TRNAUS – 20.1

TRNSYS EXTENSIONS FOR SOLAR WATER HEATING

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ABSTRACT

This report outlines extensions of the TRNSYS simulation program for the analysis of a range of solar collectors and solar water heaters that are used or being investigated in Australia. The emphasis is in the area of thermosyphon systems, heat exchangers, evacuated tubular collectors, non-tracking concentrators and solar boosted heat pump water heaters.

Extensions are detailed for

- TYPE 101 Solar collector
- TYPE 137 Solar boosted heat pump
- TYPE 138 Stratified tank model
- TYPE 145 Thermosyphon solar water heater including collector loop heat exchanger options
- TYPE 160 Stratified tank model with mantle heat exchanger and falling film heat exchanger options
- TYPE 176 One-shot user over-ride of boosting
- TYPE 177 Delay timer
- TYPE 178 Event detection (tank sterilization controller)

Extensions include coded or TRNSYS deck programming for

- modelling specified energy load delivery
- in-tank gas boosting for single tank solar/gas systems
- reverse flow in thermosyphon systems
- thermosyphon flow over-temperature cut-off valve
- load quality binning
- heat pipe coupling between a collector and a storage tank
- evacuated tube collectors
- bi-axial incidence angle modifiers
- heat exchangers in thermosyphon loops
- serpentine riser solar collectors

TRNAUS – TRNSYS extensions for solar water heaters

1 INTRODUCTION

The majority of solar thermal system developments in Australia have been based on experimental evaluation of prototype systems. As the performance of solar devices is strongly seasonally dependent the cost and time involved in long term monitoring of prototype systems is a barrier to the development of innovative designs. To assist with the evaluation of new solar applications this report outlines a set of extensions for the TRNSYS [Klein 1999] simulation package to suit the range of solar water heating products in use or being developed in Australia. A Typical Mean Year solar data base for Australia is also outlined. To use the TRNAUS routines the user must have an existing TRNSYS installation.

2 TRNAUS FEATURES

TRNAUS extends the range of system configurations that TRNSYS can model as follows

2.1 Nonlinear solar collector efficiency characterization.

Solar collector performance can now be characterized by some of the nonlinear correlation functions recommended in Australian Standard AS 2535. The thermosyphon routine also incorporates nonlinear solar collector characterization.

2.2 Optical response function

The solar collector routine has also been extended to allow optical response functions of concentrating collectors to be specified via a map of optical acceptance. If detailed optical data is available from ray tracing analysis this extension allows a more accurate specification of optical effects than the standard bi-axial optical response product function.

2.3 Theoretical model of an evacuated tubular solar collector.

A model of an evacuated tubular collector with a diffuse reflector has been incorporated. This model is based on the collector developed by the School of Physics, University of Sydney [Harding et. al. 1985].

2.4 Collector heat removal via heat pipe.

Direct coupling of a horizontal storage tank to a collector array via heat pipes is now included (partially in the code and partially in the TRNSYS deck). The condenser of the heat pipes is considered to be in the bottom region of the tank and the heat pipe evaporator is in the collector field (either a concentrating, evacuated tubular collector or flat plate collector).

2.5 Thermosyphon systems with collector loop heat exchanger.

Thermosyphon systems with heat exchanger coupling to a temperature stratified storage tank are now included. The program has been extended to analyse collector to tank heat exchangers in the form of a wrap around coil outside a vertical tank, an immersed coil or a horizontal tank in tank heat exchanger.

2.6 Analysis of heat loss due to reverse flow in thermosyphon systems.

The magnitude of reverse thermosyphon flow can be evaluated for a given sky temperature. This routine computes heat loss due to reverse thermosyphoning but does not remove the fluid or energy from the storage tank, hence this component option indicates the potential heat loss but does not withdraw the energy from the system.

2.7 Serpentine riser in collector

The thermosyphon circulation analysis has been modified so that a serpentine riser collector plate can be analysed.

2.8 Series - parallel connection of collectors.

For a linear collector (ie $\eta = a - b(T_i - T_a)/I$) and a fixed array fluid flow the array efficiency is not effected by different series/parallel arrangements of the collectors. However if the collector has a nonlinear characteristic the arrangement of collectors in different series/parallel configurations can effect the array performance. The program can now evaluate the effect of collector array configuration.

2.9 Thermal cut-off valve in thermosyphon loop

A thermal cut off valve can now be modelled in the thermosyphon collector loop. Flow cut-off valves are used in some Australian designs to minimise the effect of collector overheating in summer. The valve stops thermosyphoning through the collector when the temperature in the bottom of the tank reaches a specified value.

2.10 Over temperature dump valve

A thermally controlled dump valve has been added to the stratified storage tank model. Dump valves are used to control excess temperatures in the storage tank. Energy dumping can be a significant problem in summer for a system incorporating high quality collectors.

2.11 Two auxiliary elements in stratified storage tank

The stratified storage tank routine has been extended to include two auxiliary boost elements with switch over logic. This routine can be used to study off-peak boosted systems that have a continuous boost back up element near the top of the tank. When the bottom element is active the top element is disabled.

2.12 Solar boosted heat pump water heater

Heat pump water heaters with solar boosted evaporators in place of the normal fan forced air source evaporators have been manufactured in Australia since the early 1980's. The advantage of direct coupling of the heat pump circuit to the solar absorber is that the solar input will raise the evaporator temperature above ambient temperature and hence improve the heat pump performance. A model of a solar boosted heat pump system with an unglazed evaporator and a wrap-around heat exchanger connecting the water tank to the heat pump condenser has been developed.

2.13 Load quality

The thermally stratified water storage tank routine has also been extended to compute energy and volume delivery in temperature bands <45°C and < 57°C. These temperature bands correspond to class A and class B system operation as defined in Australian Standard AS 2813.

2.14 Energy load specification.

To compare alternative designs or configurations of a system the relative energy efficiency of each system must be evaluated. In the basic load control routines of TRNSYS the load can only be expressed as a volume draw off. An example of a TRNSYS deck that implements energy draw off load control is shown in appendix 6.

2.15 Analysis of conduction in a horizontal tank improved.

The conduction model used in the thermosyphon routine of TRNSYS underestimates the effect of conduction in thermosyphon systems that have in-tank boosting, these are the most common systems in Australia. During the night or after a particularly large load the plug flow analysis used in TYPE138 may introduce a large element in the tank. This may cause an error in the determination of conduction from the boost zone in the top of the tank to the cold load flow in the bottom of the tank. The conduction analysis has been modified such that the user may specify a parameter that sets the maximum size of the fluid element to be used in the evaluation of conduction in the tank. If the plug flow analysis has introduced an element larger than this size then the elements will be broken up before the conduction analysis. A maximum element size of 0.1 (10% of tank volume) has been found to give reliable results. This is particularly important in horizontal tanks that have in-tank boosting,

3 NONLINEAR SOLAR COLLECTOR CHARACTERIZATION TYPE101

In TRNSYS 15 complex collector efficiency functions can be defined via a performance map, however, establishment of the details of such maps is very time consuming. The Australian Solar Test Standard AS 2535 defines a wide range of functions that can be used to describe the performance of most known solar collector types. The collector routine (TYPE101) in TRNAUS includes the following collector characterising functions

3.1 Efficiency mode 2

$$\eta = a - b\frac{(T_w - T_e)}{G} - c\frac{(T_w - T_e)^2}{G} \quad (1)$$

This function is applicable to flat plate collectors with a temperature dependant heat loss coefficient

3.2 Efficiency mode 3

$$\eta = a - b\frac{(T_w - T_e)}{G} - c\frac{(T_w^4 - T_e^4)}{G} \quad (2)$$

This function is applicable to evacuated collectors where the modes of heat loss are conduction from the headers and radiation from the absorbing surface.

3.3 Unglazed solar collector

The major difference in assessing the efficiency of glazed and unglazed solar collectors is that the performance of an unglazed collector depends on four primary environmental factors, short wave radiation, long wave radiation, ambient temperature and wind speed (G, G_L, T_a, u) whereas the performance of a glazed collector depends primarily on only two environmental factors (G, T_a). Both collectors are influenced by secondary factors such as diffuse radiation fraction and ground reflection.

To allow for the effect of wind speed on unglazed collector performance and long wave radiation exchange with the sky and surroundings the following efficiency function is used [Morrison and Gilliaert 1992].

$$\eta = a - (b + cV)\frac{(T_w - T_a)}{G_n} \quad (3)$$

where

G_n	=	net irradiance = $G + G_L$
G	=	solar irradiance
G_L	=	relative long wave irradiance
	=	$\sigma(T_{sky}^4 - T_a^4)$

3.4 Theoretical evacuated tubular collector characterization

The heat loss modes of the Dewar flask type evacuated tube collectors have been included in Type 101, (Harding et. al. [1985]). The heat extraction efficiency of an evacuated tubular collector is determined by the optical efficiency of the tube-reflector array and the heat loss from the panel of tubes. Heat loss from an evacuated tubular collector occurs by

(i) conduction through the insulation surrounding the header pipes

$$Q_1 = K_1 (T_w - T_a) \qquad (4)$$

(ii) conduction from the tube via residual gas, retaining clips and at the open end of the Dewar type tube

$$Q_2 = K_2 (T_s - T_a) \qquad (5)$$

(iii) radiation from the absorber tube to the envelope

$$Q_3 = K_3 E_s (T_s^4 - T_a^4) \qquad (6)$$

The instantaneous efficiency of a panel of evacuated tubes containing N tubes per square metre of panel, with optical efficiency η_{opt} is given by

$$\eta = \eta_{opt} - K_1 \frac{(T_w - T_a)}{G} - N K_2 \frac{(T_s - T_a)}{G} - N{*}E_s{*}K_3 \frac{(T_s^4 - T_a^4)}{G} \qquad (7)$$

The tube absorber surface temperature (T_s) depends on the manifold design used to extract heat from the tubes and on the heat flux from the glass absorber tube to the fluid. If the temperature difference (T_s - T_w) is assumed to be linearly proportional to the heat flux through the tube then

$$T_s - T_w = \frac{\eta {*}G {*}N}{\eta_s {*}G_s {*}N_s} {*} dT \qquad (8)$$

where dT is a specified (measured) absorber to fluid temperature for irradiation of G_s on an array of N_s tubes/m^2 operating with efficiency η_s.
(Note this differs slightly from the assumption made by Harding [1985]).

The TRNAUS component description of the evacuated tubular collector function allows specification of the coefficients η_{opt}, K_1, K_2, K_3 and N as input parameters. The evacuated tube selective surface emissivity and tube surface temperature differentials are built in for the following three configurations of tubes

(i) Water in glass $dT = (T_s - T_w) = 7$

(ii) U tube with fin $dT = (T_s - T_a) = 22$

(iii) U tube without fin $dT = (T_s - T_a) = 66$

Values of the efficiency parameters for an evacuated tube with 38mm/35mm outer/inner tube diameters mounted over a diffuse reflector are η_{opt} = 0.625, K_1 = 0.26, K_2 = 0.039, K_3 = 8.5*10^{-9}, ε_s = 0.05+0.000125T_S . These parameters can be altered to suit other evacuated tubular collector manifolding arrangements.

3.5 Application of Nonlinear Collector Characterisation

Both the modified collector functions (eqns 1 and 2) and the evacuated tubular model can be include as part of pumped and thermosyphon system descriptions. The parameter, inputs and outputs lists for the modified TYPE1 solar collector module are given in appendix 1. The bi-axial incidence angle modifiers for an evacuated tubular collector are specified via optical mode =4. An incidence angle modifier map can be specified via optical modes 5 and 6.

4. INCIDENCE ANGLE MODIFIER EXTENSIONS

The solar collector incidence angle modifier features of TRNSYS now include the following options

4.1 Symmetric Collectors (eg flat plate collectors)

4.1.1 ASHRAE 93-77 function

$K_{\tau\alpha} = 1 - b*(1/\cos(\theta) - 1)$

where $K_{\tau\alpha}$ is the incidence angle relative to the collector aperture normal

4.1.2 Data Table of Incidence Angle Modifier Values

Table of values of incidence angle modifier data has been increased to allow 50 values to be used.

4.2 Collectors with North-South and East-West Symmetry

The optical response of non-symmetric (north-south versus east-west) collectors such as evacuated tubular collectors can be specified by a bi-axial optical data table.

4.2.1 Bi-axial modifier data table

Specified as a table of values for North-South (K_{NS}) and East-West planes (K_{EW}). The overall incidence angle modifier is assumed to be the product of the two orthogonal modifiers.

$$K_{\tau\alpha} = K_{NS} * K_{EW} \quad (9)$$

4.2.2 Incidence angle modifier map (optical mode 5)

A two dimensional table of values of incidence angle modifiers may be entered for collectors with NS and EW symmetry. Up to 50 points in the North-South plane and up to 50 points in East-West incidence plane may be specified.

NOTE for this class of collector the incidence angle modifier data only has to be specified for positive angles in each of the two planes.

4.3 Collectors with East-West Symmetry only (optical mode 6)

An incidence angle modifier map for up to 50 points of positive and negative North-South angles, and up to 25 values of positive only East-West incidence angles. Non-symmetric response in the North-South plane is defined for negative North-South incidence angles when the sun is above the collector normal and positive North-South angles when the sun is below the collector normal

4.4 Incidence Angle Terminology

The terms North-South and East-West incidence angle refer to a collector with one of two orthogonal lines of symmetry. If the collector is skewed with respect to East-West then the terms North-South and East-West incidence angle refer to angles in the longitudinal and transverse planes of the collector.

Incidence angles are defined relative to the normal of the collector aperture. If the collector axis is to be inclined then the inclination must be in the longitudinal plane, ie for a collector with the primary axis in the NS plane the inclination must be towards the north (or south).

4.5 Examples of Data Input

4.5.1 Bi-axial modifiers

Bi-axial incidence angle modifiers are specified via optical mode = 4. Incidence angle modifier data is listed in a separate data file with the following format

Table 1

Format of data file for bi-axial incidence angle data

Line	Information		
1	Incidence angles (up to 50 values)		
2	North-South and East-West modifiers for first angle		
3	" "	second	"
.	" "	third	"
.	" "	"	"
.	" "	last	"

A typical data file is shown in table 2

Table 2

Bi-axial incidence angle data file

```
3  4  5  7  9  10  25  45  65  85
1.          1.
0.95        1.
0.79        0.99
0.33        0.998
0.14        0.997
0.085       0.996
0.085       0.943
0.085       0.737
0.085       0.344
0.0         0.0
```

4.5.2 Optical response map specification

The code for simulating the incidence angle modifier for a concentrating collector has been extended to allow incidence response data to be specified as a performance map (optical modes = 5 & 6). The incidence angle modifier may be specified for up to 50 values of transverse incidence angle and longitudinal angle. The format of the optical performance data file is the same as for the TRNSYS DATA function eg

Table 3

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Format of data file for nonsymmetric bi-axial incidence angle data

Line	Information
1	East-West angles (increasing)
2	North-South angles (increasing)
3	Data for East-West angle No1 and the range of North-South angles.
4	Data for East-West angle No2 etc

A typical data file for ten North-South angles and five East-West angles is given in table 4.

Table 4

Typical Optical Map Data File

```
5 15 35 55 75
2.5 7.5 10 12.5 15 17.5 20 22.5 60 90
1.
1.01
0.864
0.703
0.587      data for East-West
0.477      angle = 5 deg. and
0.373      for 10 North-South angles
0.287
0.182
0.0
0.98
0.98
0.838
0.68
0.567      data for next East-West
0.46       angle
0.361
0.278
0.176
0.0
           -- (5 sets of 10 values)
```

Alternatively the data may be specified as shown in table 5.

Table 5

Alternative Optical Map Data File

5 15 35 55 75
2.5 7.5 10 12.5 15 17.5 20 22.5 60 90
1.0 1.01 0.864 0.703 0.587 0.477 0.373 0.287 0.182 0.0
0.98 0.98 0.838 0.68 0.567 0.46 0.361 0.278 0.178 0.0
total of 5 lines of incidence angle modifier values for NS
angles 2.5 to 90 degrees.

The incidence angle must be specified in increasing order as required by the TRNSYS DATA function.

5 THERMALLY STRATIFIED TANK MODEL TYPE138

The temperature distribution in the storage tank of a thermosyphon or low flow rate pumped solar water heater has a major effect on the system performance. Most simulation models use finite difference techniques to simulate the tank temperature stratification, ie the tank is divided into a series of fixed size nodes and the variation of temperature with time is computed using an energy balance on each tank node. The energy balance on a stationary control volume of a storage tank includes enthalpy of the fluid entering and leaving, conduction between adjacent segments and heat loss from the outer surface. The degree of mixing between incoming fluid and the contents of the tank (and therefore stratification) depends upon the number of segments that are utilised. At low flows, there is very little mixing, and a large number of nodes may be required to predict the degree of stratification. Simulations of thermosyphon solar preheat tanks have usually been performed with 10 to 15 nodes [Ong 1976, Young et. al. 1981], while simulations of one tank systems have required 20 nodes for vertical tanks and 30 nodes for horizontal tanks [Morrison and Tran 1985]. A detailed study of the short term characteristics of a horizontal tank thermosyphon system [James and Proctor 1982] required 100 tank nodes to obtain reliable data on the interaction of the solar and auxiliary inputs. As the number of nodes is increased, the solution time step must be reduced to maintain satisfactory numerical accuracy. For a 20 node tank model, simulation time steps of less than 5 minutes may be required [Morrison and Tran 1985]. The time step restriction in fixed node models is due to numerical stability requirements that require the computation time step to be less than the fluid convection time through a node.

The modelling approach used in the TRNSYS stratified tank component is based on the SOLSYS model [Kuhn et. al. 1980]. Energy balances are formulated for moving segments of fluid such that the convection terms do not appear. The advantage of this technique is that the components of the fixed node energy balance equation that have long time constants (heat loss and conduction) are separated from the components that may have short time constants (convection due to collector and load flow). The energy balance equation that includes only heat loss and conduction can then be readily solved with time steps up to one hour, without the numerical accuracy problems that may be present when there is a convection term in the energy balance equation. Convection is analysed by a record keeping process on segments of fluid passing in and out of the tank.

The following features have been incorporated in the TRNAUS extension of the stratified tank component

5.1 Heat pipe coupling between the collector and the tank

Transfer of heat between a solar collector and the storage tank via a heat pipe has been modelled on the basis of heat input into the bottom of the tank. The temperature of the heat pipe condenser is taken as the average tank temperature over the immersion depth of the heat pipe condenser in the tank. The temperature drop across the heat pipe condenser is modelled as a linear function of the heat transfer rate. The collector/heat pipe evaporator element is modelled by a constant flow rate TYPE101 collector with flow rate set > 500 l/hr to simulate a uniform heat pipe evaporator temperature. The heat pipe component only accepts positive heat transfer into the tank, reverse heat transfer is assumed to be blocked by the thermal diode nature of heat pipes. Appendix 5 outlines part of a TRNAUS data deck for modelling a heat pipe collector system.

The heat pipe performance can be modelled in two ways

(a) If the collector/heat pipe condenser system has been tested as a unit the efficiency can be expressed in terms of (*Twc - Ta*) where *Twc* is the mean water temperature around the heat pipe condenser. Set heat pipe condenser length to 100 times the actual value, (resistance of heat pipe condenser included in test data).

(b) If the design of the heat pipe condenser is to be studied the collector performance can be expressed in terms of (*Tevap - Ta*) where *Tevap* is the mean heat pipe evaporator temperature. The temperature drop across the heat pipe condenser is evaluated on the basis of the thermal resistance of the condenser wall and free convection on the outside of the condenser. The collector flow rate can be adjusted to simulate a temperature rise along the length of the heat pipe (other than across the condenser).

5.2 Thermal dump valve

A temperature operated relief valve has been incorporated in the top of the stratified storage tank model. When the temperature in the top of the tank exceeds the relief valve upper set temperature the valve opens and dumps the contents of the tank that are at a temperature greater than the valve lower (closing) temperature. The valve is assumed to release water from the top of the tank at a maximum rate of 1 L/min.

5.3 Two position auxiliary input

The stratified storage tank component has been modified to incorporate two electric boost elements. This type of configuration would usually be used in a system using a bottom off-peak boost element and an upper continuous boost element. Separate thermostats can be specified for each element. The upper element is disconnected when the lower element is energised.

5.4 Computation sequence

The execution time of the stratified tank module has been reduced by rearranging the computation sequence. The conduction, heat loss and dump valve analysis is now performed only once per time step. Iterations involving TYPE138 are now restricted to variations of load flow, collector flow and auxiliary input.

5.5 Load energy binning

The Australian Standard AS 2813 for solar simulation testing of solar water heaters and the Outdoor Test Standard AS 2984 stipulate two quality standards for hot water delivery. Class A rating requires all energy to be delivered at temperatures greater than 57°C; Class B rating specifies a minimum delivery temperature of 45°C. The load analysis section of the stratified tank component has been modified to give outputs of total delivered energy and volume and the proportion of energy and volume at temperatures less than 57°C and 45°C. The parameters, inputs and outputs lists for the TYPE138 routine are given in appendix 2.

6 THERMOSYPHON ANALYSIS TYPE145

The thermosyphon component in TRNSYS is restricted to a linear collector characterising function. The thermosyphon component has now been directly coupled with the new TYPE101 collector component so that all the collector characterising functions in TYPE101 can be included in a thermosyphon system simulation. Also all the features of the stratified tank component are now available as options in the thermosyphon component. In addition to the extension of the collector and tank features the thermosyphon loop analysis has been extended to include

6.1 Heat exchanger thermosyphon circuits

The thermosyphon simulation routine has now been extended to incorporate a heat exchanger in the thermosyphon loop. The heat exchanger may take the form of a wrap around coil on a vertical tank, an immersed coil in vertical and horizontal tanks or a horizontal tank in tank annular heat exchanger. For the wrap around and immersed coil systems the heat exchanger is assumed to operate between the bottom of the tank and the specified entry point of the collector return line in the tank.

6.1.1 Horizontal mantle tank

For a horizontal mantle system the active heat exchange area is assumed to be the sections of the inner tank that are colder than the heat source inlet temperature.

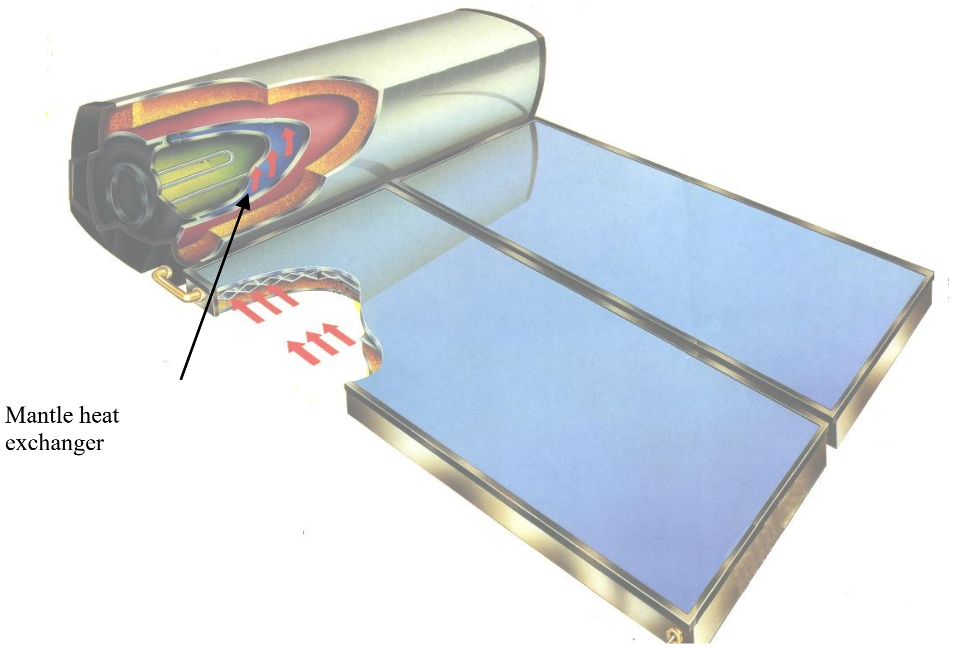

Fig 1. Close-coupled thermosyphon solar water heater with a mantle heat exchanger in the collector loop.

The flow connections to the mantle in Figure 1 are at the bottom of the mantle. The advantage of bottom connections is that heat loss due to reverse flow at night is suppressed compared to a system with a top level input to the mantle.

A model of a thermosyphon solar water heater with a collector loop heat exchanger was developed by Morrison (1994) from the detailed open-loop model in TRNSYS. Bickford and Hittle (1995) compared the predictions of this model with measured performance data obtained in a solar simulator and showed that the model over predicted collector energy gain by up to 10%. The model also over estimated the degree of stratification in the storage tank, when it was operated as a preheater. This model has now been extended to include improved analysis of conduction down the shallow depth of a horizontal tank and through the curved tank walls. In the original TRNSYS horizontal tank model reported by Morrison and Braun (1985) the equivalent conductivity of the tank walls and tank contents was quantified by a single value for all elements of the tank. This is correct for a vertical tank, however, for a horizontal tank the effect of wall conduction increases significantly for the top and bottom sections. Heat conduction in the walls of a tall vertical tank with height greater than 1m has only a minor effect on thermal stratification, however, for a horizontal tank wall heat conduction has a substantial impact on thermal stratification in the top and bottom sections of the tank, see Eames and Norton (1998). The effective thermal conductivity is based on a cross section area weighting of the tank contents and the walls as given by eqn(10).

$$k_e = (k_{water} A_{water} + k_{wall} A_{wall}) / A_{water} \tag{10}$$

where

k_{water} and k_{wall} are the thermal conductivity of water and the tank wall material.
A_{water} and A_{wall} are the cross sectional areas of the tank contents and the tank walls

For a vertical tank k_e is the same for all tank elements, however, for a horizontal tank the horizontal cross section of the tank contents varies with height. The variation of effective thermal conductivity k_e with depth for a 450 mm diameter steel tank with 3 mm walls is shown in Figure 2. Due to the high wall conduction in the top and bottom of a horizontal tank, stratified conditions cannot be maintained in the top and bottom layers for extended periods.

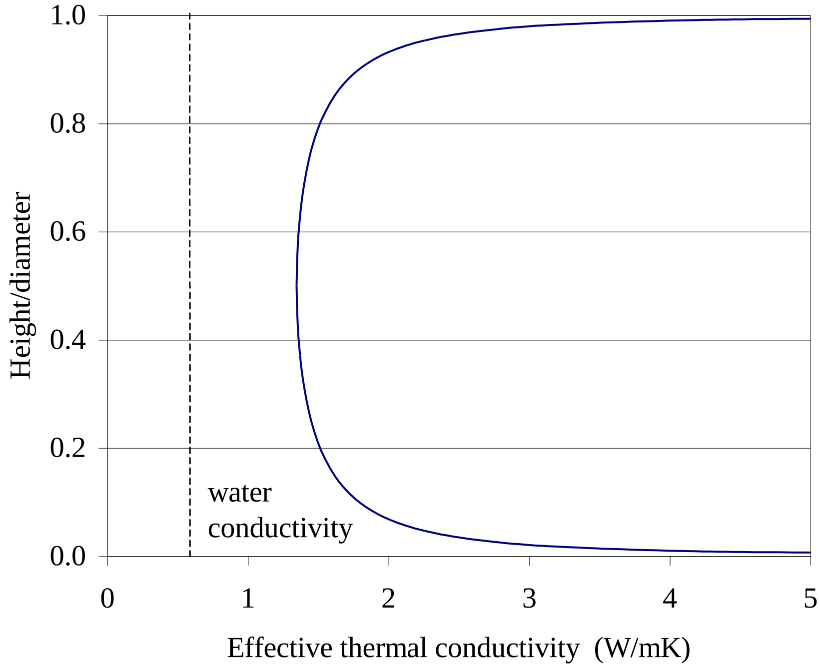

Fig 2. Effective thermal conductivity as a function of depth in a 450 mm diameter horizontal tank with 3 mm steel walls.

The new thermosyphon solar water heater simulation model incorporating a collector-loop heat exchanger was developed using the solar collector model (TYPE101), the stratified tank model (TYPE138) and a new heat exchanger routine integrated within the thermosyphon loop model (TYPE145).

6.1.2 Heat exchanger in tank with measured UA

A thermosyphon loop with a heat exchanger in the bottom of a horizontal tank can be modelled for specified UA for the heat exchanger as given by

UA = UAhx1 +UAhx2 * (Ti+Tt)/2

where Ti = heat exchanger hot inlet temperature
Tt = tank temperature at bottom level of heat exchanger
UAhx1 = measured heat exchanger performance coefficient
UAhx2 = measured temperature sensitivity of heat exchanger UA

6.2 Serpentine collectors

The effect of extra circuit friction caused by serpentine risers in the collectors can now be simulated. The length of the collector riser is now specified independently of the collector module dimensions. The friction in a circuit with serpentine collectors risers is assumed to be due to pipe friction only, the effects of the serpentine bends on pipe friction are assumed to be negligible. The number of bends in the serpentine path should not be included in the number of right angle bends in the thermosyphon circuit.

6.3 Thermal cut off valve

Overheating can be a major problem in thermosyphon systems incorporating high quality collectors. Tank temperatures above 75°C must be avoided in glass lined tanks to conserve the tank lining. High temperatures also introduce the problem of scalding. One way of limiting the tank temperatures in thermosyphon systems is to restrict the thermosyphon flow when the tank temperature is high. This will cause the collectors to stagnate and significantly reduce the heat input into the tank. This design feature has been incorporated in the new thermosyphon component.

The thermal cut off valve can be located in the collector inlet line or the collector outlet line.

If the valve is located at the tank outlet to the collector then the thermosyphon flow is assumed to stop when the temperature in the bottom of the tank exceeds the set temperature of the thermal cut off valve.
If the valve is located at the collector return to the tank then the thermosyphon flow is assumed to stop when the collector return temperature to the tank exceeds the set temperature of the thermal cut off valve.

This feature operates with both open and closed collector loop systems.

6.4 Reverse circulation in thermosyphon systems

The configuration of thermosyphon solar water heaters is partially dictated by the need to ensure that reverse flow does not occur at night. The conventional recommendation for minimising this problem is to mount the collectors so that the vertical separation between the top of the collectors and the bottom of the tank is greater than 200 mm [12]. However close coupled systems violate this design rule and yet appear to operate satisfactorily. There is very little published data on the magnitude of reverse flow and the conditions under which it occurs. A survey of design recommendations, revealed an average recommended separation of 500 mm, with a range from 200 to 2000 mm. These figures are significantly larger than the separation used in most close coupled systems. The thermosyphon component of TRNSYS has been extended to include analysis of reverse flow and the magnitude of the associated energy loss.

To model thermosyphon circulation the temperature variation in the collector and connecting pipes must be evaluated as a function of position so that the weight difference of the two sides of the collector loop can be evaluated. If there are large temperature changes along the connecting pipes or in the collector, simplifying assumptions such as equal mean temperature in the collector loop and tank [Close 1962] cannot be used, due to the nonlinear relationship between temperature and density. An analytic expression can be developed for the difference in the density of fluid on the two sides of the loop, however due to the exponential form of the relation between temperature and position and the nonlinear relationship between temperature and density, analytic solutions are very complex .
The method used to evaluate reverse thermosyphon flow is to compute the temperature gradients along the collector supply and return lines using a lumped element model. The temperature variation through the collector and the connecting pipes is modelled by dividing

each component into 10 segments. The fluid density in each segment is evaluated from the local temperature using the relation of Close [1962]. Evaluation of the temperature distribution and friction pressure drop in terms of flow rate is described in [Morrison and Tran 1985, Morrison and Braun 1985 , Morrison and Ranatunga 1980].
Night time heat loss from a collector is a function of the local ambient temperature and the sky temperature. If the sky temperature is significantly below ambient temperature the fluid passing down the collector will be cooled below ambient and when it moves up the return pipe to the tank it will be heated by the warmer surroundings if the pipe is not exposed to the cold sky. The combination of cooling below ambient temperature in the collector and heating in the return pipe causes reverse flow to occur in all thermosyphon configurations not fitted with a non-return valve.
As long term data on sky temperature is not usually available, simulation of reverse flow has to be carried out using an assumed sky temperature. On cloudy nights sky temperature is equal to ambient temperature but on clear nights sky temperature may be 20 to 30K below ambient temperature. The night time heat loss (Q_l) from a collector with convection and radiation heat loss coefficients *hc* and *hr* for the cover exposed to the cold sky is

$$Q_l = h_c (T_c - T_a) + h_r (T_c - T_{sky}) \tag{11}$$

where T_c = cover temperature.

If $T_s = T_a - dT$ then

$$Q_l = (h_r + h_r)(T_c - T_a + dT * \frac{h_r}{h_c + h_r} \tag{12}$$

Hence the effective sink temperature for heat loss from a collector is

$$T_e = T_a - \frac{h_r}{h_c + h_r} dT \tag{13}$$

For flat plate collectors the convection and radiation heat loss coefficients are approximately equal, hence the effective environment temperature governing heat loss from a flat plate collector is midway between ambient air temperature and sky temperature [Cooper 1981].

Analysis of reverse thermosyphoning can be activated by setting the thermosyphon parameter IREV = 1 (second last parameter), in the TYPE145 thermosyphon component and imposing an effective ambient temperature = (*Tsky* + *Tair*)/2. This component computes the heat loss due to reverse thermosyphoning but does not remove the fluid or energy from the storage tank, hence this component option indicates the potential heat loss but does not withdraw the energy from the system. If parameter IREV is set to 2 the following thermosyphon circuit operating factors are printed to the results file each time step

Time,
Incident radiation (W/m^2),
Ambient temp °C,
Thermosyphon loop flow rate (kg/hr),
Temperature at entry to thermosyphon loop,
Temperature at collector entry, °C
Temperature at collector outlet, °C
Temperature at flow return to tank, °C
Net heat gain/loss from the thermosyphon loop, W

Note the terms entry and outlet refer to the flow direction through the thermosyphon loop; the position of these points shifts when the flow reverses.

7 CONTROLLERS

Specialised control routines TYPE176, TYPE177 and TYPE178 have been developed for limiting supplementary energy input .

7.1 USER OVER-RIDE OF BOOSTER OPERATION TYPE176

This is a control module to model time limited or one-shot user control of an auxiliary booster. The module has two possible operation modes

- sets a logic signal to 1 for specified time after the input signal (temperature) drops below a set value. This can be used to model the behaviour of a user who switches an off-peak boost element to continuous boost for a fixed time.

or

- initiates the operation of a booster for one cycle of operation (terminated by a standard thermostat in a tank module). This mode has a lock-out feature that only allows one boost cycle to occur each day, this models the SEA-Victoria requirement for dayrate boosting of off-peak water heaters. The reset of the TYPE176 lockout occurs at midnight after the one-shot boost

This routine has been designed to be used in conjunction with the regular in-tank thermostat. This routine can be used to simulate user over-ride of the auxiliary heater by pressing a start switch on a timer, eg for user selected operation of the booster when the delivery temperature drops to a nominated temperature.
The output of TYPE176 should be logically added to any time-limited auxiliary enable signal for the power supply to the tank. When the power supply is enabled the power will be controlled by the in-tank thermostat for a time period given by the runtime parameter or if the runtime parameter is negative one cycle of the booster operation per day will be set by the combination of TYPE176 and the regular thermostat (the reset of the TYPE176 lockout occurs at midnight after the one-shot boost). If the user boost is to be locked out at night then the output of TYPE176 should be multiplied by a control signal (TYPE14) set to 0 from say 10PM to 6AM. TYPE176 data deck description is given in appendix 7.

7.2 Delay timer TYPE177

This routine can be used to set a control signal to 0 for a specified time after the first input becomes 1. If the input drops to 0 then the time delay is cancelled and the output goes to 1. An example of the application of this routine is to set a control signal high for a specified period after a pump turns on. Such a signal can be used to delay input from a supplementary source for a specified period after a solar collector starts operating. TYPE177 data deck description is given in appendix 8.

7.3 Event detection (tank sterilization controller) TYPE 178

This routine is used to set a control signal to 1 if the input has not exceed a threshold level in the previous specified time period. An example of the application of this routine is to set a control signal to initiate a tank sterilization boost to the specified threshold temperature if the input signal, say the temperature in a tank, had been below the threshold for the specified period.

For tank sterilization applications this routine will hold the control signal at 1 until the input has reached the threshold level and been maintained for a specified time period. This can be used to implement the tank sterilization cycle requirements in AS3498.

The TYPE178 data deck description and an example application are given in appendix 9.

7.4 Differential controller with three maximum limits TYPE102

This routine has the same functions as the standard TYPE2 controller except it has three maximum limit variable inputs. The deck description is given in Appendix 10.

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8. SOLAR BOOSTED HEAT PUMP

The primary application of this model is for efficiency rating of commercially available systems hence the performance of the heat pump compressor is determined from standard compressor rating test data rather than by detailed modelling of the compressor and refrigerant circuit. The extensions of the TRNSYS package required to model this system are modifications of the stratified tank subroutine to include a wrap-around heat exchanger and the development of a solar boosted refrigerant evaporator subroutine that accounts for solar input, sensible heat gain from the atmosphere and latent heat gain due to condensation on the evaporator. The evaporator in the heat-pump circuit may be a flat plate fully exposed to solar radiation or a flat panel wrapped around the storage tank. The model allows for evaporator input from direct and diffuse radiation (if the collector is exposed to the sky), sensible heat input and condensation on the evaporator. Examples of heat-pump water heater performance are given in [Morrison 1994].

8.1 Heat pump model

This module simulates the operation of a heat pump water heater based on standard compressor capacity test data and solar collector efficiency data. The routine models the temperatures in the evaporator and condenser including analysis of the temperature drop across the condenser heat exchanger. Analysis of energy gain from the evaporator includes the effects of solar irradiation, sensible heat gain from the air and condensation on the evaporator. Analysis of the refrigerant circuit is limited to determination of the average evaporator and condenser temperatures and refrigerant flow rate. The current model does not include detailed modelling of conditions in the refrigerant circuit. The parameters, inputs and outputs for this routine are given in appendix 4. The compressor performance data is read from a data file with the following format.

Line Number	Data
1	Evaporator temperatures
2	Condenser temperatures
3 -	Compressor power W, Capacity W

An example input file for compressor data is given in table 6, for evaporator temperatures -15 to 30 and condenser temperatures of 30 to 70.

Table 6

Compressor Performance Data

-15	-5	5	15	30
30	45	60	70	
380	590			
450	500			
525	420			
620	340			
390	975			
470	830			
560	650			
670	550			
380	1510			
470	1300			
590	1030			
690	850			
340	2250			
450	1900			
600	1530			
700	1220			
270	3300			
380	2900			
560	2700			
670	2070			

8.2 Solar-boosted evaporator

As the temperature of the evaporator will be close to ambient temperature an unglazed panel is adequate for day-time operation and allows the possibility of air-source operation at night and during rain periods. The heat transfer processes in the refrigerant evaporator include direct solar input, sensible heat gain from the atmosphere if the panel temperature is less than ambient, long wave radiation exchange with the sky and surroundings and latent heat gain due to condensation if the panel temperature drops to the dew point temperature (at night and during rain).

In the absence of condensation the efficiency of an unglazed solar absorber can be expressed as [Morrison and Gilliaert 1992]

$$\eta = a - (b + cV)(T_i - T_a)/G_n \qquad (14)$$

where
- V = wind speed
- T_i = refrigerant evaporator temperature
- G_n = net irradiance = $G + G_L$
- G = solar irradiance
- G_L = relative long wave irradiance = $\sigma(T_{sky}^4 - T_a^4)$

Typical efficiency coefficients for a roll-bond aluminium absorber panel with no back insulation are a = 0.75, b = 12.2 W/m^{2}K, c = 6.4 W/(m^{2}K m/s), where the absorber area is taken as the plan area for a roof mounted evaporator.
The heat removal fluid temperature in the collector may be considered to be constant due to the evaporation process. The effect of long wave radiation exchange with the sky can be quantified in terms of atmospheric dew point temperature (*Tdp*) by the following expression [Martin and Berdahl 1984] for the sky emissivity ε_{sky}.

$$\varepsilon_{sky} = 0.711 + 0.56\,(T_{dp}/100) + 0.73\,(T_{dp}/100)^2 \qquad (15)$$

For a horizontal surface the relative long wave irradiance exchange with the sky is

$$G_L = (\varepsilon_{sky} - 1)\,\sigma T_a^4 \qquad (16)$$

If the collector is inclined the relative long wave irradiance will be reduced by the view factor between the collector and the sky $(1 + \cos\beta)/2$, where β = collector inclination. If the sky is partially cloudy the long wave exchange will be reduced. As cloud cover (C) is commonly expressed as 1/8ths of the sky hemisphere the net long wave exchange [Morrison and Gilliaert 1992] for an inclined absorber under a partially cloudy sky is

$$G_L = (\varepsilon_{sky} - 1)\,\sigma T_a^4\,\frac{(8-C)}{8}\,\frac{(1 + \cos\beta)}{2} \qquad (17)$$

During night-time operation under humid conditions and during rain periods the evaporator panel temperature is set by latent heat gain from condensation and sensible heat gain from rain on the panel. To evaluate heat gain due to condensation on the collector, hourly data for atmospheric moisture content must be available. The mass transfer coefficient h_m for condensation can be related to the convective heat transfer coefficient h_c as follows

$$h_m = h_c\,D/k\,(Sc/Pr)^{1/3} \qquad (18)$$

where
Sc = Schmidt No
Pr = Prandtl No
D = mass diffusion coefficient
k = thermal conductivity

The best information regarding the convective heat transfer coefficient for the absorber plate is the heat loss coefficient ($b + cV$) obtained from the solar collector efficiency test (eqn 14). Hence the heat transfer due to condensation is given by

$$q_c = (b+cV)\,D/k\,(Sc/Pr)^{1/3}\,(Mw/RuT)\,h_{fg}\,(P_a - P_w) \qquad (19)$$

where
Mw = molecular weight of water
Ru = universal gas constant
T = air temperature
h_{fg} = latent heat of valorisation of water
P_a = atmospheric water vapour pressure, Pa
P_w = saturation water vapour pressure of water film on the panel, Pa

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For an ambient temperature of 20°C

$$q_c = 0.0163\ (b + cV)\ (P_a - P_w) \quad \text{W/m}^2 \qquad (20)$$

As typical meteorological weather data files do not usually include rain events the condensation heat gain expression is applied whenever $P_a > P_w$, thus the model predicts high heat gain when the heat pump is operating during rain periods.

The modes of heat gain to the collector are determined by the heat-pump evaporator temperature. During day-time the solar irradiance raises the panel temperature above ambient so that only direct solar gain is possible. During cloudy periods, and at night, the panel temperature will be below ambient temperature, hence heat gain is possible from solar input and sensible heat gain from the atmosphere. If the evaporator temperature falls below the dew point temperature condensation will occur on the collector. The proportion of daily energy gain from these three modes will depend on the time of day that the compressor operates.

8.3 Energy inputs to integral evaporator system

The primary solar aperture area of the compact wrap-around evaporator model (Fig 3) is the vertical cross section of the cylindrical evaporator panel. For a system with clear exposure towards the equator the solar beam aperture is equivalent to a vertical tracking surface with aperture area equal to the cross-section of the cylindrical panel. The evaporator area for sensible heat gain from the atmosphere and for latent heat gain from condensation is equal to the full circumferential area of the cylindrical evaporator panel. The convective heat transfer from the cylindrical form of the evaporator would be less than for the flat plate form due to the shielding of the inner surface of the wrap-around evaporator plate from the wind, however, free convection currents are induced along the inner surface of the evaporator by the cold chimney effect of the channel between evaporator and the tank.

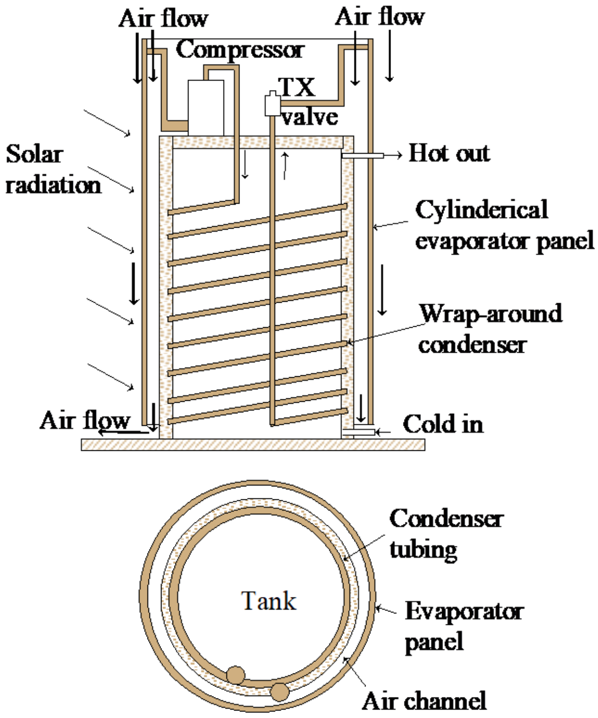

Fig 3. Heat pump water heater with integral evaporator panel around the tank.

The performance of the compact unit also depends on its location relative to adjacent walls and ground level wind speed. For an installation outside of the tropics, located against a wall facing the equator the vertical wrap-around evaporator will receive sky diffuse radiation on the front and sides of the cylindrical evaporator with some diffuse scattering from the backing wall.

The effective radiation input is

G_e = beam radiation + sky diffuse + ground reflected + backing wall reflected

$$G_eA = B_{st} * D * L + D_h A\, F_{c\text{-}s} + \rho_g\, G_h\, A\, F_{c\text{-}g} + \rho_w\, G_v\, A\, F_{c\text{-}w}$$

$$G_e = B_{st}/\pi + D_h\, F_{c\text{-}s} + \rho_g\, G_h\, F_{c\text{-}g} + \rho_w\, G_v\, F_{c\text{-}w} \qquad (21)$$

where
- A = surface area of cylindrical absorber
- B_{st} = beam irradiance on a vertical sun-tracking surface
- D_h = sky diffuse irradiance on a horizontal surface
- G_h = global irradiance on a horizontal surface
- G_v = global irradiance on a vertical surface facing the equator
- ρ_g = ground reflectance
- ρ_w = backing wall reflectance
- $F_{c\text{-}s}$ = configuration factor between the cylindrical absorber and the sky $\cong 0.25$
- $F_{c\text{-}g}$ = configuration factor between the cylindrical absorber and the ground $\cong 0.25$

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$F_{c\text{-}w}$ = configuration factor between the cylindrical absorber and a backing wall ≅ 0.5

The effective radiation can be generated in a TRNSYS deck using two TYPE16 radiation processors (eg UNIT 1 for a fixed vertical surface and UNIT 2 for a vertical sun tracking surface) and the following equation expression.

$$Ge = [2,7]/\pi + [2,5]*F_{c\text{-}s} + \rho_g*[2,4]*F_{c\text{-}g} + \rho_w*[1,6]*G_v*F_{c\text{-}w} \quad (22)$$

8.4 Storage tank and condenser

A model of a storage tank with a wrap-around heat exchanger was developed from the TYPE138 stratified tank routine in the TRNSYS simulation package. The thermal resistance for heat transfer from the wrap-around heat exchanger includes conduction through the refrigerant tube walls, thermal resistance of the bond between the tube and the wall, conduction through the single sided fin corresponding to the section of the tank wall associated with one pass of the refrigerant tube and free convection from the tank wall to the water in the tank.

The resistance to heat transfer of a wrap-around coil soldered to the water vessel is due primarily to conduction in the tube the tank walls, the glass lining of a carbon steel tank and free convection inside the tank. The refrigerant heat transfer coefficient in the tube has very little influence on the thermal resistance of the heat exchanger system. The primary heat transfer resistance is due to the free convection on the water side of the tank wall.

8.5 Solution procedure

The heating capacity of a direct expansion heat pump system is evaluated by establishing the evaporating and condensing saturation temperatures that satisfy the following energy balance conditions.

$$Q_{EVAP} = Q_u + Q_e \quad (23)$$

$$Q_{HX} = Q_{EVAP} + W_{comp} \quad (24)$$

where Q_u = solar and sensible heat gain by the evaporator
Q_e = condensation heat gain by the evaporator
Q_{HX} = heat transfer through the wrap-around heat exchanger
W_{comp} = compressor work input.

Other aspects of long term system performance simulation such as load extraction from the storage tank, thermostat operation, control of heat pump time of operation etc., were modelled using standard TRNSYS components.

9. GAS BOOSTED SOLAR WATER HEATERS (in-tank firing)

Analysis of gas boosting is included in the TYPE 38 stratified tank routine in TRNSYS via the specification of the UA value of the gas firing tube. In practice this UA value is seldom known hence this approach to evaluating the performance of gas boosting is not practical.
The performance of a gas fired water heater is commonly defined in terms of the following factors:

- Burner efficiency
- Maintenance rate

The burner efficiency approximately defines the proportion of combustion heat that passes into the water storage vessel. The approximation is due to the evaluation of this factor (AS 4552) via a heat-up test rather than an instantaneous heat transfer test. The maintenance rate is the gas energy consumption required to maintain the water heater at a constant temperature (45K above ambient temperature) plus the pilot gas consumption. The performance of a gas fired single tank solar water heater or a gas storage water heater in series with a solar preheater can be simulated using a TYPE138 TANK with electric boosting with additional calculation of gas combustion inefficiency. Pilot energy use is included in the tank heat loss specification.

If the auxiliary input to a TYPE138 (or TYPE4) tank is Q_{Aux} then the equivalent gas consumption is given by

$$Q_{gas} = Q_{aux}/effic * standby\ time$$

where Q_{Aux} = auxiliary input computed by TYPE138 (or TYPE4) tank routine, MJ/hr
effic = burner efficiency
standby time = non burner operation time

NOTE: pilot usage is included in maintenance rate (and hence tank heat loss)

The tank *UA* value required by the TRNSYS routines can be evaluated from the maintenance rate Q_{MR} as follows:

$$UA(Tw - Ta) \times 3600 = Q_{MR} \times effic$$

During the maintenance rate test [AS4552] a temperature differential of 45K is maintained hence:

$$UA = \frac{Q_{MR} * 10^6}{45 * 3600} * effic$$

where Q_{MR} = maintenance rate, MJ/hr
Tw = mean water temperature °C
Ta = ambient temperature °C
UA = tank heat loss per unit temperature difference, W/K

The UA value is entered as the tank heat loss parameter in TYPE138 and the gas consumption is calculated using the equation function in TRNSYS to evaluate Q_{gas}. A typical TRNSYS deck for a single tank gas boosted solar water heater is shown in Appendix 12.

10. AUSTRALIAN SOLAR RADIATION DATA (Typical Meteorological Year)

Australian solar irradiation data catalogued in the Australian Solar Radiation Data Handbook [Frick et. al. 1987] has been combined with other meteorological data and organised into condensed one year records of hourly meteorological data (Typical Meteorology Year Data). Each data record lists global solar irradiation on a horizontal surface, direct beam solar irradiation on a sun tracking surface, dry bulb ambient temperature, wet bulb ambient temperature, wind speed and direction and cloud cover. Details of this data are given by Morrison and Litvak (1988). The locations of the available data are given in Table 7.

Table 7
Measured hourly solar data

Site	Latitude	Longitude	Time	Elevation
	deg.min	deg.min	zone	m
	South	East		
New South Wales				
Sydney	33.93	151.10	14	32
Wagga	35.15	151.50		224
Williamtown	32.48	151.50		12
Northern Territory				
Alice Springs	23.49	133.54	14.5	547
Darwin	12.25	130.52		35
Queensland				
Brisbane	27.25	153.05	14	6
Longreach	23.26	144.16		195
Rockhampton	23.23	150.29		8
South Australia				
Adelaide	34.58	138.32	14.5	11
Mt.Gambier	37.45	140.47		63
Oodnadatta	27.34	135.25		113
Woomera	31.09	136.49		165
Tasmania				
Hobart	42.50	147.30	14	8
Victoria				
Laverton	37.53	144.45	14	14
Melbourne	37.50	144.58		123
Mildura	34.15	142.05		53
West Australia				
Albany	34.57	117.48	16	71
Forrest	30.50	128.07		157
Geraldton	28.48	114.47		35
Hall's Creek	18.14	127.40		423
Kalgoorlie	30.47	121.28		360
Perth	31.56	115.58		11
Port Headland	20.23	118.37		8
ACT				
Canberra	35.19	149.12	14 571	571

Table 8
Start time of data record

	Longitude deviation from local time zone	Time at end of first data period			
		Local time		Mean solar time	
		HH:MM	HH	HH:MM	HH
NEW SOUTH WALES					
Sydney	1.17	1:00	1.00	1:04	1.07
Wagga	-2.53	1:40	1.67	1:30	1.50
Williamstown	1.83	1:23	1.38	1:30	1.50
NORTHERN TERRITORY					
Alice Springs	-8.60	1:34	1.57	1:00	1.00
Darwin	-11.63	1:17	1.28	0:30	0.50
QUEENSLAND					
Brisbane	3.08	0:48	0.75	1:00	1.00
Longreach	-5.73	1:23	1.38	1:00	1.00
Rockhampton	0.48	1:28	1.47	1:30	1.50
SOUTH AUSTRALIA					
Adelaide	-3.97	1:16	1.20	1:00	1.00
Mt. Gambier	-1.72	1:37	1.67	1:30	1.50
Oodnadatta	-7.08	1:28	1.47	1:00	1.00
TASMANIA					
Hobart	-2.5	1:41	1.68	1:30	1.50
VICTORIA					
Laverton	-5.25	1:21	1.35	1.00	1.00
Melbourne	-5.03	1:20	1.33	1:00	1.00
Mildura	-7.92	1:32	1.53	1:00	1.00
WEST AUSTRALIA					
Albany	-2.20	1:39	1.65	1:30	1.50
Forrest	8.12	1:28	1.47	2:00	2.00
Geraldton	-5.22	1:21	1.35	1:00	1.00
Hall's Creek	7.67	1:29	1.48	2:00	2.00
Perth	-4.03	1.16	1.27	1.00	1.00
Port Headland	-1.38	1:36	1.50	1:00	1.00
ACT					
Canberra	-0.80	1:04	0.93	1:00	1.00

10.1 Extension of hourly climatic data bank

Delsante extended the measured data bank to include three years of data for Adelaide, Brisbane, Canberra and Sydney. Delsante also computed solar radiation from cloud cover measurements and developed coincident hourly climatic data records for an additional 63 locations in Australia. Data from Delsante for the locations given in Table 9 has been reformatted into the form required for use in TRNSYS.

Table 9
Location with solar irradiation data computed from cloud cover

Amberley	Qld
Cairns	
Mt Isa	
Oakey Army	
Townsville	
Cobar	NSW
Coffs Harbour	
Moree	
Nowra	
Orange	
Richmond	
Tamworth	
Sale	Victoria
Hobart	Tasmania
Broome	Western Australia

10.2 Weather data for New Zealand

TMY data for New Zealand has been developed for Auckland and Dunedin as specified in Table 10.

Table 10
TMY data for New Zealand

Location	Latitude (degrees)	Longitude shift from standard time longitude (degrees)	Time datum	Time at end of first record hrs
Auckland	-37	-5.5	New Zealand standard time	1.0
Dunedin	-45.8	-9.5	New Zealand standard time	1.0

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Appendix 1. TRNAUS Solar Collector Component Description TYPE101

Mode 1. Efficiency Specification

PARAMETER NO.		DESCRIPTION
1		Collector Mode : Specify 1
2	Ns	number of collectors in series
3	A	total collector array area, m^2
4	Cpc	specific heat of collector fluid, kJ/kg K
5	**Efficiency Specification Mode**	
	1	$\eta = a - b\,(T_i - T_a)/I$
	2	$\eta = a - b\,(T_w - T_a - R)/I\ - c\ (T_w - T_a + R)^2/I$
	-2	$\eta = a - (b + c{*}V)\,(T_w - T_a)/I\ - d\,(T_w - T_a)^2/I$ (unglazed absorber) with wind speed dependent heat loss coefficient and allowance for condensation and long wave radiation
	3	$\eta = a - b\,(T_w - T_a + R)/I\ - c\,(T_w^4 - (T_a - R)^4)/I$
Evacuated tubes (Dewar flask type)		
	4	Water-in-glass construction
	5	U-tube with fin
	6	U-tube without fin
	7	Evacuated tube rack (two rows of tubes)
Efficiency Mode 1. $\eta = a – b\,(T_i - T_a)/I$		
6	Gtest	flow rate per unit area at test conditions, kg/hr m^2
7	a	intercept efficiency
8	b	negative of the slope of the efficiency curve, kJ/(hr m^2 K)
9	ε	effectiveness of the collector loop heat exchanger, if < 0, then no heat exchanger)
10	Cpf	specific heat of fluid entering the cold side of the heat exchanger kJ/kg K
Efficiency Mode 2. $\eta = a – b\,(T_w – T_a – R)/I\ - c\ (T_w – T_a + R)^2/I$		
6	a	intercept efficiency
7	b	$(T_w – T_a + R)$ coefficient kJ/(hr m^2 K)
8	c	$(T_w – T_a + R)^2$ coefficient kJ/(hr m^2 K^2)
9	R	sky temperature allowance, K
10	-	not used (but must be included in parameter list)
Efficiency Mode –2. ($\eta = a - (b + c{*}V)\,(T_w – T_a)/I\ - d\,(T_w – T_a)^2/I$)		
6	a	intercept efficiency
7	b	$(T_w – T_a)$ coefficient kJ/(hr m^2 K)
8	d	$(T_w – T_a)^2$ coefficient kJ/(hr m^2 K^2)
9	0	sky temperature allowance, K (set to zero for unglazed absorber)
10	c	wind speed coefficient of collector heat loss coefficient
Efficiency Mode 3. $\eta = a – b\,(T_w – T_a + R)/I\ - c\,(T_w^4 - (T_a – R)^4)/I$		
6	a	intercept efficiency
7	b	$(T_w – T_a + R)$ coefficient kJ/(hr m^2 K)
8	c	$(T_w^4 - (T_a – R)^4)$ coefficient kJ/(hr m^2 K^4)
9	R	sky temperature allowance, K
10	-	not used (but must be included in parameter list)
Efficiency Modes 4, 5 & 6 $\eta = a – b\,(T_w – T_a)/I\ - c{*}N{*}\,(T_s – T_a)/I – d{*}N{*}\varepsilon s\,(T_s^4 - T_a^4)/I$		
6	a	intercept efficiency
7	b	$(T_w – T_a)$ coefficient per tube kJ/K
8	c	$(T_s – T_a)$ coefficient per tube kJ/K
9	d	$(T_s^4 - T_a^4)$ coefficient per tube, kJ/K^4

10	N	number of tubes per m^2 of array

Efficiency Modes 7 $\eta = a - b\,(T_w - T_a)/I \; - c*N*(T_s - T_a)/I - d*N*\varepsilon s\,(T_s^4 - T_a^4)/I$

6	a	intercept efficiency
7	b	$(T_w - T_a)$ coefficient per tube kJ/K
8	c	$(T_s - T_a)$ coefficient per tube kJ/K
9	d	$(T_s^4 - T_a^4)$ coefficient per tube, kJ/K^4
10	DT	temperature drop across the tube surface at 500 W input/tube
Optical Mode		
11	0	no incidence angle modification
	1	use incidence modifier constant from ASHRAE 93-77
	2	modifier data as a function of incidence angle
	3	use cover and absorber properties
	4	bi-axial incidence angle modifier data
	5	optical map for collector that is symmetric in the North-South and East-West planes (only positive angles specified)
	6	optical map for collector that is symmetric in the East-West plane only. (Full optical map for both planes)
Optical Mode =1		
12	Bo	incidence angle modifier constant from ASHRAE 93-77
Optical Mode =2 or 4 (orthogonal symmetry incidence angle modifier map)		
12	Lui	logical unit containing incidence angle modifier data
13	No	number of values of incidence angle in data (≤50)
Optical Mode =3		
12	α	collector plate absorptance
13	Ng	number of identical covers
14	Zr	index of refraction of cover material
15	KL	product of extinction coefficient and cover thickness
Optical Mode =5 & 6		
12	Lui	logical unit number of file containing optical data
13	N_1	number of values of transverse angles (≤50) (NS or longitudinal plane)
14	N_2	number of values of longitudinal angles (≤25) (EW or transverse plane)

INPUT NO		**DESCRIPTION**
1	Ti	temperature of fluid entering cold side of heat exchanger OR collector inlet if no heat exchanger, C
2	mc	collector array fluid mass flow rate, kg/hr
3	mf	heat exchanger cold side fluid mass flow rate, kg/hr
4	Ta	ambient temperature, C
5	It	incident radiation, kJ/(hr m^2)
Optical Mode = 0 and Efficiency Mode = -2		
6	T_{wet}	wet bulb temperature C
7	C	cloud cover (1/8ths)
8	V	wind speed m/s
Optical Mode = 1,2 or 3		
6	I	total horizontal radiation kJ/(hr m^2)
7	I_d	horizontal diffuse radiation kJ/(hr m^2)
8	σ	ground reflectance
9	θ	incidence angle, (deg)
10	β	collector slope, (deg)
Optical Mode = 1,2 or 3 and Efficiency Mode = -2		
11	Twet	wet bulb temperature C
12	C	cloud cover (1/8 ths)
13	V	wind speed m/s

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Optical Mode = 4, 5 & 6

6	Idt	incident diffuse radiation
7	θ	solar incidence angle, (deg)
8	θ_z	solar zenith angle, (deg)
9	θ_{az}	solar azimuth angle, (deg)
10	β	collector slope, (deg)
11	θ_{azc}	collector azimuth, (deg) facing equator = 0; east positive

Optical Mode = 4,5 &6 and Efficiency Mode =-2

12	Twet	wet bulb temperature C
13	C	cloud cover (1/8 ths)
14	U	wind speed m/s

OUTPUT NO		DESCRIPTION
1	T_o	outlet fluid temperature, C
2	m_o	outlet fluid flow rate, kg/hr
3	Q_u	rate of energy gain, kJ/hr
4	Q_c	part of collector output due to condensation on the collector,kJ/hr
5	Q_a	part of collector output when irradiation < 90 kJ/hr (kJ/hr)
6	θ_l	Angle of incidence in longitudinal plane (plane along direction = collector azimuth vector)
7	θ_t	Angle of incidence in transverse plane (plane perpendicular to collector azimuth direction)
8	G_L	Long wave radiation kJ/(m^2 hr)
9	$K\tau\alpha$–b	Incidence angle modifier for beam
10	$K\tau\alpha$–d	Incidence angle modifier for diffuse
11	$K\tau\alpha$	Effective incidence angle modifier

Appendix 2 Stratified Tank Component Description TYPE138

PARAMETER		DESCRIPTION
1:	HX Mode	
		1 - complete mixing of heated fluid at return level
		2 - fully stratified inlet
		3 - heat pipe fitted to bottom of tank
		4 – collector loop heat exchanger in form of a coil wrapped around the tank
		5 – collector loop heat exchanger in form of coil in tank heat exchanger
		6 – collector loop heat exchanger in form of horizontal tank in tank heat exchanger
		7 – load mixing in bottom of tank (at Hcold level), collector return fully stratified
		8 - collector loop heat exchanger in tank with measured UA coefficients
2	Vt	tank volume, m^3 Note for mode =6, Vt = potable water + heat exchanger volume
3	Ht	tank height for vertical tank, tank diameter for horizontal tank, inner tank diameter for mode 6 heat exchanger m
4	Hr	height of collector return to tank above bottom of the tank, OR for HX Mode 3; height of top of heat pipe condenser above bottom of tank, m OR for HX Modes 4,5 and 8 (heat exchanger extends between the bottom of the tank and the height Hr height of heat exchanger inlet above bottom of tank, m. OR for HX Mode 6; the fluid flow in the mantle is assumed to cover the section of the mantle from the bottom up to the thermal equilibrium level between the collector loop input to the mantle and the tank contents.
5	-	not used
6	–	not used
7	$t_w k_w$	tank wall thickness times wall conductivity, kJ/(hr K) (used to determine conduction degradation of stratification)
8		Tank configuration
	1	vertical cylinder
	2	horizontal cylinder
9	UA	overall UA of the tank, kJ/(hr K)
10	r_i	insulation thickness ratio between the top and sides of a vertical tank
	OR	
		thickness ratio between top and bottom for a horizontal cylinder
11	T_i	initial temperature of preheat portion of the tank, C
12	H_c	height of cold inlet above the tank bottom, m $= 1.316 * H_t \left(1 - \frac{rated\ vol}{physical\ vol}\right)$ (Rated volume= AS1056 delivery for ΔTout=12K)
Top auxiliary element	**(NOTE: Top element is inactive if second element is active)**	
13	Q_{he}	auxiliary input rating, kJ/hr
14	H_a	height of top auxiliary element above the bottom of the tank,
15	H_t	height of top thermostat above the bottom of the tank, m
16	T_{set}	thermostat set temperature, C (also initial temperature for section of tank above element)
17	T_{db}	Temperature dead band for auxiliary heater, K
18	UA_f	conductance for heat loss to gas flue when auxiliary is off (=0 for

		electric auxiliary) kJ/(hr K)
19	V_{max}	maximum size of tank elements during conduction analysis, (fraction of tank). typically =0.05
20	T_{max}	dump valve operating temperature, C
21	T_{min}	dump valve closing temperature, C

Second electric element specification (below first element)

22 optional	Q_{he}	auxiliary input rating kJ/hr
23 "	H_a	height of auxiliary above the bottom of the tank, m
24 "	H_t	height of thermostat above the bottom of the tank, m
25 "	T_{set}	thermostat set temperature (also initial temperature for section of tank above element)
26 "	T_{db}	Temperature dead band for auxiliary heater, K

Tank Mode = 3, collector loop heat pipe condenser specification

last -2	D_{cond}	diameter of heat pipe condenser in contact with water, K
last -1	L_{cond}	length of heat pipe condenser, K
last	R_{bond}	thermal resistance of heat pipe condenser wall per metre length, K hr /kJ m

Tank Mode = 4, collector loop wrap around heat exchanger specification

last -4	D_{coil}	diameter of wrap around coil tubing, m
last -3	L_{coil}	length of wrap around coil m
last -2	R_{bond}	thermal resistance coil to tank bonding / metre length, K hr/(kJ m)
last -1	$t_w\, k_w$	tank wall thickness times wall conductivity, kJ/(hr K)
last	$t_p\, k_p$	heat exchanger tubing wall thickness * wall conductivity, kJ/(hr K)

Tank Mode = 5, collector loop coil-in-tank heat exchanger specification

last -2	D_{coil}	diameter of coil tubing, m
last -1	L_{coil}	length of coil, m
last	R_{bond}	conduction thermal resistance of coil wall/ metre length K hr/(kJ m) $=\ln(R_2/R_1)/(2\pi k)$ for simple unfinned pipe

Tank Mode = 6, collector loop horizontal tank in tank heat exchanger specification

last -2	D_{HX}	Diameter of inside surface of mantle wall, m
last -1	L_{HX}	length of mantle heat exchanger, m
last	R_{bond}	conduction thermal resistance of tank wall/metre length K hr/(kJ m)

$$= \frac{1}{\pi D_{HX}} \left(\frac{t_{wall}}{k_{wall}} + \frac{t_{glass}}{k_{glass}} \right)$$

Tank Mode = 7, collector loop horizontal tank in tank heat exchanger specification

last -2	- no used but must be specified
last -1	- no used but must be specified
last	- no used but must be specified

Tank Mode = 8, collector loop heat exchanger in tank – measured characteristic

last -2	- constant UA coefficient
last -1	- UA temperature coefficient
last	- no used but must be specified

INPUT NO		DESCRIPTION
1	T_h	temperature of fluid from heat source, C
2	m_h	fluid mass flow rate from heat source, kg/hr
3	T_l	temperature of replacement fluid from load, C
4	m_l	mass flow rate from load, kg/hr
5	T_{env}	temperature of environment for tank heat loss, C
6		enable signal for first auxiliary heater

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		(NOTE: First element is inactive if second element is active)
7		enable signal for second auxiliary heater

OUTPUT NO		**DESCRIPTION**
1	T_{ret}	temperature of fluid returned to heat source, C = T_{botomt} for HX Mode = 1,2 & 7 = T_{HXOUT} for HX Mode = 3 to 6
2	m_h	Fluid mass flow rate to heat source, (kg/hr)
3	T_d	temperature of fluid delivered to load, C
4	m_l	mass flow rate to load, kg/hr
5	Q_{env}	rate of heat loss from tank, kJ/hr
6	Q_{sup}	rate of energy supply to load, kJ/hr
7	E	change of internal energy of tank since start of simulation
8	Q_{aux}	rate of total auxiliary input to tank, (kJ/hr) (sum of two elements)
9	Q_{in}	rate of energy input to tank by fluid stream from heat source, (kJ/hr) for Mode = 3 to 6, only heat input is considered
10	T	average storage temperature, C
11	H_t	thermosyphon pressure in tank (used internally), Pa
12	V < 45°C	load volume delivered at temperature less than 45°C m^3/hr
13	V < 57°C	load volume delivered at temperature less than 57°C m^3/hr
14	E < 45°C	load energy delivered at temperature less than 45°C kJ/hr
15	E < 57°C	load energy delivered at temperature less than 57°C kJ/hr
16	T_{ret}	input temperature to collector loop, C (same as output No1) = tank bottom temperature for mc>0 = tank temperature at level of collector return to tank, if mc<0
17	E_{dump}	energy dumped due to tank over heating, kJ/hr
18	Q_{aux2}	rate of auxiliary input to tank by element 2 (bottom element), kJ/hr
19	Tbot	temperature at bottom of tank C
20	T_w	water temperature in tank adjacent to the heat exchanger, C (average over depth of heat exchanger)

Appendix 3 TYPE145 Thermosyphon Solar Water Heater Component Description

PARAMETER		DESCRIPTION
1		**Efficiency Mode**
	1	η vs $(T_i - T_a)/I$
	2	η vs $(T_w - (T_a - R))/I$ and $(T_w - (T_a - R))^2/I$
	3	η vs $(T_w - (T_a - R))/I$ and $(T_w^4 - (T_a - R)^4)/I$
	4 to 6 =	Evacuated tube array
	4	water in glass
	5	U tube with fin
	6	tube without fin
2	A_c	collector area m^2
Efficiency Mode =1		
3	a	intercept of the efficiency vs $(T_i - T_a + R)/I$ function
4	b	Negative of the slope of the efficiency vs $(T_i - T_a + R)/I$ function kJ/(hr m^2 K)
5	Gtest	mass flow rate per unit collector area during testing, kg/(hr-m^2)
6	-	not used, (but must be included in parameter list)
Efficiency Mode =2		
3	a	intercept efficiency
4	b	$(T_w - T_a + R)$ coefficient kJ/(hr m^2 K)
5	c	$(T_w - T_a + R)^2$ coefficient kJ/(hr m^2 K^2)
6	R	sky temperature allowance, K
Efficiency Mode = 3		
3	a	intercept efficiency
4	b	$(T_w - T_a + R)$ coefficient kJ/(hr m^2 K)
5	c	$(T_w^4 - (T_a + R)^4$ coefficient kJ/(hr m^2 K^4)
6	R	sky temperature allowance, K
Efficiency Mode = 4, 5 and 6		
3	a	optical efficiency
4	b	$(T_w - T_a)$ coefficient per tube
5	c	$(T_s - T_a)$ coefficient per tube
6	d	$(T_s^4 - T_a^4)$ coefficient per tube, see parameter 14 for number of tubes/m^2
7	β	collector slope, (deg)
8	Lu	logical unit number of file containing head vs flow rate data. Data units, m and kg/hr. (see parameter 9)
9	Ndata	number of lines of data in Lu_s OR if Lu < –1 number of parallel collector risers
10	d_r	riser diameter, m. not used if Lu >0
11	l_r	riser length, m
12	d_h	header diameter, m
13	H	header length of collector array (one header only), m
14	Nx	number of collector nodes for thermal head calculations (not used if efficiency mode >2) OR number of evacuated tubes per m^2 if Efficiency mode =4,5 or 6
15	H_c	vertical separation between collector outlet and inlet, m
16	H_o	vertical separation between cold tank outlet and collector inlet, m
17	d_i	diameter of collector inlet pipe
18	l_i	length of collector inlet pipe m

19	Nb1	number of right angle bends (or equivalent) in inlet pipe
20	U_i	loss coefficient of collector inlet pipe, based on pipe outer diameter, kJ/(hr-m^2-K)
21	d_o	diameter of collector outlet pipe, m
22	l_o	length of collector outlet pipe, m
23	Nb2	number of right angle bends (or equivalent) in collector outlet pipe
24	U_o	loss coefficient of collector outlet pipe, based on pipe outer diameter, kJ/(hr-m^2-K)
25	**Tank HX Mode**	
	1	complete mixing of heated fluid at return level, direct connection.
	2	fully stratified inlet
	3	not available for thermosyphon mode
	4	collector loop wrap around heat exchanger
	5	Collector coil in tank heat exchanger
	6	Collector loop horizontal tank in tank heat exchanger
	7	load mixing in bottom of tank (at Hc level),direct connection collector return fully stratified
	8	Collector loop heat exchanger in tank with measured UA characteristics
26	V_t	tank volume, m^3
27	H_t	tank height (vertical cylinder), Tank diameter (horizontal cylinder), inner tank diameter for mode 6 heat exchanger m
28	Hr	height of collector return to tank above bottom of the tank, OR for HX mode 3; height of top of heat pipe condenser above bottom of tank, m OR for HX Modes 4 and 5 height of heat exchanger inlet above bottom of tank, m. OR for HX Mode 6; if set =0 then fluid in the mantle is assumed to rise or fall in the mantle to its thermal equilibrium level before passing over the mantle area.
29	-	Not used (but must be included in parameter list)
30	–	Not used (but must be included in parameter list)
31	$t_w\ k_w$	tank wall thickness times wall conductivity, kJ/(hr K)
32		Tank Configuration
	1	vertical cylinder
	2	horizontal cylinder
33	UA	overall UA for tank, (kJ/(hr-K)
34	r_i	insulation thickness ratio between the top and sides of a vertical tank OR insulation thickness ratio between top and bottom for a horizontal tank
35	T_i	initial temperature of preheat portion of the tank, C
36	H_c	height of cold inlet above the bottom of the tank, m
37	Q_{he}	auxiliary input rating, kJ/hr
38	H_a	height of auxiliary above the bottom of the tank, m
39	H_t	height of thermostat above the bottom of the tank, m
40	T_{set}	thermostat set temperature, C (also initial temperature for section of tank above element)
41	T_{db}	temperature dead band for auxiliary heater, K
42	UA_f	conductance for heat loss to gas flue when auxiliary is off (=0 for electric auxiliary) kJ/(hr K)
43	V_{max}	maximum size of tank elements during conduction analysis, (fraction of tank). typically =0.1
44	T_{max}	dump valve operating temperature, C
45	T_{min}	dump valve closing temperature, C

Tank HX Mode = 1 or 2		**Direct connection to tank**
46	-	Not used (but must be included in parameter list)
47	-	Not used (but must be included in parameter list)
48	-	Not used (but must be included in parameter list)
49	-	Not used (but must be included in parameter list)
50	-	Not used (but must be included in parameter list)
Tank HX Mode = 3		**Heat pipe condenser specification**
		Not available in thermosyphon circuit
Tank HX Mode = 4		**Wrap around heat exchanger specification (vertical tank only)**
46	D_c	diameter of wrap around coil tubing, m
47	L_c	length of wrap around coil m
48	R_b	thermal resistance of coil to tank bonding / metre length, K hr/(kJ m) (=twall/(kwall A/L)) where A/L = πD for full circumference HX.
49	$t_w\ k_w$	tank wall thickness times wall conductivity, kJ/(hr K)
50	$t_p\ k_p$	heat exchanger tubing wall thickness times wall conductivity kJ/(hr K)
Tank HX Mode = 5		**Coil in tank heat exchanger specification**
46	D_c	diameter of coil tubing, m
47	L_c	length of coil, m
48	R_b	conduction thermal resistance of coil wall/ metre length K hr/(kJ m)
49	-	Not used (but must be included in parameter list)
50	-	Not used (but must be included in parameter list)
Tank HX Mode = 6 & 7		**Horizontal tank in tank heat exchanger specification**
46	D_{HX}	Inside diameter of outer wall of mantle heat exchanger , m
47	L_{HX}	length of mantle heat exchanger , m
48	R_{bond}	conduction thermal resistance of tank wall/metre length K hr m/kJ $= \frac{1}{\pi D_{HX}}\left(\frac{t_{wall}}{k_{wall}} + \frac{t_{glass}}{k_{glass}}\right)$
49	-	Not used (but must be included in parameter list)
50	-	Not used (but must be included in parameter list)
Tank HX Mode = 8		**Horizontal tank – measured heat exchanger UA**
46	D_{HX}	Hydraulic diameter of heat exchanger tubes on collector side ,used for internal friction evaluation, must equal dimension of test unit, only single tube is considered , m
47	L_{HX}	length of mantle heat exchanger (used for internal friction evaluation, must equal dimension of test unit), m
48	-	Not used (but must be included in parameter list)
49	UA1	Intercept of UA versus average temperature of heat exchanger

		kJ/(h K)
50	UA2	Slope of UA versus average temperature of heat exchanger kJ/(h)
51		**OPTICAL MODE**
	0	no incidence angle modification
	1	use incidence modifier constant from ASHRAE 93-77
	2	modifier data as a function of incidence angle
	3	not available
	4	bi-axial incidence angle modifier data
	5	optical map for collector that is symmetric in the North-South and East-West planes.
	6	optical map for collector symmetric in the East-West plane only
Optical Mode =1		
52	Bo	incidence angle modifier constant (ASHRAE 93-77)
Optical Mode =2 or 4		
52	Lui	logical unit containing incidence angle modifier data
53	No	number of values of incidence angle in data (<=25)
Optical Mode =5 & 6		
52	Lui	logical unit number of file containing optical data
53	N_1	number of values of transverse angles (<=50)
54	N_2	number of values of longitudinal angles (<=25)
last - 1	IREV -	reverse thermosyphon
	0	do not analyse reverse flow
	1	analyse reverse flow
	2	print detailed output each time step (produces large output file, only select for short simulations)
last	T_t	operating temperature for thermosyphon flow restriction valve (set >100 for no flow restriction), C If Tt > 0 flow restriction valve is mounted on tank outlet to collector If Tt < 0 flow restriction valve is mounted on collector outlet to tank and valve temperature setting is ABS(Tt)

INPUT NO		DESCRIPTION
1	I_t	incident radiation on collector aperture (kJ/(hr-m^2)
2	I_h	horizontal total radiation (kJ/(hr-m^2)
3	I_d	horizontal diffuse radiation (kJ/(hr-m^2)
4	θ	solar beam incidence angle to collector, (deg)
5	σ	ground reflectance
6	T_a	ambient temperature, C
7	T_l	temperature of load input to tank, C
8	m_l	mass flow rate from load, (kg/hr)
9	T_{env}	environmental temperature for losses from storage C
10	-	enable signal for auxiliary heater
Efficiency Modes 4 to 6 or Optical Modes 2 to 6		
11	I_{dt}	diffuse radiation incident on collector aperture, (kJ/hr m^2)
12	θ_z	solar zenith angle, (deg)
13	θ_{az}	solar azimuth angle, (deg)
14	θ_{azc}	collector azimuth angle, (deg)

OUTPUT		DESCRIPTION
1	T_h	Temperature of hot fluid entering tank C
2	Q_u	useful output energy from collector (at collector outlet) kJ/hr

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3	T_r	temperature of fluid returned to collector, C
4	m_h	mass flow rate to collector, kg/hr
5	T_d	temperature of fluid delivered to load, C
6	m_l	mass flow rate to load, kg/hr
7	Q_{env}	rate of heat loss from tank, kJ/hr
8	Q_{sup}	rate of energy supply to load kJ/hr
9	E	change of internal energy of tank since start of simulation
10	Q_{aux}	rate of auxiliary input to tank, kJ/hr
11	Q_{in}	rate of energy input to tank (collector output - pipe losses) kJ/hr
12	T	average storage temperature, C
13	V < 45°C	load volume delivered at temperatures less than 45°C m^3/hr
14	V < 57°C	load volume delivered at temperatures less than 57°C m^3/hr
15	E < 45°C	load energy delivered at temperatures less than 45°C kJ/hr
16	E < 57°C	load energy delivered at temperatures less than 57°C kJ/hr
17	T_{ret}	input temperature to collector loop, C. = tank bottom temperature for mc>0 = tank temperature at level of collector return to tank if mc<0
18	E_d	energy dumped due to tank over heating, kJ/hr
19	Q_{rev}	potential heat loss due to reverse flow , kJ/hr (not removed from tank)

Appendix 4 TYPE137 Heat Pump with Solar Boosted Evaporator

PARAMETER		DESCRIPTION
1	IU	Logical unit number for heat pump rating data
2	N1	number of condenser temperatures in heat pump performance data file
3	N2	number of evaporator temperatures in heat pump performance data file

INPUT		DESCRIPTION
1	Qe	evaporator heat gain kJ/hr
2	Qc	condenser heat transfer kJ/hr
3	Tcx	water temperature over depth of condenser °C
4	Tex	ambient temperature adjacent to evaporator °C
5	ONOFF	heat pump motor switch

OUTPUT		DESCRIPTION
1	Te	evaporator temperature, °C
2	Tc	condenser temperature °C
3	Wcom	compressor power kJ/hr

Appendix 5 TRNAUS data deck for heat pipe collector modelling

```
CONSTANTS 13
LAT = -34 REF = 0.2 SLOPE = 34 AZIMUTH = 0 HE = 0.2 HTH = 0.25
MODE = 3 TDB = 3 TSET = 61 UA = 9 FLOW = 500 IR = 2 COND = 3.3

UNIT 9 TYPE 9 Weather data reader
PARAMETERS 13
6 1 -4 10 0 -5 10 0 6 .1 0 4 1
(1X,3F2.0,3F3.0)
* Output 9,4 is horizontal global irradiation
* Outout 9,6 is ambient temperature

UNIT 16 TYPE 16 Radiation processor
PARAMETERS 7
3 3 1 LAT 4871 2 1
INPUTS 6
9,4 9,19 9,20 0,0   0,0     0,0
 0   0    0   REF  SLOPE  AZIMUTH

UNIT 1 TYPE 101 Heat pipe collector model
* Collector modelled on basis of experimental test data for collector/heat pipe module
* see section 5.1.2 if collector has been tested without the heat pipe.
* Collector flow rate is fixed at 500 l/hr
* Collector output will be negative at night however the heat pipe condenser model
* in the stratified storage tank will only accept positive heat input
PARAMETERS 12
1 1 AC 4.18 2 .627 10 0 3 0 1 0
INPUTS 10
38,1  0,0  0,0 9,6 16,7 16,4 16,5  0,0  16,9 0,0
 20  FLOW FLOW 20    0    0    0   REF    0  SLOPE

UNIT 38 TYPE 138 Stratified tank
* Positive heat output from collector is given by output 38,9.
* The following parameter list applies to a heat pipe collector for which the collector is
* specified in terms of Twater - Te
* where Twater is the water temperature outside the heat pipe condenser,
* The condenser length is set to a large value (100* actual) to eliminate the thermal resistance of
* the heat pipe condenser, which  is included in the collector coefficients in TYPE1)
PARAMETERS 24
MODE .325 .44 .1 4.18 1000 COND 2 UA IR 35 0 12960 HE HTH TSET
TDB 0 .1 100 95 .02 20 0
INPUTS 6
1,1 1,2 17,1 25,2 9,6 0,0
20  FLOW 20    0  20   1
* 17,1 is cold water temperature
* 25,2 is load flow rate
```

Appendix 6 TRNAUS data deck for energy load control

Control of load draw off from TRNSYS water tanks is limited to volume specification. However in order to compare two systems, simulations of operation when both systems are supplying the same energy load is necessary. Energy load control can be built into a TRNSYS simulation by using a thermal mixing valve. The program will iterate on the volume draw off until a desired energy load is achieved.
Note :- energy load control significantly increases the program execution time (up to 4 times for some systems).
An example of part of a TRNSYS deck for load energy control is shown below.

CONSTANTS 1
TLOAD=45
* TLOAD is the mixing valve set temperature.
* The exact value of TLOAD is not critical provided it is in the range Tcold < TLOAD < Thot
* where Tcold is the cold water make up temperature and
* Thot is the minimum hot water delivery temperature.

UNIT 14 TYPE 14 LOAD FRACTION MORNING PEAK
* Load distribution each day, % / hr
* Australian standard load pattern specified in AS2813.
PARAMETERS 60

```
0,0   7,0
7,30  8,30
8,18  9,18
9,0   11,0
11,5  12,5
12,7  13,7
13,0  15,0
15,10 16,10
16,0  17,0
17,12 18,12
18,13 19,13
19,0  21,0
21,0  22,0
22,5  23,5
23,0  24,0
```

UNIT 15 TYPE 14 MONTHLY ENERGY
* daily average monthly energy load, MJ/day
PARAMETERS 48

```
0,28.8    744,28.8
744,29.6  1416,29.6
1416,31.1 2160,31.1
2160,32.2 2880,32.2
2880,34.6 3624,34.6
3624,36.6 4344,36.6
4344,37.4 5088,37.4
5088,36.3 5832,36.3
5832,35.2 6552,35.2
6552,34.3 7296,34.3
7296,31.9 8016,31.9
8016,29.4 8760 29.4
```

UNIT 17 TYPE 14 MONTHLY TMAIN
* Monthly cold water temperature
PARAMETERS 48

```
0,24.4    744,24.4
```

```
744,24.3  1416,24.3
1416,23.2 2160,23.2
2160,21.3 2880,21.3
2880,17   3624,17
3624,14.2 4344,14.2
4344,13.2 5088,13.2
5088,13.4 5832,13.4
5832,17.4 6552,17.4
6552,19.3 7296,19.3
7296,20.2 8016,20.2
8016,23.8 8760,23.8
```

```
UNIT 18 TYPE 15 LOAD FLOW RATE GENERATOR
* This unit computes the load volume required to achieve the specified energy load for a fixed delivery
* temperature of TLOAD
PARAMETERS  16
-1 TLOAD 0 4 0 -7 2 0 1 -1 239.2 1 -1 100 2 -4
INPUTS 3
17,1 15,1 14,1
0.0   0.0  0.0

UNIT 25 TYPE 11 TEMPERING VALVE
* This unit computes the load volume required to achieve the desired energy delivery
PARAMETERS 2
4 4
INPUTS 4
17,1 18,1   1,3       0,0
20    0    TSET TLOAD
* Third input to UNIT25 is the variable load delivery temperature in this example it is the output
*temperature of a stratified storage tank

UNIT 1 TYPE 138 STRATIFIED TANK
PARAMETERS 24
MODE .34 1.47 HCOL 4.18 1000 COND 1 UA IR TSET .0 3 HAUX HTH TSET TDB
0 .1 100 95 .01 50 0
INPUTS 6
34,2 21,2 17,1 25,2 9,6 26,1
80   500   20  0   20   1
```

Appendix 7 TYPE 176 User Over-ride of Booster Operation

PARAMETER		DESCRIPTION
1	NSTK	Number of oscillation of the controller in a timestep after which γo (the first output) ceases to change
2	tp	Time period for which the output signal is set to 1 after the input falls below Tset. If the time period is negative the module will act as a one-shot controller for variable specified as input number 3. If tp is negative only one boost cycle will occur, then the control will be locked out until midnight. (models the SEA-Vic one-shot per day boost specification).
3	Tset	Set point value. Output will be set to 1 when input 1 falls below Tset

INPUT NO		DESCRIPTION
1	T1	Control temperature
2	γi	Input control function (Output 1 [176,1])
3		Variable controlled by output 1 (eg auxiliary power) – for one-shot operation. If the operating time period tp > 0 this variable is ignored.

OUTPUT		DESCRIPTION
1	γo	Output control function

An example of the application of this routine to control the operation of an electric booster in a Type 138 tank is shown below. Two control functions are combined in the control signal auxonoff, a time of day boost controlled by a TYPE14 time sequence signal ([14,1]) and a one-shot boost controlled by the TYPE176 module.

```
Constants 2
        * one-shot mode specified (ontime negative
          ontime = -1
          *  45C operation temperature
          Tset=45

          unit 176 type 176  one cycle boost
          parameters 3
          5 ontime Tset
          Inputs 3
          138,3 176,1 138,8
          tset  0     0

          eqn 1
          auxonoff=max([14,1],[176,1])
```

Appendix 8 TYPE 177 Delay timer

This type is used to set a control signal to 0 for a specified time after the first input becomes 1. If the input drops to 0 then the time delay is cancelled and the output goes to 1.

PARAMETER		DESCRIPTION
1	delay	time period for which the output signal is set to 0 after the first input turns on (hrs)

INPUT NO		DESCRIPTION
1	In1	Control signal
2	Out2	Output 2 [177,2]

OUTPUT		DESCRIPTION
1	γo	output control function
2	out2	

An example of the application of this routine to set a control signal (eg for operation of an electric booster) for 5 hours after a pump turns on (2,1)is shown below.

```
Constants 1
          * delay timer
             delay = 48

             unit 77 type 177
             parameters 1
             delay
             Inputs 2
             2,1 77,2
               0    0
```

Appendix 9 TYPE 178 Event detection

This type is used to set a control signal to 1 if the first input has not exceed a threshold level in the previous specified time period.

PARAMETER		DESCRIPTION
1	Threshold	Threshold level for checking input(1)
2	Period	Time period over which the first input is checked against the threshold hrs
3	Hold_time	Time period that output is held at 1 after event is detected

INPUT NO		DESCRIPTION
1	In1	Variable to be checked against the threshold level

OUTPUT		DESCRIPTION
1	γo	output control function

An example of the application of this routine to set a control signal to 1 if the input has not exceeded the threshold for the past 3 days. The control signal is held at 1 until the input has reached the threshold temperature and that temperature has been maintained for 0.5 hours. This could be used to initiate a tank sterilization cycle if the input signal say the temperature in a tank (eg 60,23) has been below the threshold for the last 3 days.

```
Constants 3
        * Threshold level
          Threshold = 60
          Period= 3*24
          Hold_time = 0.5

          unit 78 type 178
          parameters 3
          Threshold  Period Hold_time
          Inputs 1
           60,23
            0
```

If the input (eg 60,23) has been below 60°C for three days then the output (78,1) is set to 1 and held at 1 until the input has reached 60°C for 0.5 hours. The output could be used to turn on a boost element to achieve the required sterilization temperature and hold for the required time. The output is reset to 0 after the sterilization cycle is completed.

Appendix 10 TYPE 102 Differential controller with three maximum limits

This controller generates a control function γ_o that can have values of 0 or 1. The control value is a function of the difference between input 1 and input 7. The new value of is dependent on whether γ_i = 0 or 1. The controller is used with γ_o connected to γ_i (input 5).
The controller also applies limits to inputs 2,3 and 7.

Differential control

Input 1 – input 7 controlled in dead band ranges set by input 5 and input 6 (same as TYPE2 but differential is taken between inputs 1 and 7 rather than inputs 1 and 2 as in TYPE2.

Limits

Limit on value of input 2 set by parameter 4	γ_o =0 if Input2 > par4
Limit of value of input 3 set by parameter 2	γ_o =0 if Input3 > par2
Limit on value of input 7 set by parameter 3	γ_o =0 if Input7 > par3

PARAMETER		DESCRIPTION
1	NSTK	Number of oscillations of the controller in a timestep after which the output ceases to change.
2	Tmax1	Limit for input 3
3	Tmax2	Limit for input 7
4	Tmax3	Limit for input 2

INPUT NO		DESCRIPTION
1	TH	Upper input temperature
2		Check variable 1
3		Check variable 2
4	γ_o	Input control function
5		Upper dead band temperature difference (input 1 – input 7)
6		Lower dead band temperature difference (input 1 – input 7)
7		Lower input temperature

OUTPUT		DESCRIPTION
1	γo	output control function

An example of the application of this routine to set a control signal to 1 based on a collector output temperature signal [1,1] and another temperature [60,32] and two additional variables [5,1] and [4,1]to be checked for high values is given below

```
UNIT 20 TYPE 102  Falling film flow controller
PARAMETERS 4
5 Tcol_max Ttank_max  Tret_max
INPUTS  7
* differential control function applied between input 1 and input 7
* limit on collector outlet temperature set by par(2) and input 3
* limit on Ttop average is set by parameter 3 and input 7
* limit on Thxout is set by parameter 4 and input 2
1,1  5,1  4,1  20,1   0,0   0,0    60,32
25   25    25    0     Ton  Toff    20
```

Appendix 11   Gas Boosted Water Heater Simulation

```
*GAS STORAGE  SYSTEM

Constants 2
QMR = 0.6 * 3.6   (kJ/h)
*Tank heat loss equivalent to gas tank maintenance rate
UA = QMR*Effic/45     (kJ/h)/K


eqns 4
*Daily energy delivery
* PKLOAD = peak winter load MJ/day
*dyengy = daily total energy load
dyengy = [13,1] * PKLOAD
*Load volume at load temp TLOAD
*This load flow is used in conjunction with a TYPE11 tempering valve to set required energy
*delivery from the tank
*TLOAD = outlet temperature of mixing valve (use 45)
*effy = gas burner efficiency kJ/hr
*burner = gas burner consumption rate kJ/hr
ldflw = dyengy * [14,1] / (TLOAD-[17 ,I]) /0.00418
*gas burner rate
auxgas=burner*effic
*gas consumption
gas= [5,8]/effy

UNIT 25 TYPE 11 TEMPERING VALVE
*Sets up load volume for required energy load
PARAMETERS 2
4 8
INPUTS 4
17,1 ldflw 5,3 0,0
20 0 TSET TLOAD

UNIT 5 TYPE 138
*Gas storage water heating system
PARAMETERS 21
7 VOL H 0 4.18 1000 KWALL 1 UA 1.2
TSET HCOLD AUX 0 0.05 TSET Tdb 0.1 95 90
INPUTS 6
0,0 0,0 17,1 25,2 9,6 0,0
0 0 TSET 0 20 1
```

Appendix 12 TYPE 160 - Modified Type60 detailed storage tank

TYPE160 is a modification of the TYPE60 tank with the following additional features

- Thermostat set temperature and power of both internal heaters may be specified as inputs rather than parameters
- Selection of mantle or falling film heat exchangers in the collector loop.

SPECIFICATION OF MANTLE HEAT EXCHANGER OR FALLING FILM HEAT EXCHANGER

PARAMETER		DESCRIPTION
1 to second last		As for TYPE60
last	hx	1 = collector loop mantle heat exchanger 2 = collector loop falling film heat exchanger other values ignored

THERMOSTAT SETTINGS AS INPUTS RATHER THAN AS PARAMETERS

To select thermostat setting and heater power (both heaters) as inputs set Tset1 < 0 (Parameter 18). The parameter values of Quax1, Tset2 & Qaux2 (parameters 20, 23 & 25) are ignored if Tset1 <0. Values of thermostat dead bands ΔTdb1 & ΔTdb2 are still set as parameters

THERMOSTAT SETTINGS AS INPUTS

INPUT NO		DESCRIPTION
1 to last-4		As for TYPE60
Last -3	Tset1	Thermostat set temperature upper element (parameter 18 must be negative to move thermostat settings to inputs rather than parameter)
Last -2	Qaux1	Power input to upper electric element (parameter 20 ignored)
Last -1	Tset2	Thermostat set temperature lower element(parameter 23 ignored)
Last	Qaux2	Power input to lower electric element (parameter 25 ignored)

OUTPUT	DESCRIPTION
	As for TYPE60

Appendix 13 TYPE 99 – Thermosyphon sidearm heat exchanger

TYPE99 is a model of a thermosyphon sidearm heat exchanger based on measured effectiveness and pressure drop characteristics. This model is used in conjunction with a TYPE138 tank.

-

PARAMETER		DESCRIPTION
1	Hcol	Height of thermosyphon sidearm input to tank
2	Hhx	Vertical height of sidearm heat exchanger
3	H1	Vertical height of bottom of heat exchanger above the outlet

INPUT NO		DESCRIPTION
1	T_coldin	Temperature of thermosyphon loop inlet to heat exchanger (°C)
2	T_hotin	Temperature of hot pumped flow inlet to heat exchanger (°C)
3	Flow_hot	Pump flow rate on hot side of heat exchanger (kg/h)
4	Ht	Thermosyphon pressure in tank, (Pa)

OUTPUT		DESCRIPTION
1	Hx_Tout	Temperature of thermosyphon loop outlet from heat exchanger (°C)
2	P_Tout	Outlet temperature of hot pumped flow from heat exchanger (°C)
3	Hx_flow	Sidearm thermosyphon flow rate (kg/h)

Eqn 1
Ht = [138,11]

```
unit 99 type 99  Sidearm HX
parameters 3
Hcol Hhx H1
inputs 4
T_coldin  T_hotin Flow_hot     Ht
 20             20           0       10000
```