 PRINT "S = 1 ; PLATE SEPARATION IN CM
123 PRINT "D = 1 ; FIN SEPARATION IN CM
124 PRINT "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
125 IF J = "Y" THEN GOTO 470
126 IF A = "N" THEN GOTO 470
127 PRINT "COLLECTOR INITIAL PARAMETERS ARE"
128 PRINT "M = 1/4; j = 10 ; MASS FLOW RATE (kg/hr)
129 PRINT "Ta = 16.2 ; AMBIENT TEMP (C)
130 PRINT "Ti = 1 ; IN FLUID TEMPERATURE (C)
131 PRINT "T1 = (T2-TA)/2+TA"
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134 PRINT "Ta = 8 ; TRANSMISSIVITY & ABSORBIVITY OF COVER AND ABSORBER
135 PRINT "E = 0.85 ; EMISSIVITY OF ABSORBER
136 PRINT "K = 0.34 ; CONDUCTIVITY OF REAR INSULATION (W/mC)
137 PRINT "Ti = 0.075 ; INSULATION THICKNESS (m)
138 PRINT "A = 1 ; COLLECTOR AREA (m2)
139 PRINT "L = 2 ; COLLECTOR LENGTH IN METERS
140 PRINT "W = 1 ; WIDTH OF COLLECTOR IN METERS
141 PRINT "S = 1 ; PLATE SEPARATION IN CM
142 PRINT "D = 1 ; FIN SEPARATION IN CM
143 PRINT "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
144 IF J = "Y" THEN GOTO 470
145 IF A = "N" THEN GOTO 470
146 REM ----------- INPUT CONSTANT DATA
147 REM U = 0.00000000567 ; STEFAN-BOLTZMANN CONSTANT (W/m2K4)
148 REM V = 0.0000188 ; VISCOSITY OF AIR IN DUCT (kg/m/s)
149 REM c = 0.0241 ; THERMAL CONDUCTIVITY OF AIR IN DUCT (W/m/K)
150 REM c = 1000 ; HEAT CAPACITY OF AIR AT CONSTANT PRESSURE (J/kg/C)
151 REM
152 REM----------
20 REM -- THIS PROGRAM CALCULATES THE STEADY STATE EFFICIENCY OF A REAR DUCT
27 REM --
30 REM A IR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
33 REM p237 Figure 6.12.1 (d)
APPENDIX C

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

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

NOMENCLATURE

- \text{DY1-5}\): plate and duct-back thicknesses (5)
- \text{f(\theta)}\): transmittance - absorbtance function of the collector
- \text{F_R}\): collector heat-removal factor
- \text{HPA(I)}\): heat-transfer coefficient plate (or duct-back) to air in the I'th segment of the duct
- \text{M}\): duct air flow rate
- \text{NI}\): number of duct segments
- \text{PON}\): threshold power for switch on of air flow
- \text{S}\): irradiance in cover plane
- \text{SO}\): solar beam irradiance
- \text{S1}\): diffuse irradiance on a horizontal surface
- \text{SP}\): irradiance absorbed by plate
- \text{TA}\): ambient temperature
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 plate (diffuse) | 0.10 |
| Emissivity of duct surfaces (diffuse) | 0.91 |
| Emissivity of the cover (diffuse) | 0.85 |

| Thermal properties of air at 283 K for ambient air, at 303 K elsewhere |
| Latitude | 52°N |
| Collector tilt (to horizontal) | 35° |
| Collector orientation | South-facing |

<table>
<thead>
<tr>
<th>Thickness of plate and of duct-back</th>
<th>Collector time-constant (flow 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY1 0.2 mm</td>
<td>85 s</td>
</tr>
<tr>
<td>DY2 0.5 mm</td>
<td>170 s</td>
</tr>
<tr>
<td>DY3 1.0 mm</td>
<td>300 s</td>
</tr>
<tr>
<td>DY4 2.0 mm</td>
<td>580 s</td>
</tr>
<tr>
<td>DY5 5.0 mm</td>
<td>1400 s</td>
</tr>
</tbody>
</table>

Air flow in the rear-duct

<table>
<thead>
<tr>
<th>Flow</th>
<th>Stagnation (M=0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow 0</td>
<td>all TI M = 0.0600 kg s$^{-1}$ (PON, irrelevant)</td>
</tr>
<tr>
<td>Flow 1</td>
<td>TI = 303 K M = 0.0600 kg s$^{-1}$ PON = 128 W</td>
</tr>
<tr>
<td>Flow 2</td>
<td>TI = 323 K M = 0.0562 kg s$^{-1}$ PON = 124 W</td>
</tr>
</tbody>
</table>

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

3.2 Steady-state efficiency curve

We obtained a standard steady-state thermal efficiency curve, of the form \( \eta = \frac{F - (f(\theta) - U_L (T_i - T_A)/S)}{S} \) (1)

where $f(\theta)$ is such that

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

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 $F - f(\theta)$ (equation (1)). The program yields a value of 0.830 for $f(\theta)$, and therefore $F = 0.823$. The slope gives $-F_U L$, 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 $F_U L$ increases as $T_i$ increases ($T_A$, $S$ constant), largely because the radiative heat transfer coefficients increase with increasing temperature differences, and though $F$ decreases it does not offset the increase in $U_L$. These values of $f(\theta)$, $F$ 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 insolutions, the prefix S0 denoting the clear sky irradiance normal to the beam, and the prefix S1 the overcast diffuse irradiance on a horizontal surface. In the cases in Figure 3(b) the only variation in insolation is the diurnal envelope shown. By contrast in Figures 3(c) and (d) the insolation flips between the two envelopes shown, the square wave periods being indicated, the conditions remaining diffuse throughout. In clear sky conditions the sky temperature is 20 K below 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

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

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 \( \bar{\eta} \) is never being wrongly evaluated.

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

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

The advantage of low mass could, in principle, be more marked under intermittent insolation. S1D1-S1D3 provide such conditions (Figure 3), the periodicities lying within the range of time-constants in Table 1. However, Figure 2 shows that, even in marginal conditions, very little further advantage in low mass is obtained, though DY1-DY3 are more spread out than with the diurnal envelope alone.
reason for such a slight improvement is that whereas a low mass collector will "follow" the insolation, possibly switching the air flow on and off, a high mass collector, once it has warmed to the point where the air flow switches on, will tend to stay at a fairly constant temperature. The overall effect, for a wide variety of conditions, is that the time-averaged temperatures of the air flow are not very sensitive to the mass. Therefore there is very little difference in the amount of heat extracted. A similar conclusion was reached by Klein et.al [1].

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

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

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

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

REFERENCES


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


Figure 1 Flat-plate, rear duct, air heating solar collector.
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) $S_{UJ}/T_{AJ}, \text{ flow 2}$  (ii) $S_{OM}/T_{AM}, \text{ flow 2}$  (iii) $S_{OD}/T_{AD1}, \text{ flow 2}$  
(iv) $S_{OM}/T_{AM}, \text{ flow 3}$  (v) $S_{LM}/T_{AM}, \text{ flow 2}$  (vi) $S_{SD}/T_{AD1}, \text{ flow 3}$  
(vii) $S_{LD1}/T_{AD1}, \text{ flow 2}$  (viii) $S_{OD}/T_{AD2}, \text{ flow 3}$  (ix) $S_{LD2}/T_{AD1}, \text{ flow 2}$  
(x) $S_{LD3}/T_{AD1}, \text{ flow 2}$  (xi) $S_{LD}/T_{AD1}, \text{ flow 2}$.
Figure 3 Simulated ambient conditions. For further details see text.
APPENDIX D

TRANS: Computer program for analysing collector data under transient conditions.
213
279 FOR K=1 TO NC
280 FOR L=1 TO NC
281 IF L=K THEN GOTO 210
282 YY=YY+YY
283 FOR K=1 TO NC
284 IF K=K THEN GOTO 110
285 ZZ=ZZ+ZZ
286 NEXT K
287 NEXT L
289 IF I=I AND X(L)=0 THEN GOTO 650
290 IF I=I THEN GOTO 110
291 NEXT K
292 GOTO 300
293 FOR K=1 TO NC
294 L=K+K
295 X(L)=X(L)-1
296 T(L)=T(L)-1
297 NEXT K
298 READE 1 I,X(NK),Y,T(NK)
299 IF I=0 AND X(NK)=0 THEN GOTO 650
300 I=I+1
301 NEXT K
302 GOTO 110
303 IF I=0 AND X(K)=0 THEN GOTO 650
304 IF I=I THEN GOTO 110
305 NEXT K
306 X(K)=0
307 NEXT K
308 IF I=I AND X(L)=0 THEN GOTO 650
309 IF I=I THEN GOTO 110
310 NEXT K
311 FOR K=1 TO NC
312 L=K+K
313 X(L)=X(L)-1
314 T(L)=T(L)-1
315 NEXT K
316 NEXT K
317 GOTO 110
318 IF I=0 AND X(K)=0 THEN GOTO 650
319 IF I=I THEN GOTO 110
320 NEXT K
321 FOR K=1 TO NC
322 L=K+K
323 X(L)=X(L)-1
324 T(L)=T(L)-1
325 NEXT K
326 NEXT K
327 GOTO 110
328 IF I=0 AND X(K)=0 THEN GOTO 650
329 IF I=I THEN GOTO 110
330 NEXT K
331 FOR K=1 TO NC
332 L=K+K
333 X(L)=X(L)-1
334 T(L)=T(L)-1
335 NEXT K
336 NEXT K
337 GOTO 110

240 FOR N=1 TO 8
400 NEXT L
410 NEXT K
420 IF K<56 THEN GOTO 210
430 YY=YY+YY
440 FOR K=1 TO NC
450 ZK=ZK+ZK
460 XY(X)=XY(X)+XY(X)
470 FOR L=1 TO NC
480 XY(X)=XY(X)+XY(X)
490 ZZ(Z)=ZZ(Z)+ZZ(Z)
500 PT(K,L)=0
510 FOR M=1 TO NC
520 FOR N=1 TO NC
530 PT(K,L)=PT(K,L)+PT(K,M)*P(N,N)*P(N,N)
540 NEXT N
550 NEXT M
560 NEXT L
570 NEXT K
580 FOR L=1 TO NC
590 FOR M=1 TO NC
600 P(K,L)=P(K,L)-PT(K,L)/DENOM
610 NEXT L
620 NEXT K
630 NP=NP+1
640 GOTO 210
650 IF NP=NC THEN STOP 1 STOP IF NOT ENOUGH DATA POINTS
651 REM EVALUATES ESTIMATES OF PARAMETERS AND STANDARD ERRORS
655 FOR K=1 TO NC
660 X(K)=0
670 FOR L=1 TO NC
680 X(K)=X(K)+P(K,L)*Y(L)
690 NEXT L
700 NEXT K
710 FOR K=1 TO NC
720 YY=YY-Z*X(K)*YY(K)
730 FOR L=1 TO NC
740 YY=YY-X(K)*Z*X(K)*XX(L)
750 NEXT L
760 NEXT K
770 FOR K=1 TO NC
780 FOR L=1 TO NC
790 PT(K,L)=0
800 FOR M=1 TO NC
810 FOR N=1 TO NC
820 PT(K,L)=PT(K,L)+P(K,M)*P(N,N)*P(N,N)
830 NEXT N
840 NEXT M
850 NEXT L
860 Z(K)=Z(K)+SQR(PT(K,K)*YY/(NP-NC))
870 NEXT K
880 PRINT "Table F.3"
890 FOR K=1 TO NC
900 PRINT K,X(K),Z(K)
910 L=L+1
920 FOR L=1 TO NC