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

Thesis

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

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

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Nomenclature

Chapter 2

**Ac** Collector area \((m^2)\)

**As** Storage tank surface area \((m^2)\)

**c** Appropriate specific heat \((J \, Kg^{-1} \, °C^{-1})\)

**cp** Volume heat capacity at constant pressure \((J \, Kg^{-1} \, °C^{-1})\)

**Ch** Initial capital expenditure per house \((\£)\)

**ET** 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

**Fh** Fuel cost per year per house \((\£)\)

**FR** Collector/heat-exchanger efficiency factor

**F'** Collector efficiency factor

**i** Discount rate

**Ith** Threshold solar irradiance \((W \, m^{-2})\)

**Kh** Repeated capital expenditure per house \((\£)\)

**L** Monthly total heat demand for space heating and hot water \((J)\)

**Ls** 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

**PVCh** Present value cost per house

**Q** Heat energy \((J)\)

**QN** Net heat transferred to storage during the month \((J)\)

**QT** Solar energy collected during the month \((J)\)

**Rh** Running costs per year per house \((\£)\)

**s** Pebble shape factor

**Ta** Ambient temperature \((°C)\)

**Tat** Ambient temperature averaged over periods when the radiation level is above the threshold \((°C)\)

**Tg** Monthly average ground temperature \((°C)\)

**Ts** Store temperature \((°C)\)

**Ts** Monthly average store temperature \((°C)\)

**Tso** Store temperature at the beginning of the month \((°C)\)
\[ \Delta T \] Temperature change (°C)

\[ t_m \] Total number of seconds in a month

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

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

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

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

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

\[ (\bar{\tau} \bar{\alpha}) \] Monthly average transmittance-absorptance product
Nomenclature

Chapter 3

\[ A_C \text{ Collector area (m}^2) \]
\[ P_R \text{ Collector heat-exchanger efficiency factor} \]
\[ f \text{ Fraction of monthly total demand met by solar energy} \]
\[ H_T \text{ Monthly average daily radiation incident on the collector surface per unit area (Jm}^{-2}) \]
\[ L \text{ Monthly total heating demand for space heating and hot water (J)} \]
\[ N \text{ Days in month} \]
\[ T_a \text{ Monthly average ambient temperature (°C)} \]
\[ T_{\text{ref}} \text{ An empirically derived reference temperature (100° C)} \]
\[ t_m \text{ Total number of seconds in a month} \]
\[ U_L \text{ Collector overall loss coefficient (Wm}^{-2} \text{ °C}^{-1}) \]
\[ (\tau\alpha) \text{ Monthly average transmittance-absorptance product} \]
Nomenclature
Chapter 4

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

Cₚ  Specific heat of transfer fluid at constant pressure (J/kg°C)

Dₜ  Characteristic length (m)

F'  Absorber plate (or collector) efficiency factor

Fₚ  Collector heat removal factor

g  Acceleration of gravity (ms⁻²)

h₁  Convective heat transfer coefficient, duct top to heat transfer fluid (W/m²°C)

h₂  Convective heat transfer coefficient, duct base to heat transfer fluid (W/m²°C)

hₚ  Radiative heat transfer coefficient (W/m²°C)

hₜ  Wind heat transfer coefficient (W/m²°C)

H  Duct height (m)

I  Equivalent normal solar irradiance (W/m²)

k  Thermal conductivity (W/m°C)

L  Collector length (m)

m  Mass flow rate of transfer fluid (kg/s)

Nu  Nusselt number

Pr  Prandtl number

Qu  Energy per unit time, useful (W)

Ra  Rayleigh number

Re  Reynolds number

T₁  Duct top, temperature (°C)

T₂  Duct base, temperature (°C)

Tₐ  Ambient air-temperature (°C)

Tₖ  Cover temperature (°C)

Tₑ  Exit fluid temperature (°C)

Tᵢ  Inlet fluid temperature (°C)

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

Tₚ  Average absorber temperature (°C)

Uₜb  Bottom loss heat transfer coefficient (W/m²°C)

Uₑ  Edge loss heat transfer coefficient (W/m²°C)

Uₚ  Collector overall heat transfer (loss) coefficient (W/m²°C)
\( U_t \)  Top loss heat transfer coefficient (Wm\(^{-2} \cdot \circ C^{-1})

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

\( W \)  Collector width (m)

\( x \)  Insulation thickness (m)

\( \alpha \)  Absorptance of the collector absorber surface for solar radiation

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

\( \epsilon_c \)  Cover emmisivity

\( \epsilon_p \)  Absorber plate emissivity

\( \eta \)  Efficiency

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

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

\( \tau \)  Transmittance of the solar collector

\( (\tau \alpha) \)  The product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance

\( \sigma \)  Stefan-Boltzmann constant
Nomenclature

Chapter 5

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

A$_c$ Collector area (m$^2$)

c$_p$ Volume heat capacity at constant pressure (J$\text{kg}^{-1}\text{°C}^{-1}$)

P' Absorber plate (or collector) efficiency factor

P" Collector flow factor

P$_1$ Correction factor for partial shading of the collector

P$_2$ Correction factor for variation of $\tau_a$ with the angle of incidence

P$_3$ Correction factor for variation in optical properties from normal for diffuse irradiance

P$_{R}$ Collector heat removal factor

h$_w$ Wind heat transfer coefficient (Wm$^{-2}\text{°C}^{-1}$)

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

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

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

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

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

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

M Fluid capacity of collector (Kg)

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

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

Q$_u$ Energy per unit time, useful (W)

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

r Correlation coefficient

t Time (s)

T$_a$ Ambient air temperature (°C)

T$_b$ Average back plate temperature (°C)

T$_e$ Exit fluid temperature (°C)

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

T$_i$ Inlet fluid temperature (°C)
\(T_{im}\) Measured fluid inlet temperature (°C)
\(T_m\) Mean fluid temperature \((T_e + T_i)/2\) (°C)
\(T_p\) Absorber plate temperature (°C)
\(T_p\) Mean absorber temperature (°C)
\(T_{sky}\) Equivalent black body sky temperature (°C)
\(T^*\) Reduced temperature \((T_i - T_a)/I\) (m² °C w⁻¹)
\(U_L\) Collector overall heat transfer (loss) coefficient (Wm⁻² °C⁻¹)
\(V\) Wind velocity (ms⁻¹)
\(\eta\) Efficiency
\(\tau_\alpha\) Product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance.
\(\tau_c\) Collector time constant under flow conditions (s)
\(\tau_d\) Cut off time (s)
\((\tau_\alpha)_e\) Effective transmittance absorptance product
\((\tau_\alpha)_a\) Product of the absorptance and transmittance for normal irradiance
\(\Delta T^*\) Time increment
\(\theta\) Angle of incidence; degrees from normal
## Nomenclature
### Chapter 6

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>( h_{p-c} )</td>
<td>Convection coefficient between absorber plate and cover (W/m(^2) °C(^{-1}))</td>
</tr>
<tr>
<td>( h_{rp-c} )</td>
<td>Radiation coefficient between absorber plate and cover (W/m(^2) °C(^{-1}))</td>
</tr>
<tr>
<td>( h_{rc-a} )</td>
<td>Radiation coefficient from the cover to sky (W/m(^2) °C(^{-1}))</td>
</tr>
<tr>
<td>( h_w )</td>
<td>Wind heat transfer coefficient. (W/m(^2) °C(^{-1}))</td>
</tr>
<tr>
<td>I</td>
<td>Equivalent normal solar irradiance (W/m(^2))</td>
</tr>
<tr>
<td>I(_{th})</td>
<td>Threshold solar irradiance (W/m(^2))</td>
</tr>
<tr>
<td>Ta</td>
<td>Ambient air temperature (°C)</td>
</tr>
<tr>
<td>Ti</td>
<td>Inlet fluid temperature (°C)</td>
</tr>
<tr>
<td>U</td>
<td>Collector heat loss coefficient P'UL (W/m(^2) °C(^{-1}))</td>
</tr>
<tr>
<td>U_L</td>
<td>Collector overall heat transfer (loss) coefficient (W/m(^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_0 )</td>
<td>Zero loss collector efficiency, ( P'(\alpha T) )</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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aspect ratio or area of main heater</td>
</tr>
<tr>
<td>a</td>
<td>Accommodation coefficient</td>
</tr>
<tr>
<td>c</td>
<td>Average velocity of molecules (ms⁻¹)</td>
</tr>
<tr>
<td>cₚ</td>
<td>Specific heat at constant pressure (J Kg⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>cᵥ</td>
<td>Specific heat at constant volume (J Kg⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>d</td>
<td>Molecular diameter (m)</td>
</tr>
<tr>
<td>Dₜ</td>
<td>Hydraulic diameter (m)</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration of gravity (ms⁻²)</td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof number</td>
</tr>
<tr>
<td>h</td>
<td>Combined heat transfer coefficient from absorber to cover (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>h'</td>
<td>Heat transfer coefficient of material of known conductivity (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>h₀</td>
<td>Heat transfer coefficient for flow across panel wall (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hₙ</td>
<td>Heat transfer coefficient for flow across the inside of the panel due to convection and conduction (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hₚ</td>
<td>Heat transfer coefficient for flow across panel (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hᵣ</td>
<td>Heat transfer coefficient for flow across the inside of the panel due to radiation (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>hₛ</td>
<td>Heat transfer coefficient for flow across standard insulation (Wm⁻² °C⁻¹)</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity (Wm⁻¹ °C⁻¹)</td>
</tr>
<tr>
<td>L</td>
<td>Linear dimension (m)</td>
</tr>
<tr>
<td>m</td>
<td>Wall molecule mass (Kg)</td>
</tr>
<tr>
<td>m'</td>
<td>Gas molecule mass (Kg)</td>
</tr>
<tr>
<td>M</td>
<td>Mass of one mole (kg mol⁻¹)</td>
</tr>
<tr>
<td>Nₐ</td>
<td>Avogadro's number</td>
</tr>
<tr>
<td>Nu</td>
<td>Nussult number</td>
</tr>
<tr>
<td>p</td>
<td>Gass pressure (Nm⁻²)</td>
</tr>
<tr>
<td>Pₜ</td>
<td>Critical pressure when Ra = Raₜ</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>q</td>
<td>Power dissipated in central heater (W)</td>
</tr>
</tbody>
</table>
\( Q \)  
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)

\( T_0 \)  
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)

\( \varepsilon_1 \)  
Emissivity of surface at temperature \( T_1 \) (°C)

\( \varepsilon_2 \)  
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]

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<th>Sector</th>
<th>Fuel</th>
<th>Solid</th>
<th>Liquid</th>
<th>Gas</th>
<th>Electric</th>
<th>Heat</th>
<th>Total 1976</th>
<th>Total 2025</th>
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<tr>
<td>Iron &amp; Steel</td>
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<td>-</td>
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<td>3.2</td>
<td>-</td>
<td>4.4</td>
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<td>-</td>
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<td>1.6</td>
<td>-</td>
<td>4.4</td>
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<td>Specific heat capacity $C_p$/JK$^{-1}$ Kg$^{-1} \times 10^3$</td>
<td>Volume heat capacity $\rho C_p$/MJ K$^{-1}m^{-3}$</td>
<td>Freezing point $Fp/°C$</td>
<td>Boiling point $Bp/°C$</td>
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<td>Caloria HT43 (oil)</td>
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<td>Porosity</td>
<td>Cost (1980) £25/m³</td>
<td>Notes</td>
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<td>Mitec</td>
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<td>150</td>
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<td>Molten salt</td>
<td>Cost £0.32/Kg (1980)</td>
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### TABLE 2.3 Basic Prometheus configuration to heat 100 houses

**Store**

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

**Collector**

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<td>heat transfer factor (Fₚ)</td>
<td>0.9</td>
</tr>
<tr>
<td>overall heat loss coefficient</td>
<td>1.0 Wm⁻²°C⁻¹</td>
</tr>
<tr>
<td>optical efficiency averaged over useful incident angles (τα)</td>
<td>0.8</td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Excavation and site</td>
<td>lorry loading with 0.4m³ shovels plus hedge removal</td>
</tr>
<tr>
<td>preparation</td>
<td></td>
</tr>
<tr>
<td>Base - hardcore</td>
<td>200 mm thick includes tight packing</td>
</tr>
<tr>
<td>- asphalt</td>
<td>200 mm, acid resisting</td>
</tr>
<tr>
<td>- concrete</td>
<td>200 mm</td>
</tr>
<tr>
<td>Sheet piling</td>
<td>Steel</td>
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<tr>
<td>Concrete sections</td>
<td>cost as delivered</td>
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<tr>
<td>Insulation</td>
<td>glass fibre</td>
</tr>
<tr>
<td>Pebbles</td>
<td>shingle, including transportation</td>
</tr>
<tr>
<td>Collector</td>
<td>without back insulation</td>
</tr>
<tr>
<td>Plumbing</td>
<td>fans and ducting</td>
</tr>
<tr>
<td>On site construction</td>
<td>already included in cost but not in Energy Input</td>
</tr>
</tbody>
</table>

TOTAL £ (1978) 458607 13.6 x 10^5 KWh(t)

[ ] Refer to Chapter 2 references,

[ ] is the average value from several references or the average of several values quoted from the same reference.
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>

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

\[ \text{PVC}_h \quad i=0 \quad \text{f}=0.04 \quad 8500 \quad 17800 \quad 20200 \]

\[ i=0 \quad \text{f}=0.02 \quad 7500 \quad 11700 \quad 12500 \]
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector type</td>
<td>Flat plate</td>
<td>Evacuated</td>
<td>Concentrating</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>selective</td>
<td>tube</td>
<td>collector</td>
<td>performance</td>
</tr>
<tr>
<td>Collector area /m²</td>
<td>2100</td>
<td>4600</td>
<td>14000</td>
<td>2800</td>
</tr>
<tr>
<td>Storage volume /m³</td>
<td>7500</td>
<td>17700</td>
<td>38500</td>
<td>11200</td>
</tr>
<tr>
<td>Insulation thickness/m</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Operating temperature of store/°C</td>
<td>72-42</td>
<td>95-60</td>
<td>70-30</td>
<td>130-30</td>
</tr>
<tr>
<td>Number of houses heated by system</td>
<td>50</td>
<td>300</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>Energy consumption GJ/annum per house</td>
<td>32.4</td>
<td>25</td>
<td>54</td>
<td>27.5</td>
</tr>
<tr>
<td>Cost of collectors £1980/m²</td>
<td>60</td>
<td>64</td>
<td>64</td>
<td>72</td>
</tr>
<tr>
<td>Cost of store £1980/m³</td>
<td>16</td>
<td>11</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Collector area/Storage volume (m²/m³)</td>
<td>0.28</td>
<td>0.26</td>
<td>0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>Total system capital cost £1980</td>
<td>322900</td>
<td>659000</td>
<td>1740000</td>
<td>570000</td>
</tr>
</tbody>
</table>

Collector area required to heat type A5 house (27.5 GJ/annum)/m² | 35.7 | 16.9 | 17.8 | 28 |

Storage volume required for type A5 house /m³ | 127 | 65  | 49  | 112 |

Cost per A5 house/£1980 | 5480 | 2416 | 2215 | 5700 |

[ ] Chapter 2 reference numbers
**TABLE 2.7** Specific investment costs for water storage systems as reported by Per-Olov Karlsson

<table>
<thead>
<tr>
<th>Store</th>
<th>Store temperature rise/(°C)</th>
<th>Cost/£1982 per Kwh recovered energy seasonal storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel tank</td>
<td>80</td>
<td>0.28 - 0.39</td>
</tr>
<tr>
<td>Pit storage</td>
<td>50</td>
<td>0.19 - 0.30</td>
</tr>
<tr>
<td>Rock cavern</td>
<td>70</td>
<td>0.11 - 0.21</td>
</tr>
<tr>
<td>Storage in clay</td>
<td>12</td>
<td>0.07 - 0.13</td>
</tr>
<tr>
<td>Multiple well systems in rock</td>
<td>50</td>
<td>0.07 - 0.12</td>
</tr>
<tr>
<td>Aquifers</td>
<td>15</td>
<td>0.025 - 0.08</td>
</tr>
<tr>
<td>Prometheus (pebble bed, using data from Table 2.6)</td>
<td>100</td>
<td>0.43</td>
</tr>
</tbody>
</table>

TABLE 2.8   Summary of domestic communal interseasonal storage systems

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

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

<table>
<thead>
<tr>
<th>Month</th>
<th>Days in month</th>
<th>Solar radiation on a South-facing vertical surface (KWh/m²/month)</th>
<th>Solar radiation on a South-facing surface 30° to horizontal (KWh/m²/month)</th>
<th>Ambient Temperature (°C)</th>
<th>Degree days baseline 15.5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>31</td>
<td>28</td>
<td>25.2</td>
<td>5.2</td>
<td>346</td>
</tr>
<tr>
<td>Feb</td>
<td>28</td>
<td>42</td>
<td>45</td>
<td>4.6</td>
<td>304</td>
</tr>
<tr>
<td>March</td>
<td>31</td>
<td>74</td>
<td>91</td>
<td>5.7</td>
<td>282</td>
</tr>
<tr>
<td>April</td>
<td>30</td>
<td>75</td>
<td>115</td>
<td>8.2</td>
<td>197</td>
</tr>
<tr>
<td>May</td>
<td>31</td>
<td>87</td>
<td>146</td>
<td>11.8</td>
<td>113</td>
</tr>
<tr>
<td>June</td>
<td>30</td>
<td>90</td>
<td>166</td>
<td>14.9</td>
<td>-</td>
</tr>
<tr>
<td>July</td>
<td>31</td>
<td>84</td>
<td>150</td>
<td>17.2</td>
<td>-</td>
</tr>
<tr>
<td>Aug</td>
<td>31</td>
<td>78</td>
<td>123</td>
<td>16.8</td>
<td>-</td>
</tr>
<tr>
<td>Sept</td>
<td>30</td>
<td>72</td>
<td>95</td>
<td>13.9</td>
<td>56</td>
</tr>
<tr>
<td>Oct</td>
<td>31</td>
<td>59</td>
<td>66</td>
<td>10.8</td>
<td>132</td>
</tr>
<tr>
<td>Nov</td>
<td>30</td>
<td>39</td>
<td>37</td>
<td>6.7</td>
<td>256</td>
</tr>
<tr>
<td>Dec</td>
<td>31</td>
<td>25</td>
<td>22</td>
<td>5.3</td>
<td>333</td>
</tr>
</tbody>
</table>
### TABLE 3.3 Thermal characteristics of new houses with different levels of insulation

<table>
<thead>
<tr>
<th>House type</th>
<th>Insulation level</th>
<th>Total house specific loss (W°C⁻¹)</th>
<th>Net annual space and water heating demand (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>Basic (1975 Building Regs.)</td>
<td>304</td>
<td>46.4</td>
</tr>
<tr>
<td>A1</td>
<td>A0 + orientate house north-south</td>
<td>304</td>
<td>41.7</td>
</tr>
<tr>
<td>A2</td>
<td>A1 + 50 mm loft insulation (100 mm total)</td>
<td>291</td>
<td>39.5</td>
</tr>
<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
<td>255</td>
<td>33.7</td>
</tr>
<tr>
<td>A4</td>
<td>A3 + 50 mm loft insulation (150 mm total)</td>
<td>251</td>
<td>33.0</td>
</tr>
<tr>
<td>A5</td>
<td>A4 + extra layer of glazing (i.e. double)</td>
<td>213</td>
<td>27.5</td>
</tr>
<tr>
<td>A6</td>
<td>A5 + cavity increased to 100 mm</td>
<td>186</td>
<td>23.5</td>
</tr>
<tr>
<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
<td>182</td>
<td>22.7</td>
</tr>
<tr>
<td>A8</td>
<td>A7 + all windows on south side</td>
<td>182</td>
<td>20.2</td>
</tr>
<tr>
<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
<td>177</td>
<td>19.7</td>
</tr>
<tr>
<td>A10</td>
<td>A9 + extra layer of glazing (i.e. triple)</td>
<td>164</td>
<td>18.4</td>
</tr>
<tr>
<td>A11</td>
<td>A10 + cavity increased to 200 mm</td>
<td>150</td>
<td>16.7</td>
</tr>
</tbody>
</table>
TABLE 3.4  Thermal characteristics of Basic Type BO house

<table>
<thead>
<tr>
<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (W m⁻² °C⁻¹)</th>
<th>UA (W°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>73.9</td>
<td>1.0</td>
<td>73.9</td>
</tr>
<tr>
<td>Roof</td>
<td>41.2</td>
<td>0.6</td>
<td>24.7</td>
</tr>
<tr>
<td>Floor</td>
<td>41.2</td>
<td>0.5</td>
<td>20.6</td>
</tr>
<tr>
<td>Window</td>
<td>13.3</td>
<td>5.5</td>
<td>73.2</td>
</tr>
<tr>
<td>Total fabric specific loss</td>
<td></td>
<td></td>
<td>192 W°C⁻¹</td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td></td>
<td>68 W°C⁻¹</td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td></td>
<td>260 W°C⁻¹</td>
</tr>
</tbody>
</table>
TABLE 3.5 Thermal Characteristics of existing houses with different levels of retrofitted insulation.

<table>
<thead>
<tr>
<th>House type</th>
<th>Insulation level</th>
<th>Total house specific loss ($W^0C^{-1}$)</th>
<th>Net annual space water heating demand (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0</td>
<td>Basic (average UK housing stock)</td>
<td>260</td>
<td>34.9</td>
</tr>
<tr>
<td>B1</td>
<td>B0 + 50 mm of loft insulation (100 mm total)</td>
<td>249</td>
<td>33.1</td>
</tr>
<tr>
<td>B2</td>
<td>B1 + fibre-fill cavity (50 mm)</td>
<td>219</td>
<td>28.3</td>
</tr>
<tr>
<td>B3</td>
<td>B2 + 50 mm of loft insulation (150 mm total)</td>
<td>215</td>
<td>27.7</td>
</tr>
<tr>
<td>B4</td>
<td>B3 + extra layer of glazing (i.e. double)</td>
<td>182</td>
<td>23.1</td>
</tr>
<tr>
<td>B5</td>
<td>B4 + extra layer of glazing (i.e. triple)</td>
<td>170</td>
<td>21.7</td>
</tr>
<tr>
<td>B6</td>
<td>B5 + 100 mm external wall insulation</td>
<td>156</td>
<td>19.6</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Issue</td>
<td>2.3</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Price</td>
<td>$0.00</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
</tbody>
</table>

Notes:
- All issues are collector items.
- The 1960 issue was released on December 17th.
- The 1961 issue was released on January 10th.
- The 1962 issue was released on February 14th.
- The 1963 issue was released on March 19th.
- The 1964 issue was released on April 24th.
- The 1965 issue was released on May 29th.
- The 1966 issue was released on June 24th.
- The 1967 issue was released on July 29th.
- The 1968 issue was released on August 24th.
- The 1969 issue was released on September 29th.
- The 1970 issue was released on October 24th.

Table 4.1: Art Collector, Aesthetics and Aesthetic Systems in the United Kingdom.
<table>
<thead>
<tr>
<th>Column</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 June 1983</td>
<td>1243</td>
<td>59.0</td>
<td>751</td>
<td>14.8</td>
<td>21.2</td>
<td>51.1</td>
<td>65.9</td>
<td>77.1</td>
<td>2.59</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
</tr>
<tr>
<td>1246</td>
<td>65.8</td>
<td>757</td>
<td>14.4</td>
<td>21.0</td>
<td>50.8</td>
<td>66.2</td>
<td>77.2</td>
<td>2.46</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1249</td>
<td>64.4</td>
<td>758</td>
<td>15.4</td>
<td>22.9</td>
<td>50.5</td>
<td>66.1</td>
<td>77.2</td>
<td>2.15</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
<td></td>
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<tr>
<td>1252</td>
<td>65.7</td>
<td>778</td>
<td>14.7</td>
<td>21.7</td>
<td>51.1</td>
<td>66.2</td>
<td>77.1</td>
<td>1.40</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1255</td>
<td>65.4</td>
<td>799</td>
<td>15.2</td>
<td>21.1</td>
<td>51.1</td>
<td>66.1</td>
<td>77.2</td>
<td>1.40</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1258</td>
<td>65.4</td>
<td>801</td>
<td>14.9</td>
<td>21.1</td>
<td>51.1</td>
<td>66.1</td>
<td>77.2</td>
<td>1.40</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1261</td>
<td>65.6</td>
<td>807</td>
<td>15.3</td>
<td>21.1</td>
<td>51.1</td>
<td>66.3</td>
<td>77.3</td>
<td>2.10</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1264</td>
<td>65.9</td>
<td>824</td>
<td>15.2</td>
<td>20.9</td>
<td>51.1</td>
<td>66.2</td>
<td>77.2</td>
<td>2.10</td>
<td>+0.08</td>
<td>+0.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 Aug. 1983</td>
<td>1209</td>
<td>67.5</td>
<td>810</td>
<td>6.1</td>
<td>27.4</td>
<td>59.2</td>
<td>83.9</td>
<td>76.4</td>
<td>2.77</td>
<td>+0.05</td>
<td>+0.07</td>
<td></td>
</tr>
<tr>
<td>1210</td>
<td>64.0</td>
<td>813</td>
<td>6.6</td>
<td>27.1</td>
<td>60.2</td>
<td>81.0</td>
<td>76.3</td>
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**Table 5.1** Data collected during steady state testing of the D.C. Hall collector

**Column Index**

1. **Time (hrs : min)**
2. Mass flow rate (kg hr⁻¹)
3. Total insolation ($Wm²$)
4. Air temperature rise passing through collector ($T_{in} - T_{out}$), $°C$
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 ($\eta$)
11. $(T_{in} - T_{out})/T_{in}$
12. $(T_{in} - T_{out})/T_{out}$

*Note: The above table contains data collected during steady state testing of the D.C. Hall collector, with columns representing different parameters such as time, mass flow rate, insolation, air temperature rise, ambient air temperature, and efficiency.*
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<th>Test No.</th>
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<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>(T_e - T_a)</th>
<th>Collector efficiency</th>
<th>Wind speed</th>
<th>Absorber Temp.</th>
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TABLE 5.2 (b) Results of steady state testing of structured polycarbonate collector.
TABLE 5.3 Collector configuration modelled for transient analysis by RRDCT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Collector length (along flow)</td>
<td>4.00 m</td>
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<tr>
<td>Collector width</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Cover to plate spacing</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Rear Duct gap</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Back insulation dry glass fibre</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Edge insulation dry glass fibre</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Material of plate and duct-back</td>
<td>Duraluminium HS 15 TB</td>
</tr>
<tr>
<td>Plate absorbtance</td>
<td>0.95 at θ = 0 falling slightly as θ increases</td>
</tr>
<tr>
<td>Emissivity of upper surface of the plate (diffuse)</td>
<td>0.10</td>
</tr>
<tr>
<td>Emissivity of duct surface (diffuse)</td>
<td>0.91</td>
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<tr>
<td>Emissivity of cover (diffuse)</td>
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<tr>
<td>Cover polycarbonate thickness</td>
<td>2.00 mm</td>
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<tr>
<td>Mass flow rate</td>
<td>0.06 kg s⁻¹</td>
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<tr>
<td>Thickness of plate and of duct-back DY1</td>
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</tr>
<tr>
<td>DY2</td>
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TABLE 5.4 Results of transient and steady state testing with multi node model

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<th>Transient 0.5mm (DY2)</th>
<th>Transient 2mm (DY4)</th>
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<td>4</td>
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<tr>
<td>N</td>
<td>-</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>τc/(min)</td>
<td>-</td>
<td>2.8</td>
<td>9.7</td>
</tr>
<tr>
<td>FRUL/(Wm⁻²K⁻¹)</td>
<td>2.83*</td>
<td>2.768</td>
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<tr>
<td>FRtα</td>
<td>0.683</td>
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<tr>
<td>KFRtα</td>
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<td>0.706</td>
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<td>σFRUL</td>
<td>-</td>
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<tr>
<td>σFRtα</td>
<td>0.0008</td>
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</table>

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

*= at low fluid inlet temperatures
| Column | Data Index | Incident Insolation (W/m²) | Output Power per Unit Spectral Area, W/m² | Shown

1. Data Index
2. Incident Insolation, W/m²
3. Output Power per Unit Spectral Area, W/m²
4. Shown
<table>
<thead>
<tr>
<th>n</th>
<th>( F_R(1a), k_n )</th>
<th>( \sigma F_R(1a), k_n )</th>
<th>( n/F^a )</th>
<th>( T^* )</th>
</tr>
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<td>0.026</td>
</tr>
</tbody>
</table>

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

Data sets accepted for analysis 80

Points on thermal performance characteristic 80

From least squares fits each way

Minimum ETAo = 0.2543187816

Maximum ETAo = 0.71484616622

U = 7.33893217894

U = 13.961808148
TABLE 5.8  Temperature distribution within DY1 collector (0.2mm thick plate and duct back) during ASHRAE steady state testing, $T_a = 293k$, $I_\text{sky} = 700\, \text{Wm}^{-2}$, Wind = 1m s$^{-1}$, $T_{\text{sky}} = 273k$

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$T_p/k$</th>
<th>$T_b/k$</th>
<th>$T_m/k$</th>
<th>$F_{RUL}$ (Wm$^{-2}$ $^\circ\text{C}^{-1}$)</th>
<th>$\eta$</th>
<th>$F_{\text{ave}}, \text{UL}$ (Wm$^{-2}$ $^\circ\text{C}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>332.73</td>
<td>333.01</td>
<td>322.1</td>
<td>317.86</td>
<td>2.762</td>
<td>0.645</td>
<td>3.111</td>
</tr>
<tr>
<td>343</td>
<td>364.98</td>
<td>366.28</td>
<td>357.16</td>
<td>354.00</td>
<td>2.902</td>
<td>0.476</td>
<td>3.230</td>
</tr>
<tr>
<td>383</td>
<td>396.47</td>
<td>396.94</td>
<td>391.47</td>
<td>389.73</td>
<td>3.044</td>
<td>0.293</td>
<td>3.362</td>
</tr>
<tr>
<td>423</td>
<td>427.23</td>
<td>428.06</td>
<td>425.00</td>
<td>425.11</td>
<td>3.185</td>
<td>0.095</td>
<td>3.503</td>
</tr>
<tr>
<td>433</td>
<td>435.13</td>
<td>435.94</td>
<td>433.57</td>
<td>434.06</td>
<td>3.226</td>
<td>0.037</td>
<td>3.564</td>
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</table>

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

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$T_p/k$</th>
<th>$T_b/k$</th>
<th>$T_m/k$</th>
<th>Energy lost per unit time per unit area W m$^{-2}$</th>
<th>$F_{RUL}$ (Wm$^{-2}$ $^\circ\text{C}^{-1}$)</th>
<th>$F_{\text{ave}}, \text{UL}$ (Wm$^{-2}$ $^\circ\text{C}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>300.34</td>
<td>300.41</td>
<td>301.23</td>
<td>301.67</td>
<td>40.34</td>
<td>4.034</td>
<td>4.663</td>
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<tr>
<td>343</td>
<td>333.32</td>
<td>333.79</td>
<td>336.20</td>
<td>338.16</td>
<td>146.66</td>
<td>2.932</td>
<td>3.247</td>
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<tr>
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<td>365.41</td>
<td>366.41</td>
<td>370.42</td>
<td>374.20</td>
<td>266.50</td>
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<td>3.282</td>
</tr>
<tr>
<td>423</td>
<td>396.74</td>
<td>398.43</td>
<td>403.88</td>
<td>409.87</td>
<td>397.80</td>
<td>3.060</td>
<td>3.404</td>
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<tr>
<td>433</td>
<td>404.46</td>
<td>406.34</td>
<td>412.12</td>
<td>418.73</td>
<td>432.40</td>
<td>3.088</td>
<td>3.439</td>
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<tr>
<td>*303</td>
<td>301.62</td>
<td>301.71</td>
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<td>20.98</td>
<td>2.098</td>
<td>2.035</td>
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<tr>
<td>*433</td>
<td>405.92</td>
<td>407.78</td>
<td>413.13</td>
<td>419.46</td>
<td>410.30</td>
<td>2.93</td>
<td>3.245</td>
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* $T_{\text{sky}} = 293k$
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<th>0.600</th>
<th>2.5</th>
<th>2.25</th>
<th>2.0</th>
<th>1.6</th>
<th>0.95</th>
<th>0.95</th>
<th>0.82</th>
<th>0.77</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.625</td>
<td>2</td>
<td>1.75</td>
<td>1.5</td>
<td>1.2</td>
<td>0.95</td>
<td>0.95</td>
<td>0.82</td>
<td>0.77</td>
</tr>
<tr>
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<td>1.75</td>
<td>1.5</td>
<td>1.25</td>
<td>1.1</td>
<td>0.95</td>
<td>0.95</td>
<td>0.82</td>
<td>0.77</td>
</tr>
<tr>
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<td>1.25</td>
<td>1.1</td>
<td>0.95</td>
<td>0.95</td>
<td>0.82</td>
<td>0.77</td>
<td>0.72</td>
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<tr>
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Table 5.10: Summary of collector testing results
<table>
<thead>
<tr>
<th>Material</th>
<th>Reflective index (n)</th>
<th>Solar Transmittance (0.2-4.0μm)</th>
<th>Infrared Transmittance (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 to good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Teflon F.F.P. (Fluorocarbon)</td>
<td>1.343</td>
<td>5 mil</td>
<td>5 mil</td>
<td>12.55 x 10⁻⁵</td>
<td>200-220</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Tedlar P.V.F. (fluorocarbon)</td>
<td>1.46</td>
<td>4 mil</td>
<td>4 mil</td>
<td>5.95 x 10⁻⁵</td>
<td>110-170</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mylar (Polyester)</td>
<td>1.64-1.67</td>
<td>5 mil</td>
<td>5 mil</td>
<td>2.00 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>O.30</th>
<th>0.49</th>
<th>Copper (zinc)</th>
<th>Most</th>
<th>Selective paint</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06 - 0.05</td>
<td>0.82 - 0.93</td>
<td>Sydney University of Technology</td>
<td>Copper</td>
<td>Gradual metal carbonate film</td>
</tr>
<tr>
<td>0.15</td>
<td>0.68</td>
<td>Sydney/MDF</td>
<td>Blue stainless steel</td>
<td></td>
</tr>
<tr>
<td>0.08 - 0.06</td>
<td>0.87</td>
<td>In-house</td>
<td>Stainless steel</td>
<td></td>
</tr>
<tr>
<td>0.18</td>
<td>0.90</td>
<td>DVS</td>
<td>Copper</td>
<td></td>
</tr>
<tr>
<td>0.10 - 0.10</td>
<td>0.96</td>
<td>Smiley/Grange</td>
<td>Copper oxide</td>
<td>ILLS oxide coated black enamel</td>
</tr>
<tr>
<td>0.13</td>
<td>0.93 - 0.99</td>
<td>Philips</td>
<td>Aluminum</td>
<td>Anodic aluminum</td>
</tr>
<tr>
<td>0.13</td>
<td>0.96 - 0.97</td>
<td>Maxord/MPP</td>
<td>Adhesive</td>
<td>Black chrome (BC)</td>
</tr>
<tr>
<td>0.13</td>
<td>0.99 - 0.96</td>
<td>Taber block</td>
<td>Black nickel</td>
<td>Black nickel</td>
</tr>
<tr>
<td>0.16</td>
<td>0.96 - 0.99</td>
<td>Sasunese</td>
<td>Black nickel</td>
<td>Black nickel</td>
</tr>
<tr>
<td>0.16 - 0.10</td>
<td>0.97</td>
<td>Auminum</td>
<td>Black nickel</td>
<td>Black nickel</td>
</tr>
<tr>
<td>0.11</td>
<td>0.90 - 0.90</td>
<td>Olympia</td>
<td>Black nickel</td>
<td>Black nickel</td>
</tr>
<tr>
<td>0.15</td>
<td>0.90 - 0.97</td>
<td>Optical</td>
<td>Black nickel</td>
<td>Black nickel</td>
</tr>
<tr>
<td>0.15 - 0.15</td>
<td>0.90 - 0.97</td>
<td>Electrodepos</td>
<td>Aluminum</td>
<td>Black nickel</td>
</tr>
</tbody>
</table>

**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</th>
<th>Feature Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cover 1</td>
<td>plate glass, thickness</td>
<td>6.0 mm</td>
</tr>
<tr>
<td>cover 2</td>
<td>polycarbonate, thickness</td>
<td>2.0 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness of the Plate and of the Duct-back:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>DY1</td>
</tr>
<tr>
<td>DY2</td>
</tr>
<tr>
<td>DY3</td>
</tr>
<tr>
<td>DY4</td>
</tr>
<tr>
<td>DY5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Air Flow in the Rear-duct:</th>
</tr>
</thead>
<tbody>
<tr>
<td>flow 0</td>
</tr>
<tr>
<td>flow 1</td>
</tr>
<tr>
<td>flow 2</td>
</tr>
<tr>
<td>flow 3</td>
</tr>
</tbody>
</table>
### TABLE 7.1 Some typical thermal accommodation coefficients

<table>
<thead>
<tr>
<th>Gas</th>
<th>Surface</th>
<th>Surface condition</th>
<th>Temp. (°C)</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(absorbed gas)</td>
<td></td>
<td></td>
</tr>
<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>
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<tr>
<td></td>
<td>W</td>
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<td>32</td>
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<tr>
<td></td>
<td>W</td>
<td>Clean</td>
<td>-30</td>
<td>0.804</td>
</tr>
<tr>
<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>$h_p/(W m^{-2}°C^{-1})$</th>
<th>$Q/A/(W m^{-2})$</th>
<th>$T_s/°C$</th>
<th>$T_r/°C$</th>
<th>$h_r/(W m^{-2}°C^{-1})$</th>
<th>$h_c/(W m^{-2}°C^{-1})$</th>
<th>$ΔT/°C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air at atmospheric pressure</td>
<td>10.1</td>
<td>14</td>
<td>0.798</td>
<td>3.19</td>
<td>10.1</td>
<td>13.84</td>
<td>0.163</td>
<td>0.704</td>
<td>3.68</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>10.35</td>
<td>36.49</td>
<td>0.185</td>
<td>1.750</td>
<td>23.83</td>
</tr>
<tr>
<td>Air, $p = 81$ torr</td>
<td>10.2</td>
<td>24.9</td>
<td>0.925</td>
<td>13.60</td>
<td>10.2</td>
<td>24.22</td>
<td>0.172</td>
<td>0.847</td>
<td>13.34</td>
</tr>
<tr>
<td>Freon/Air</td>
<td>10.1</td>
<td>17.8</td>
<td>1.635</td>
<td>12.59</td>
<td>10.1</td>
<td>17.17</td>
<td>0.166</td>
<td>1.789</td>
<td>6.44</td>
</tr>
<tr>
<td>Carbon Tet/Air</td>
<td>10.4</td>
<td>27.9</td>
<td>1.986</td>
<td>34.75</td>
<td>10.4</td>
<td>26.16</td>
<td>0.175</td>
<td>2.303</td>
<td>14.02</td>
</tr>
<tr>
<td>Air, $p = 0.3$ torr</td>
<td>10.5</td>
<td>31.3</td>
<td>2.081</td>
<td>43.28</td>
<td>10.5</td>
<td>29.14</td>
<td>0.178</td>
<td>2.450</td>
<td>16.48</td>
</tr>
<tr>
<td>Air, $p = 0.35$ torr</td>
<td>10.6</td>
<td>34.9</td>
<td>2.461</td>
<td>59.80</td>
<td>10.6</td>
<td>33.91</td>
<td>0.182</td>
<td>3.082</td>
<td>18.32</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>11.2</td>
<td>48.83</td>
<td>0.198</td>
<td>1.148</td>
<td>35.26</td>
</tr>
</tbody>
</table>
FIGURE 1.1(b) 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 m³/week
Standard deviation: 0.351 m³/week

Contribution due to
OAPs flats
(1 or 2 occupants)

Dwelling mean weekly hot water consumption m³

**FIGURE 2.5** MEAN WEEKLY HOT WATER CONSUMPTION FOR 87 VARIOUS SITES. FROM ‘THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS’ BY C.A. RICKUP.[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.

Figure 2.9 Demonstration project in Studsvik. [26]

Figure 2.10

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

ONE-FAMILY HOUSES (SMALL SCALE)

APARTMENT BUILDING (INTENSE POPULATED AREAS) (LARGE SCALE)

FIGURE 2.12  DIFFERENT APPLICATIONS FOR 'SUNSTORE' [37], SEASONAL STORAGE IN THE GROUND
FIGURE 2.13 PLAN OF PROMETHEUS RETROFITTED TO SUPPLY 83 HOUSES WITH ALL THEIR SPACE HEATING AND HOT WATER.

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

FIGURE 2.15 PROTO-PROMETHEUS
**Figure 2.16** Insolation Incident on Proto-Prometheus, 28th September 1981

**Figure 2.17** Collector, Store and Ambient Temperatures for Proto-Prometheus on 28th September 1981.
FIGURE 2.19 Proto-Prometheus Temperature Distribution (with fan on), on 22nd September 1981 at 14:25 hrs.
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 A75 building regulations (Type A) with solar heating supplied by a basic Type Prometheus.
**Figure 2.23**
Effect of changing the collector overall heat loss coefficient on the % of annual energy supplied by Prometheus 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 A house.
Figure 2.29 Design of Costed Prometheus to provide 100% of their annual heating demand (27.5 GJ) with solar energy.

Figure 2.30 Improved collector orientation.
Figure 3.1 Design of Basic Type A0 House

Figure 3.2 Net Space Heating Demand for Type A0, A5 and A11 3 Bedroom End of Terrace House.
**Figure 3.3**

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

**Figure 3.4**

Energy demand for a 3-bedroom terrace built to 1975 building regulations and energy supplied by 4, 12 and 24 m² of solar collector.
Figure 3.5 Energy Demand for a Well Insulated 3 Bedroom House, and Energy Supplied by 4, 12, and 24 m² of Solar Collector.

Figure 3.6 Comparison of Predicted Solar Energy Supply for a House Using the F-Chart Method with the Measured Solar Supply for the Milton Keynes Solar House.
Figure 37: Useful energy saved and extra costs for various insulation options and solar systems retrofitted to an existing type B0 house.
FIGURE 4.1. NONPOROUS ABSORBER-TYPE AIR HEATERS.

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

**Figure 4.4** Collector Heat Losses
**Figure 4.5** Rear Duct Collector Configuration

**Figure 4.6** Top Duct Collector Configuration
Figure 4.7 Correlations for Wind Heat Loss Coefficient

The curves correspond to the following relations:

M. D. Adams
\[ h_w = 5.7 + 3.5v \]

Watmuff
\[ h_w = 2.8 + 3.0v \]

Lloyd
\[ h_w = 0.15 \times R_{1,0} \times k \text{ for } T_0 = 10^\circ \text{C}, T_e = 15^\circ \text{C}, L = 1 \text{m}, W = 1 \text{m}. \]

Sparrow
\[ h_w = k \times 0.86 \times R_{1,0}^{1.5} \text{ for } T_0 = 10^\circ \text{C}, T_e = 15^\circ \text{C}, L = 1 \text{m}, W = 1 \text{m}. \]

Green
\[ h_w = \left( h_{10} + h_{15}^{1.5}\right)^{0.5} \text{ for } A = 1.4 \text{ m}, 45^\circ \text{ inclination} \]

KIND

For collector length 2.4 m, width 1.2 m, height 4.5 m, \( T_e = 25^\circ \text{C} \)
Figure 4.8 Flow diagram of 'EFFICZ' (see Appendix B) a program to calculate the efficiency of a paraplectic air heating collector.
**FIGURE 4.9** FLOW DIAGRAM OF 'EFFIC' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A TOP DUCT AIR-WATTING 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 'RRDCT'.

**Figure 4.12** Comparison of air outlet temperature to predicted by the computer model (solid curve) and laboratory measurements, on a similar, though not identical, collector (crosses).
Figure 4.13
Efficiency curve generated by transient model operating under steady state conditions and steady state model for collector parameters see Table 5.3.
FIGURE 5.1 PERCENTAGE OF ENERGY FALLING ABOVE A THRESHOLD INTENSITY AVERAGED OVER A PERIOD OF ONE HOUR EACH MONTH ON A HORIZONTAL SURFACE (AT HO 1966-1975)
SECTION X-X

FIGURE 5.2  D.C. HALL COLLECTOR
FIGURE 5.3 ANGULAR VARIATION OF TRANSMITTANCE OF 2mm THICK POLYCARBONATE (REFRACTIVE INDEX = 1.586, EXTINCTION COEFFICIENT = 20 m\(^{-1}\))

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

Figure 5.7 Solar transmittance of structured polycarbonate versus incident angle. Source: H.L. Redfoot et al., 'Glazing solar collectors with acrylic and double walled polycarbonate plastics.'
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 72 kg/hr⁻¹.

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

FIGURE 5.14  RECORD OF INCIDENT SOLAR RADIATION ON A HORIZONTAL SURFACE AND WIND SPEED ON 21/6/83 (CONTINUED ON NEXT PAGE).
Figure 5.15 Angle of Incidence of Solar Radiation onto D.C. Hall Collector during Steady State Efficiency Test. Position of Collector Milton Keynes, Latitude 52°, Longitude 0.75° (Horizontal).

Figure 5.16 Angle Correction for D.C. Hall Collector
FIGURE 5.17(a) AIR HEATING COLLECTOR UNDER TEST WITH A LEAK AT THE INLET

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

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

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

FIGURE 5.21 SAMPLE OUTPUT OF D.C. WALL COLLECTOR TO TESTING
OUTDOORS NOT UNDER STEADY STATE CONDITIONS.
FIGURE 5.22  STEADY STATE EFFICIENCY CURVE FOR D.C. HALL COLLECTOR TESTED OUTDOORS

FIGURE 5.23  STEADY STATE EFFICIENCY CURVE FOR STRUCTURED POLYCARBONATE COLLECTOR TESTED OUTDOORS.
**Figure 5.24** Uncorrected efficiency curve with variation of wind speed between 0 - 4 m/s. Source: [25].

**Figure 5.25** Efficiency curve corrected for variation in wind speed using a normalizing function. Source: [25].
FIGURE 5.26  VARIATION OF MASS FLOW RATE CAUSED BY CHANGE IN WIND SPEED
**FIGURE 5.27** ROUND ROBIN TESTING OF LIQUID FLAT PLATE COLLECTORS. THE COMBINED EFFECT OF METEOROLOGICAL EXTREMES AND MEASUREMENT UNCERTAINTY. SOURCE: TAYLOR [28]

**FIGURE 5.28** MEASURED DEPENDENCY OF $F(\alpha)$ ON THE DIFFUSE FRACTION FOR A SINGLE-GlAZED FLAT-PLATE COLLECTOR. SOURCE: POROSKI [34]
FIGURE 5.29 COMPUTER GENERATED STEADY STATE AND TRANSIENT EFFICIENCY CURVE FOR 0.5 mm ABSORBER PLATE
**Figure 5.30**  Transient Diffuse Radiation

**Figure 5.31**  Fluid Outlet Temperature Under Transient Conditions.

**Figure 5.32**  Integrated Response of Collector Over 1 and 2 Minutes to Transient Radiation.
**Figure 5.33** The variation in $F_{u\ell}$, $F_n(\theta \alpha)$, and $\delta F_{u\ell}$ with the number of increments used in the transient analysis.
FIGURE 5.34 COLLECTOR RESPONSE FUNCTIONS FOR optimum VALUES OF N.

FIGURE 5.35 CALCULATED COLLECTOR TIME CONSTANTS FOR DIFFERENT COLLECTOR CONFIGURATIONS. SEE TABLE 5.3.
Figure 5.36 Efficiency curve generated from transient testing results of the SP collector and processed by 'TRANS' for N=1. Uncorrected for angle of incidence of radiation.

Figure 5.37 Transient insolation during testing of SP collector on 17/6/83, continued on next page.
**Figure 5.37 Continued.** Transient Insolation during testing of 3D Collector on 14/6/93–15/6/93.
Figure 5.30 Standard error in $g_{UL}$ versus the number of previous time steps influencing the collector's present performance under transient conditions for the structured polycarbonate collector.

Figure 5.31 Estimated efficiency curve from $F(\Delta T)$ and $F_{UL}$.

Figure 5.32 Least squares fit, maximum and minimum.

Figure 5.33 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 (MANHATTAN BUILDING). 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 W/m². Average intensity 2.11 W/m², standard deviation ± 0.4 W/m².

**Figure 5.45**  Wing generator.
FIGURE 5.46 VARIATION OF WINDSPEED (m/s), 5mm ABOVE COLLECTOR SURFACE

MEASURED HEAT LOSS WITH COLLECTOR OPERATING UNDER STAGNATION AND ASSUMING (P/k) = 0.32 PLOTTED AGAINST AVERAGE AIR VELOCITY PARALLEL TO COLLECTOR PLANE AND MEASURED 5mm ABOVE COLLECTOR PLANE.

FIGURE 5.47 MEASURED AND PREDICTED HEAT LOSS $U_4$ FOR D.C. HALL 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. wall collector with non-selective absorber (Nextel). Indoor measurements and computer predictions.
FIGURE 5.50 REDESIGNED INDOOR COLLECTOR TEST FACILITY

FIGURE 5.51 STEADY STATE AND ZERO TESTING EFFICIENCY CURVES.
ASHRAE STEADY STATE

ZERO TESTING $T_{SHY} = T_m - 20$

$T_{SHY} = T_a$

$\frac{[T_p - T_a]}{I} \text{ } \left( \circ C \text{ } W \right)$

**Figure 5.52** STEADY STATE AND EFFICIENCY CURVE PLOTTED AGAINST MEAN ABSORBER PLATE TEMPERATURE ($T_p$) FOR SIMULATED COLLETOR.
FIGURE 5.53  STEADY STATE AND ZERO TESTING EFFICIENCY CURVE PLOTTED AGAINST MEAN FLUID TEMPERATURE (T_m) FOR SIMULATED COLLECTOR.
**Figure 5.54**
Collector temperature profile for model collector under steady-state and zero-testing conditions for the same fluid inlet temperature (30°C).

**Figure 5.55**
Collector temperature profile for model collector under steady-state and zero-testing conditions for the same mean absorber plate temperature (36°C).
Figure 5.56  Temperature of Absorber and Rear Duct for the Same Average Fluid Temperature With the Collector Under Zero and Steady State Testing.

Figure 5.57  $F_{w_u}$ Versus Mean Fluid Temperature for Collector DIY Under Zero Testing and As-Roared 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 Pribram Chall type collector (maxors 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 CONFERENCE ED BY S.V. SZONOLAY, VOL 2, PP 1149 - 1153.

(X STEADY STATE EFFICIENCY WHILE OPERATING AS PART OF A SOLAR HOT WATER SYSTEM.

DASHED LINE STEADY STATE EFFICIENCY MEASURED INDOORS ACCORDING TO THE BRITISH STANDARD.)
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 (41°N, 11°W).

Figure 6.5. Maximum improvement to flat plate collector performance by increasing $\tau$ and $\alpha$. 

Equation: $\frac{T_i - T_o}{\tau}$
FIGURE 6.6  REFLECTANCE OF SOLAR COLLECTOR COATINGS

FIGURE 6.8  EFFICIENCY CURVES FOR DIFFERENT METHODS OF HEAT LOSS REDUCTION

FIGURE 6.9  SOLAR TRANSMITTANCE OF PARALLEL-PLATE GLASS HONEYCOMB WITH COVERGLASS, L/D = 12. SOURCE: J.R. FELLAND AND D.K. EDWARDS 'SOLAR AND INFRARED RADIATION PROPERTIES OF PARALLEL-PLATE HONEYCOMB'
J. ENERGY, VOL.2, NO.5, SEPT-OCT 1978
FIGURE 6.10  EFFICIENCY CURVE OF ADVANCED FLAT PLATE COLLECTOR WITH XENON BETWEEN THE ABSORBER AND COVER AT A PRESSURE OF 1 TORR.

FIGURE 6.11  EFFICIENCY VERSUS MASS FLOW RATE FOR STRUCTURED POLYCARBONATE COLLECTOR: \( T_{inc} = 211 \text{ W/m}^2 \), \( T_a = 28^\circ \text{C} \), \( T_{300g} > T_a \), \( T_e = T_a \) and AIR VELOCITY = 1.5 m/s.
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 with an inlet temperature of 60°C, for three duct separations (z) and two levels of incident insolation.
Figure 6.14: Efficiency curve for a compound parabolic concentrator compared with a flat plate collector. Source: Argonne National Laboratory Tech Report.

Figure 6.15: Global and diffuse insulation month by month at 1 kW on a 45° south facing slope.
Figure 6.16
Annual energy collected versus collector temperature. Comparison of five types of collector. Source [33].

Figure 6.17
Integrated global and diffuse solar radiation from March to October as a function of the global intensity. Source [35].
WIND = 1.0 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 4 and Figure 3).\footnote{1}

(i) S0J/TAJ, flow 2  (ii) S0M/TAM, flow 2  (iii) S0D/TAD1, flow 2
(iv) S0M/TAM, flow 3  (v) S1M/TAM, flow 2  (vi) S0D/TAD1, flow 3
(vii) S1D1/TAD1, flow 2  (viii) S0D/TAD2, flow 3  (ix) S1D2/TAD1, flow 2  
(x) S1D3/TAD1, flow 2  (xi) S1D/TAD1, flow 2.
**Figure 6.20** 'FMT C' air heating solar collector developed by CEM [42]

**Figure 6.21** Incident angle modifier for the FMT C prototype. This depends on the orientation of the cover. A - the maximum occurs when the plane of the angle of incidence is perpendicular to the cylindrical axes of the tube cover. B - the maximum value occurs when the plane of the angle of incidence is normal to the cylindrical axes of the tubes in the cover [42].
FIGURE 6.22  INSTANTANEOUS EFFICIENCIES OF THE FPFC COLLECTOR AND A SINGLE GLAZED FLAT PLATE COLLECTOR AND THEIR VARIATION WITH IRRADIATION. [42]
**FIGURE 7.1** THERMAL CONDUCTIVITY OF VARIOUS GASES AT 20°C VERSUS MOLECULAR WEIGHT.

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

FIGURE 7.4  BASE FLOW BETWEEN INCLINED PLATES

FIGURE 7.6 Schematic depicting effect of gap spacing on conductance.
Figure 7.2: Plot of $h_c$ versus plate separation $S$. $T_{surf} < 160^\circ K$, $T_{surt} = 325^\circ K$, $x = 40.9$.

Figure 7.8: $h_c$ versus tilt angle to the horizontal for air wick design for various absorber temperatures ($T_a$) with cover temp $= 10^\circ C$. 
Figure 7.9 Heat transfer coefficient variation with absorber temperature for convection and radiation.
Figure 7.10  True and Predicted Heat Loss Between Two Parallel Plates 5 x 5cm
Cover Temperature 10 °C
Figure 7.11

Effective Rayleigh Number versus molecular weight for different gases. Atmospheric pressure between 1000 and 500 mm Hg, plate temperature 0° or 10°C.
Figure 7.12: Heat transfer coefficient for gases of different molecular weight, for $L = 5$ cm, cold plate temperature 10°C, hot plate temperature 30°C.
FIGURE 7.13  COST VERSUS HEAT TRANSFER COEFFICIENT FOR DIFFERENT GASES.

$S = 5$ cm, VOLUME OF GAS REQUIRED FOR EACH SQUARE METRE OF COLLECTOR IS 50 LITRES.
Figure 7.14 Variation of heat transfer coefficient \( h_c \) with pressure for a flat plate collector, \( s = 5 \text{ cm}, T_c = 293 \text{ K}, T_a = 323 \text{ K} \) 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: Nowotny, A and Garg, H.P. "Minimizing Convective Heat Loss." Solar Energy, Vol. 25, No. 6, p. 523.

**Figure 7.17** Reflected solar rays for a multi-cover solar collector.
FIGURE 7.19  HEAT TRANSFER COEFFICIENT $h_c$ DUE TO NATURAL CONVECTION FOR AIR AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL FLAT PLATES SPACING 5 cm, $T_i = 293 K$, WITH A HONEYCOMB PAD WITH SLATS ASPECT RATIO 5
Figure 7.20 Thermal conductivity versus Rayleigh number for various gases $T_1 = 10^\circ C$, $T_2 = 80^\circ C$, $S = 5 \text{ cm}$.
Figure 7.21: Rayleigh Number versus temperature for argon and air at atmospheric pressure between two parallel flat plates. Spacing s = 5 cm, cold plate temperature $T_c = 10^\circ C$. 

\[ \text{Rayleigh Number, } R_e = (\frac{L}{\alpha}) \]

Where $L$ is the characteristic length and $\alpha$ is the thermal diffusivity.
**Figure 7.22** Heat Transfer Coefficients for Several Collector Configurations

- Convexion and Conduction, Air, Atmospheric Pressure, Tilt Angle θ = 0°
- Convexion and Conduction, Air, Atmospheric Pressure, Tilt Angle θ = 60°
- Convexion and Conduction, Argon, Atmospheric Pressure, Tilt Angle θ = 0°
- Convexion and Conduction, Air, Honeycomb, Tilt Angle (60°)
- Radiation, Maxor® Absorber (ε=0.09) [Najjar] Glass Cover (g=0.08)
- Conduction Only, Air at 4×10^5 Pa
- Conduction Only, Argon at 3×10^5 Pa

θ = 5 cm, T = 10°C
FIGURE 7.23 GUARD RING HEATER

FIGURE 7.24 GUARD RING UNBALANCE VERSUS MEASURED HEAT TRANSFER ACROSS A 5cm THICK 'STYROFOAM' SP' 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, $s = 5 \text{ cm}$, versus temperature difference.

**Experimental Data Points**
- Air at atmospheric pressure
- Freon and air at atmospheric pressure
- Carbon tetrachloride and air at atmospheric pressure
- Air at $71 < p < 62,000 \text{ Pa}
- Air at $p = 0.35 \text{ Torr} \approx 50 \text{ Pa}$

$\Delta T = (T_1 - T_2) / (\text{°C})$
Figure 7.29 Theoretical and measured heat transfer $h_c$ for air and argon.
Figure 7.30 Theoretical heat transfer across structured polycarbonate of various thicknesses, both radiation and convection, assuming flat convection and a measured emissivity of 0.72.
PLATE 2.1
PROTO PROMETHEUS - 1. COLLECTOR, 2. STORE TOP INSULATION AND COLLECTOR BRRR INSULATION, 3. FAN MOTOR 4...5. MONITORING EQUIPMENT, 6. SPACE FOR INSULATION.
PLATE 2.2  PROTO PROMETHEUS STORAGE TANK FILLED WITH PEBBLES.
PLATE 5.1

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

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

SUNSTORE: Computer model of interseasonal store and sample output.
10 REM ******************** SUNSTORE *************************
20 REM
30 SHORT DEMAND(12)
40 SHORT SOL(12,24)
50 ASSIGN 1 TO "SUN DATA"
60 READ# 1 SOL(),
70 REM read average solar rad for each hour
80 ASSIGN 2 TO "TEM DATA"
90 READ# 2 TEM(),
100 DIM MONTHS(12)(13)
110 ASSIGN 3 TO "MONTH"
120 ASSIGN 3 TO MONTH()
130 REM read the number of days in month
140 ASSIGN 4 TO "DAYS"
150 READ# 4 DAYS()
160 PRINT USING 200
170 TOTSUN=0
180 PRINT "**************************************************"
190 PRINT "TOTAL ANNUAL SOLAR RADIATION = "TOTSUN"MJ/m2"
200 PRINT "******************** DATA INPUT********************"
210 PRINT USING 220
220 PRINT "***************************************"
230 FOR H=1 TO 12
240 PRINT "******** ON A HORIZONTAL SURFACE IN MJ/m2 ***********"
250 NEXT M
260 FOR H=1 TO 24
270 PRINT "******** ON A HORIZONTAL SURFACE IN MJ/m2 ***********"
280 PRINT TAB(6):MONTHS(M):
290 TOTSUN=TOTSUN+SOL(M,H):DAYS(M)
300 NEXT M
310 PRINT
320 NEXT H
330 PRINT "TOTAL ANNUAL SOLAR RADIATION = "TOTSUN"MJ/m2"
340 REM ******************** DATA INPUT********************
350 F=.95! HEAT TRANSFER FACTOR
360 c=.837! SPECIFIC HEAT OF STORE MATERIAL (kJ/KGC)
370 MET= "PEBBLES"! STORAGE MATERIAL
380 WIDTH=10! STORAGE WIDTH IN METERS
390 HEIGHT=4! STORAGE HEIGHT IN METERS
400 LENGTH=280! STORAGE LENGTH IN METERS
410 HOUSE=100! NUMBER OF HOUSES SURVEYED BY STORE
420 DENSITY=1600! DENSITY OF STORAGE MATERIAL (Kg/m3)
430 T=35 C! OVERALL COLLECTOR HEAT LOSS COEFFICIENT (W/m2)
440 COLAREA=2800! TOTAL AREA OF COLLECTORS SURVING STORE (m2)
450 COND=.036! THERMAL CONDUCTIVITY OF STORAGE INSULATING MATERIAL (W/m2C)
460 THICK=.6! THICKNESS OF INSULATING MATERIAL (cm)
470 T=80! OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES
480 YEARS=1! NUMBER OF YEARS PROGRAM TO RUN DO NOT USE MORE THAN 1 IF qAUX>1
490 T=10! TEMPERATURE OF GROUND SURROUNDING STORE (°C)
500 T=30! MINIMUM STORAGE TEMPERATURE (°C)
510 REM "******************** DATA INPUT********************"
520 REM "STORE LENGTH="LENGTH:"Meters";" WIDTH="WIDTH:"Meters";" HEI="HEIGHT:"Meters"
530 REM "VOLUME="VOLUME:"Vol:"m3"
540 REM "STORAGE MATERIAL="MET:" DENSITY="DENSITY:"Kg/m3"
550 REM "SPECIFIC CONDUCTIVITY="SPECIFIED:
560 REM "STORE INSULATION THICKNESS="THICK:"cm";" THERMAL CONDUCTIVITY="CONI:
570 PRINT USING 880
580 PRINT USING 880
590 REM "******************** COLLECTOR *************************
600 PRINT "TOTAL COLLECTOR AREA="COLAREA:"m2"
610 PRINT "FI=HEAT TRANSFER FACTOR (equivalent to Fr heat removal factor if st)"
620 PRINT "has a good heat transfer rate:"Fi
630 PRINT "UL-OVERALL HEAT LOSS COEFFICIENT:"UL
640 PRINT "Ta=OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES:"Ta
650 PRINT "TS=TOTAL HEATING LOAD FOR EACH HOUSE (heating and hot water)"
660 PRINT "FOR KM TO 12"
670 REM READ DEMAND(K) READS MONTHLY DATA OF HEATING LOAD FOR EACH HOUSE (MJ)
680 REM "******************** STORE *************************
690 REM "******** ON A HORIZONTAL SURFACE IN MJ/m2 ***********"
700 REM "TOTAL ANNUAL SOLAR RADIATION = "TOTSUN"MJ/m2"
710 REM "******************** DATA INPUT********************"
1000 REM
1010 PRINT TAB(100);"MONTHS(1);"=":DEMAND(1); print heating demand each
1020 TOTDE+TOTDE+DEMAND(1)calculate total annual heating demand.
1030 DEMAND(1)>=DEMAND(1) / (COLAREA/HOUSE) heating demand per m2 of collector
1040 /
1050 PRINT "TOTAL ENTH
1060 PRINT "NET ENTH HOUSE PER ANNUM " TOTDE/1000;"G3;" TOTDE
1070 PRINT "";
1080 PRINT USING 1080
1090 IMAGE " "; " " SYSTEM OPERATION 
1100 PRINT "ITH = Threshold Level(collector will only operate above this int
1110 PRINT "Tso = Original Store Temperature at the begining of month (C)
1120 PRINT "Ta = Ambient Temperature Averaged over periods of collector operat
1130 PRINT "Tt = Time Period of Collector Operation (Ms)
1140 PRINT "q = Normalized Net Heat to Storage = q1-1m=1s
1150 PRINT "qT = Useful Heat Collected= qN=1 rows
1160 PRINT "qM = Normalized Total Monthly Load (MJ/m2)
1170 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1180 PRINT "qT = Normalized Total Monthly Storage Losses (MJ/m2)
1190 PRINT "qT = Normalized Total Monthly Storage Losses (MJ/m2)
1200 PRINT "qN = Normalized Total Monthly Load (MJ/m2)
1210 PRINT "qT = Normalized Total Monthly Load (MJ/m2)
1220 PRINT "qT = Normalized Total Monthly Storage (MJ/m2)
1230 PRINT "qT = Normalized Total Monthly Storage (MJ/m2)
1240 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1250 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1260 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1270 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1280 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1290 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1300 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1310 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1320 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1330 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1340 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1350 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1360 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1370 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1380 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1390 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1400 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1410 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1420 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1430 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1440 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1450 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1460 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1470 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1480 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1490 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1500 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1510 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1520 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1530 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1540 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1550 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1560 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1570 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1580 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1590 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1600 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1610 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1620 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1630 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1640 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1650 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1660 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1670 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1680 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1690 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1700 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1710 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1720 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1730 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1740 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1750 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1760 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1770 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1780 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1790 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1800 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1810 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1820 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1830 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1840 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1850 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1860 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1870 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1880 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1890 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1900 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1910 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1920 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1930 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1940 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1950 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1960 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1970 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1980 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
1990 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
2000 PRINT "qN = Normalized Total Monthly Storage (MJ/m2)
2010 DATA 7750,6490,5560,3320,980,770,770,770,1760,5270,7450
2020 END
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 REM ************************ EFFI ************************
20 REM --- THIS PROGRAM CALCULATES THE STEADY STATE EFFICIENCY OF A TOP DUCT
30 REM AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
40 REM p237  Figure 6.12.1 (a)
50 REM
60 REM INPUT VARIABLE DATA
70 FOR J=0 TO 10
80 J=14.7*10 : MASS FLOW RATE (kg/hr)
90 Ta=16.2 : AMBIENT TEMP (C)
100 Ti=TA+20.4 : ABSORBER TEMPERATURE (C) IF THIS CHANGES ALSO CHANGE Ti
110 Ti=(T2-1)/2+1A : INFLUID TEMPERATURE (C)
120 WIND=5 : WIND SPEED (m/s)
130 I=236 : INTENSITY OF SOLAR RAD (W/m2)
140 Ta*=8 : TRANSMISSIVITY & ABSORPTIVITY OF COVER AND ABSORBER
150 E=0.85 : EMITTIVITY OF ABSORBER
160 K=.034 : CONDUCTIVITY OF REAR INSULATION (W/m/C)
170 Ti=.075 : INSULATION THICKNESS (m)
190 A=1 : COLLECTOR AREA (m2)
200 L=2 : COLLECTOR LENGTH IN METERS
210 W=1 : WIDTH OF COLLECTOR IN METERS
220 SH=1 : PLATE SEPARATION IN CM
230 D=1 : FIN SEPARATION IN CM
240 DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
250 IF Y THEN GOTO 470
260 IF A=4 THEN GOTO 470
270 PRINT 701
280 PRINT "**COLLECTOR INITIAL PARAMETERS ARE**
290 PRINT USING 930 :""MASS FLOW RATE",""Kg/hr"
300 PRINT USING 930 :"AMBIENT TEMP",""C"
310 PRINT USING 930 :"INLET FLUID TEMP",""C"
320 PRINT USING 930 :"ABSORBER TEMP",""C"
330 PRINT USING 930 :"WIND SPEED",""m/s"
340 PRINT USING 930 :"SOLAR RADIATION",""w/m2"
350 PRINT USING 930 :"TRANSMISSIVITY & ABSORPTIVITY",""Ta"
360 PRINT USING 930 :"EMITTIVITY OF COVER",""E1"
370 PRINT USING 930 :"EMITTIVITY OF ABSORBER",""E2"
380 PRINT USING 930 :"INSULATION CONDUCTIVITY",""W/m/C"
390 PRINT USING 930 :"INSULATION THICKNESS",""m"
400 PRINT USING 930 :"COLLECTOR AREA",""m2"
410 PRINT USING 930 :"COLLECTOR LENGTH",""m"
420 PRINT USING 930 :"COLLECTOR WIDTH",""m"
430 PRINT USING 930 :"PLATE SEPARATION",""cm"
440 PRINT USING 930 :"FIN SEPARATION",""cm"
450 PRINT
460 PRINT "**"}
470 PRINT "**COLLECTOR EFFICIENCY FACTOR IS **"
480 PRINT "**M/M**"
490 PRINT "**H/H**"
500 PRINT "**K/K**
510 PRINT "**T=T2/2,15**
520 PRINT "**S/S/100**
530 PRINT "**D=D/100**
540 PRINT "**W/W/D**
550 PRINT "**N=N**
560 PRINT "**M=M/N**
570 PRINT "**F=F**
580 PRINT "**P=P**
590 PRINT "**Q=Q**
600 PRINT "**R=R**
610 PRINT "**S=S**
620 PRINT "**T=T**
630 PRINT "**U=U**
640 PRINT "**V=V**
650 PRINT "**W=W**
660 PRINT "**X=X**
670 PRINT "**Y=Y**
680 PRINT "**Z=Z**
690 PRINT "**a=a**
700 PRINT "**b=b**
710 PRINT "**c=c**
720 PRINT "**d=d**
730 PRINT "**e=e**
740 PRINT "**f=f**
750 PRINT "**g=g**
760 PRINT "**h=h**
770 PRINT "**i=i**
780 PRINT "**j=j**
790 PRINT "**k=k**
800 PRINT "**l=l**
810 PRINT "**m=m**
820 PRINT "**n=n**
830 PRINT "**o=o**
840 PRINT "**p=p**
850 PRINT "**q=q**
860 PRINT "**r=r**
870 PRINT "**s=s**
880 PRINT "**t=t**
890 PRINT "**u=u**
900 PRINT "**v=v**
910 PRINT "**w=w**
920 PRINT "**x=x**
930 PRINT "**y=y**
940 PRINT "**z=z**
950 REM
20 REM --- THIS PROGRAM CALCULATES THE STEADY STATE EFFICIENCY OF A REAR DUCT
25 REM AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
30 REM p237 Figure 6.12.1 (d)
35 REM
40 REM
45 REM ----------------- INPUT VARIABLE DATA -----------------
60 REM
70 FOR J=0 TO 100 STEP 5
80 N=1516 ! MASS FLOW RATE (kg/hr)
90 Ta=20 ! AMBIENT TEMP. (C)
100 Tin=130+3 ! IN FLUID TEMPERATURE (C)
110 T2=142 ! ABSORBER TEMPERATURE (C) IF THIS CHANGES ALSO CHANGE Tin
120 Tin=(T2-TA)/2+TA
130 Wind=1 ! WIND SPEED (m/s)
140 I=700 ! INTENSITY OF SOLAR RAD (W/m²)
150 Tm=.83 ! TRANSMISSIVITY & ABSORPTIVITY OF COVER AND ABSORBER
160 TF=11 ! GUESS MEAN FLUID TEMPERATURE C
170 EM=.05 ! EMPSIVIVITY OF COVER
180 Em=.91 ! EMPSIVIVITY OF REAR DUCT
190 Ei=.91 ! EMPSIVIVITY OF REAR DUCT
200 Ef=.1 ! EMPSIVIVITY OF ABSORBER
210 KL=1.045 ! CONDUCTIVITY OF REAR INSULATION (W/mC)
220 Tk=1 ! INSULATION THICKNESS (M)
230 Aa=4 ! COLLECTOR AREA (m²)
240 Lm=4 ! COLLECTOR LENGTH IN METERS
250 Wm=1 ! WIDTH OF COLLECTOR IN METERS
260 Sm=1 ! PLATE SEPARATION IN CM
270 Dm=100 ! FIN SEPARATION IN CM
275 UE=0 ! DGE HEAT LOSS
280 DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N????
290 IF J=30 THEN GOTO 520
300 INPUT A$
310 IF A$="N" THEN GOTO 520
320 PRINT "BOS 701"
330 PRINT " "
340 PRINT USING 1070 ; "COLLECTOR INITIAL PARAMETERS ARE"
350 PRINT USING 1070 ; "AMBIENT TEMP.,Ta",C"
360 PRINT USING 1070 ; "INLET TEMPERATURE,Tin",C"
370 PRINT USING 1070 ; "ABSORBER TEMP.,Tm",C"
380 PRINT USING 1070 ; "WIND SPEED,Wind","m/s"
390 PRINT USING 1070 ; "SOLAR RADIATION",I,"W/m²"
400 PRINT USING 1070 ; "TRANSMISSIVITY & ABSORPTIVITY",Ta
410 PRINT USING 1070 ; "EMPSIVIVITY OF COVER",Em
420 PRINT USING 1070 ; "EMPSIVIVITY OF ABSORBER",Ef
430 PRINT USING 1070 ; "INSULATION CONDUCTIVITY",Ki,"W/mC"
440 PRINT USING 1070 ; "INSULATION THICKNESS",Ti,"m"
450 PRINT USING 1070 ; "COLLECTOR AREA",A","m²"
460 PRINT USING 1070 ; "COLLECTOR LENGTH",L,"m"
470 PRINT USING 1070 ; "COLLECTOR WIDTH",W,"m"
480 PRINT USING 1070 ; "PLATE SEPARATION",D,"cm"
490 PRINT USING 1070 ; "FIN SEPARATION",D,"cm"
500 PRINT USING 1070 ; "EDGE LOSS"",UE","W/m²C"
510 PRINT " "
520 PRINT "BOS 701"
530 PRINT USING 1070 ; "AMBIENT TEMP.,Ta",C"
540 PRINT USING 1070 ; "INLET TEMPERATURE,Tin",C"
550 PRINT USING 1070 ; "ABSORBER TEMP.,Tm",C"
560 PRINT USING 1070 ; "WIND SPEED,Wind","m/s"
570 PRINT USING 1070 ; "SOLAR RADIATION",I,"W/m²"
580 PRINT USING 1070 ; "TRANSMISSIVITY & ABSORPTIVITY",Ta
590 PRINT USING 1070 ; "EMPSIVIVITY OF COVER",Em
600 PRINT USING 1070 ; "EMPSIVIVITY OF ABSORBER",Ef
610 PRINT USING 1070 ; "INSULATION CONDUCTIVITY",Ki,"W/mC"
620 PRINT USING 1070 ; "INSULATION THICKNESS",Ti,"m"
630 PRINT USING 1070 ; "COLLECTOR AREA",A",m²"
640 PRINT USING 1070 ; "COLLECTOR LENGTH",L,"m"
650 PRINT USING 1070 ; "COLLECTOR WIDTH",W,"m"
660 PRINT USING 1070 ; "PLATE SEPARATION",D,"cm"
670 PRINT USING 1070 ; "FIN SEPARATION",D,"cm"
680 PRINT USING 1070 ; "EDGE LOSS",UE","W/m²C"
690 PRINT " "
700 PRINT "BOS 701"
710 PRINT USING 1070 ; "AMBIENT TEMP.,Ta",C"
720 PRINT USING 1070 ; "INLET TEMPERATURE,Tin",C"
730 PRINT USING 1070 ; "ABSORBER TEMP.,Tm",C"
740 PRINT USING 1070 ; "WIND SPEED,Wind","m/s"
750 PRINT USING 1070 ; "SOLAR RADIATION",I,"W/m²"
760 PRINT USING 1070 ; "TRANSMISSIVITY & ABSORPTIVITY",Ta
770 PRINT USING 1070 ; "EMPSIVIVITY OF COVER",Em
780 PRINT USING 1070 ; "EMPSIVIVITY OF ABSORBER",Ef
790 PRINT USING 1070 ; "INSULATION CONDUCTIVITY",Ki,"W/mC"
800 PRINT USING 1070 ; "INSULATION THICKNESS",Ti,"m"
810 PRINT USING 1070 ; "COLLECTOR AREA",A",m²"
820 PRINT USING 1070 ; "COLLECTOR LENGTH",L,"m"
830 PRINT USING 1070 ; "COLLECTOR WIDTH",W,"m"
840 PRINT USING 1070 ; "PLATE SEPARATION",D,"cm"
850 PRINT USING 1070 ; "FIN SEPARATION",D,"cm"
860 PRINT USING 1070 ; "EDGE LOSS",UE","W/m²C"
870 PRINT " "
880 PRINT "BOS 701"
890 PRINT USING 1070 ; "AMBIENT TEMP.,Ta",C"
900 PRINT USING 1070 ; "INLET TEMPERATURE,Tin",C"
910 PRINT USING 1070 ; "ABSORBER TEMP.,Tm",C"
920 PRINT USING 1070 ; "WIND SPEED,Wind","m/s"
930 PRINT USING 1070 ; "SOLAR RADIATION",I,"W/m²"
940 PRINT USING 1070 ; "TRANSMISSIVITY & ABSORPTIVITY",Ta
950 PRINT USING 1070 ; "EMPSIVIVITY OF COVER",Em
960 PRINT USING 1070 ; "EMPSIVIVITY OF ABSORBER",Ef
970 PRINT USING 1070 ; "INSULATION CONDUCTIVITY",Ki,"W/mC"
980 PRINT USING 1070 ; "INSULATION THICKNESS",Ti,"m"
990 PRINT USING 1070 ; "COLLECTOR AREA",A",m²"
1000 PRINT USING 1070 ; "COLLECTOR LENGTH",L,"m"
1010 PRINT USING 1070 ; "COLLECTOR WIDTH",W,"m"
1020 PRINT USING 1070 ; "PLATE SEPARATION",D,"cm"
1030 PRINT USING 1070 ; "FIN SEPARATION",D,"cm"
1040 PRINT USING 1070 ; "EDGE LOSS",UE","W/m²C"
1050 PRINT " "
1060 PRINT "BOS 701"
1070 PRINT USING 1070 ; "AMBIENT TEMP.,Ta",C"
1080 PRINT USING 1070 ; "INLET TEMPERATURE,Tin",C"
1090 PRINT USING 1070 ; "ABSORBER TEMP.,Tm",C"
1100 PRINT USING 1070 ; "WIND SPEED,Wind","m/s"
1110 PRINT USING 1070 ; "SOLAR RADIATION",I,"W/m²"
1120 PRINT USING 1070 ; "TRANSMISSIVITY & ABSORPTIVITY",Ta
1130 PRINT USING 1070 ; "EMPSIVIVITY OF COVER",Em
1140 PRINT USING 1070 ; "EMPSIVIVITY OF ABSORBER",Ef
1150 PRINT USING 1070 ; "INSULATION CONDUCTIVITY",Ki,"W/mC"
1160 PRINT USING 1070 ; "INSULATION THICKNESS",Ti,"m"
1170 PRINT USING 1070 ; "COLLECTOR AREA",A",m²"
1180 PRINT USING 1070 ; "COLLECTOR LENGTH",L,"m"
1190 PRINT USING 1070 ; "COLLECTOR WIDTH",W,"m"
1200 PRINT USING 1070 ; "PLATE SEPARATION",D,"cm"
1210 PRINT USING 1070 ; "FIN SEPARATION",D,"cm"
1220 PRINT USING 1070 ; "EDGE LOSS",UE","W/m²C"
APPENDIX C

THE EFFECT OF THERMAL CAPACITANCES ON THE PERFORMANCE OF SOLAR COLLECTORS

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

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

NOMENCLATURE

DY1-5 plate and duct-back thicknesses (5)
f(δ) transmittance - absorbance function of the collector
FR collector heat-removal factor
HPA(I) heat-transfer coefficient plate (or duct-back) to air in the I'th segment of the duct
M duct air flow rate
NI number of duct segments
PON threshold power for switch on of air flow
S irradiance in cover plane
S0 solar beam irradiance
S1 diffuse irradiance on a horizontal surface
SP irradiance absorbed by plate
TA ambient temperature
INTRODUCTION

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

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

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.
### 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>
<thead>
<tr>
<th>Collector configurations, and rear-duct air flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>collector length (along flow)</td>
</tr>
<tr>
<td>collector width (W)</td>
</tr>
<tr>
<td>cover to plate spacing</td>
</tr>
<tr>
<td>rear duct gap</td>
</tr>
<tr>
<td>back insulation</td>
</tr>
<tr>
<td>edge insulation</td>
</tr>
<tr>
<td>material of plate and duct-back cover</td>
</tr>
<tr>
<td>plate absorbtance</td>
</tr>
<tr>
<td>emissivity of upper surface of the plate (diffuse)</td>
</tr>
<tr>
<td>emissivity of duct surfaces (diffuse)</td>
</tr>
<tr>
<td>emissivity of the cover (diffuse)</td>
</tr>
<tr>
<td>thermal properties of air at 283 K for ambient air, at 303 K elsewhere</td>
</tr>
<tr>
<td>latitude</td>
</tr>
<tr>
<td>collector tilt (to horizontal)</td>
</tr>
<tr>
<td>collector orientation</td>
</tr>
<tr>
<td>thickness of plate and of duct-back</td>
</tr>
<tr>
<td>DY1</td>
</tr>
<tr>
<td>DY2</td>
</tr>
<tr>
<td>DY3</td>
</tr>
<tr>
<td>DY4</td>
</tr>
<tr>
<td>DY5</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></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 = 128 W</td>
</tr>
<tr>
<td>flow 3</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 $0.0600 \text{ kg s}^{-1}$: at $T_I = 323 \text{ K}$, $M = 0.0562 \text{ kg s}^{-1}$ (flow 3 in Table 1).

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

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

### 3.2 Steady-state efficiency curve

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

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

where $f(\theta)$ is such that

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

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

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

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

3.3 Daily-averaged efficiency

The collector configurations DY1 to DY5 were run under conditions flow 2 and flow 3 for a variety of simulated days 21 June (J), 21 March (M), 21 December (D). The simulated conditions of insolation and weather on these days are shown in Figure 3. The ambient temperature 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

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

(3)

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

In order to plot \( \bar{\eta} \) on Figure 2 it is necessary to re-define the abscissa \( \frac{(T_I-T_A)}{S} \). 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 \( \frac{(T_I-T_A)}{S} \) there is a column of results, and in every case DY1 is at the top, then comes DY2, and so on, to DY5, though in some cases DY1-DY3 merge on the scale of Figure 2. Clearly, the lower the thermal capacitance the better the performance.

Consider first those cases in which the insolation only varies over the diurnal envelope: this covers the cases (i)-(vi), (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 \( \frac{(T_I-T_A)}{S} \)). This general improvement with reducing thermal capacitance arises because with a diurnal envelope the slower warm-up of a high mass collector in the morning is not compensated by the slower cool-down in the afternoon. Note that the sinusoidal variations in 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. SD1-SD3 provide such conditions (Figure 3), the periodicities lying within the range of time-constants in Table 1. However, Figure 2 shows that, even in marginal conditions, very little further advantage in low mass is obtained, though DY1-DY3 are more spread out than with the diurnal envelope alone. The
The reason for such a slight improvement is that whereas a low mass collector will "follow" the insolation, possibly switching the air flow on and off, a high mass collector, once it has warmed to the point where the air flow switches on, will tend to stay at a fairly constant temperature. The overall effect, for a wide variety of conditions, is that the time-averaged temperatures of the air flow are not very sensitive to the mass. Therefore there is very little difference in the amount of heat extracted. A similar conclusion was reached by Klein et al [1].

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

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

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

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

REFERENCES

2 M. Yusoff and D. J. Close, Transient studies of solar air heaters, presented at the Inter-regional symposium on solar energy for development, Tokyo 5-10 February (1979).
Figure 1: Flat-plate, rear duct, air heating solar collector.
Figure 2  Steady-state efficiency ($\eta$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\eta$ are for a variety of simulated conditions (see Table 1 and Figure 3).

(i) $S_{OJ}/T_{AJ}$, flow 2  
(ii) $S_{OM}/T_{AM}$, flow 2  
(iii) $S_{OD}/T_{AD1}$, flow 2  
(iv) $S_{OM}/T_{AM}$, flow 3  
(v) $S_{LM}/T_{AM}$, flow 2  
(vi) $S_{OD}/T_{AD1}$, flow 3  
(vii) $S_{LD1}/T_{AD1}$, flow 2  
(viii) $S_{OD}/T_{AD2}$, flow 3  
(ix) $S_{LD2}/T_{AD1}$, flow 2  
(x) $S_{LD3}/T_{AD1}$, flow 2  
(xi) $S_{LD}/T_{AD1}$, flow 2.
Figure 3 Simulated ambient conditions. For further details see text.
APPENDIX D

TRANS: Computer programe for analysing collector data under transient conditions.
214

1550 NF=NF+1
1560 GOTO 1220
1570 DNF=DNF
1580 PRINT "POINTS ON THERMAL PERFORMANCE CHARACTERISTIC":NF
1590 PRINT "FROM LEAST SQUARES FITS EACH WAY"
1600 E=(SX*SX-SX*SY)/((DNF*NY-DNF*SX)*SY)
1610 U=(SX*SY-DNF*SY)/((DNF*NY-SX*SY)
1620 PRINT "MINIMUM ETAQ=":U,"U":U
1630 E=(SY*SY-SX*SY)/((DNF*NY-SX*SY)
1640 U=(SY*SY-DNF*SY)/((DNF*NY-SX*SY)
1650 PRINT "MAXIMUM ETAQ=":U,"U":U
1655 NEXT NK
1660 STOP
1670 END

1100 REM READ DATA TO GENERATE THERMAL PERFORMANCE CURVE
1110 ASSIGN 1 TO "TRANSD7800"
1120 NP=0
1130 READ# 1: I,X(NK),Y,T(NK)
1135 IF I=0 AND X(NK)=0 THEN GOTO 1570
1140 I=I+1
1150 FOR K=2 TO NK
1160 L=NE-K+1
1170 READ# 1: I,X(L),Y,T(L)
1175 IF I=0 AND X(L)=0 THEN GOTO 1570
1180 IF I=11 THEN GOTO 1130
1190 II=II+1
1200 NEXT K
1210 GOTO 1400
1220 FOR K=2 TO NK
1230 L=NE-K+2
1240 X(L)=X(L-1)
1250 T(L)=T(L-1)
1260 NEXT K
1270 READ# 1: I,X(I),Y,T(I)
1275 IF I=0 AND X(I)=0 THEN GOTO 1570
1280 IF I=11 THEN GOTO 1150
1290 II=II+1
1300 E=0
1310 X(NC)=0
1320 FOR K=1 TO NK
1330 E=E+X(K)**C(K)
1340 X(NC)=X(NC)+T(K)
1350 NEXT K
1360 Y=Y/(FRE)
1370 X(NC)=X(NC)/FRE
1380 PRINT Y,X(NC)
1390 REM CALC LEAST SOR TO THERMAL PERFORMANCE
1400 SX=SX+X(NC)
1410 SY=SY+Y
1420 SY=SY+X(NC)**(NC)
1430 SY=SY+Y**Y
1440 SX=SY+X(NC)**Y

940 NEXT K
950 NEXT K
960 E=SQR (E*E+Y/(Y-NF-NK))
970 PRINT "ETAQ=":E,"/":E
980 U=X(NC)
990 PRINT "FU=":U,"/":U/(1-U/H))
1000 PRINT "F=":F
1010 E=E/F
1070 U=U+F
1080 PRINT "ETAD=":E,"U":U
1090 PRINT "DATA SETS ACCEPTED FOR ANALYSIS":NP