TRNAUS15 – 24.6

TRNSYS15 EXTENSIONS FOR SOLAR AND AIR-SOURCE HEAT PUMP WATER HEATERS

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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 104 Stratified tank model with integral condenser heat pumps (micro-channel or external spiral wound tube or submerged coil)
- TYPE 106 Inline boosting heater with sanitation detection
- 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 (based on TYPE60)
- TYPE 176 One-shot user over-ride of boosting
- TYPE 177 Delay timer
- TYPE 178 Event detection (tank sterilization controller)
- TYPE 179 Delayed event detection with force heating
- TYPE 238 Stratified tank model with thermostat set point and dead band moved to inputs (based on TYPE138)
- TYPE 84 Moving average
- TYPE 180 Sanitation conformance
- TYPE 182 Minimum/maximum on/off times for compressor control signal

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
- Integral condensers for thermal storage tanks
- Assessing Legionella sanitation conformance to AS3498

Revisions

Revisions to this manual and corresponding TRNAUS dll code versions are listed below. The TRNAUS code version used in a simulation is listed at the top of all LST files

Update	Manual version	TRNAUS dll code version
Section 7.8 Type 182 Appendix 19 Type 182	24.5	TRNAUS version 24.5, 28/10/2024
Corrections to Type 160 outputs in Appendix 12	24.5.1	NA
Corrections to Type182	24.6	TRNAUS version 24.6, 15/11/2024

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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.
The use of the TRNAUS extension package as specified in this manual requires a revised trnlib.dll file from that released with the TRNSYS15 software. TRNSYS15 has Fortran source codes for the kernel, standard library types and specific TRNAUS types as detailed in this manual. These are all compiled and linked together into the one trnlib.dll file by the authors of the TRNAUS extension package.
Commencing in TRNAUS version 24.5, the *.lst file that is produced with each simulation details the version of the trnlib.dll that was used to run the simulation. This may be critical for audit purposes to ensure that the simulations are conducted with the correct version of the trnlib.dll file.

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 affected 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 affect 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

TRNAUS – TRNSYS15 extensions for solar & heat pump water heaters

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

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

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

3.2 Efficiency mode 3

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

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].

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

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

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

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

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

(iii) radiation from the absorber tube to the envelope

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

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

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

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

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

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 $\eta_{opt} = 0.625$, $K_1 = 0.26$, $K_2 = 0.039$, $K_3 = 8.5*10^{-}$

[9], $\varepsilon_s = 0.05+0.000125T_S$. 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 included 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 (e.g. 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.

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

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, i.e. 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 e.g.

Table 3

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

#Note, this type is not to be used in heat pump applications with integral condensers attached to or inside the storage tank. Type104 has been developed for heat pumps with integral condensers. TYPE138 is retained solely as a subroutine for TYPE145, a fatal error will be issued if Type138 is used directly in a deck.

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.

5.6 Thermostat set point temperature and dead band settings moved from parameters to inputs

TYPE238 is a modification of TYPE138 with the set point temperature and dead band of the first thermostat moved to inputs. This allows dynamic setting of the thermostat or switching signal for heat pumps based on time or other operating conditions. If the set point temperature and dead band parameters (par 16 & 17) are positive values then the parameter values are used. If the set point and dean band parameters (par 16 & 17) are negative values then the set point temperature and dead band are taken from inputs 8 & 9.

5.7 Sanitation conformance assessment - Temperature and fluid volumes for Legionella control

Four outputs from storage tanks (Types 104, 160, 138 and 145) have been added to interface with the sanitation conformance assessments made in Type180. These outputs are:-

1) Temperature (°C) at 45% of the volume of the tank (from the top) (T45),
2) Temperature (°C) at 90% of the volume of the tank (from the top) (T90),
3) Volume of water (m3) in the tank that has been heated to ≥ 55°C is tracked (San_vol),
4) Time (hr) that San_vol ≥ 0 is tracked and output as San_time.

When a thermal load is withdrawn from the tank, San_vol is reduced. The volume of water in the tank that has been ≥ 55°C is tracked each time step. The time duration (hr) that San_vol ≥ 0 is tracked and output as San_time. San_time is increased at each timestep if San_vol > 0. San_time is set to 0 when San_vol drops to 0.

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.

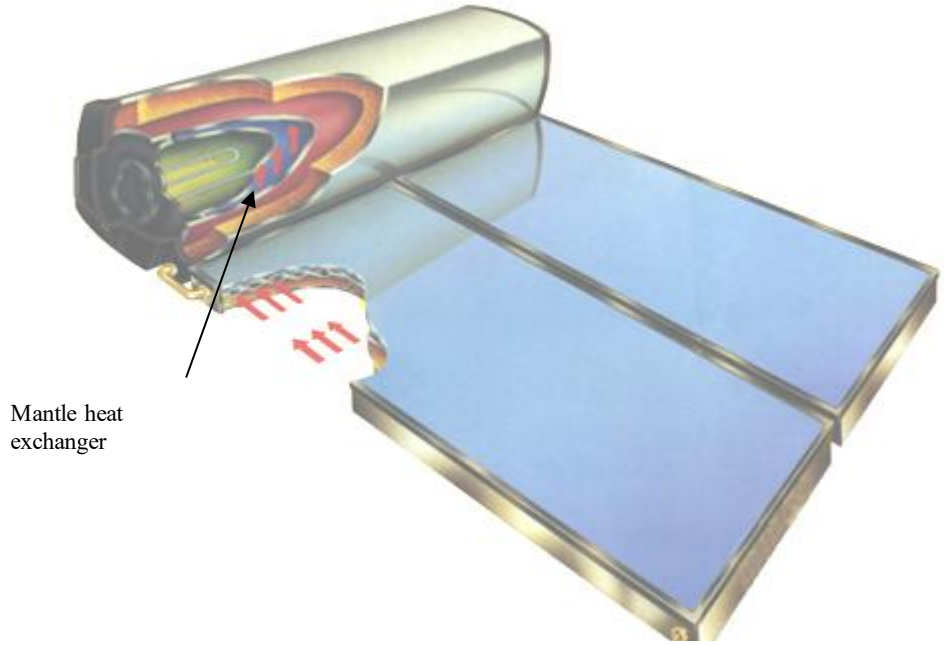


Fig 1. Close-coupled thermosyphon solar water heater with a mantle heat exchanger in the collector loop.

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.

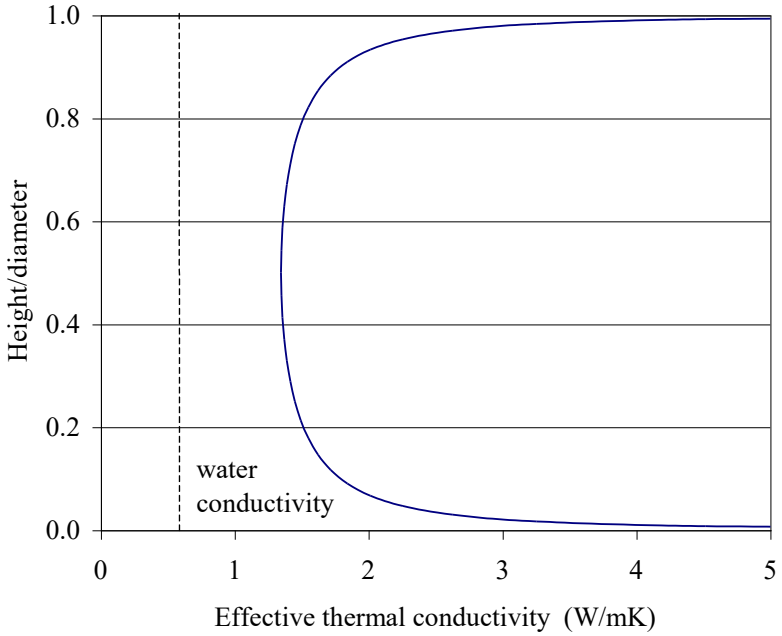


Fig 2. Effective thermal conductivity as a function of depth in a 450 mm diameter horizontal tank with 3 mm steel walls.

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 a serpentine collector tube 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.
For a horizontal mantle tank the thermosyphon flow is assumed to stop when the temperature at the outlet of the mantle heat exchanger 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

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

where T_c = cover temperature.

If $T_s = T_a - dT$ then

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

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

$$T_e = T_a - \frac{h_r}{h_c + h_r} dT \qquad (13)$$

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, 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.

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7 CONTROLLERS

Specialised control routines TYPE176, TYPE177, TYPE178, TYPE179, TYPE180 and TYPE182 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, e.g. 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 supplementary boosting for a specified period after a pumped solar collector starts operating.
Another example is for setting a lockout time for a heat pump when it restarts. The total number of heat pump heating cycles is also determined.
TYPE177 data deck description and example applications are given in appendix 8.

7.3 Event detection (tank sterilization controller) TYPE178

This routine is used to set a control signal to 1 if the input has not exceeded 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 as specified in AS3498.

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

7.4 Delayed event detection with force heating TYPE179

This routine detects if an event has occurred in a previous defined time period and if not detected, the output is set true. The event detection is either a monitored temperature greater than a defined threshold or an input signal > 0. The routine has additional functionality whereby the user can delay the output set to true until a defined hour of the 24hr day has been met. The output is held on until a monitored temperature has been met or exceeded.

One application of this routine is to detect if a daily heating cycle has occurred through other control means. In the event that a heating cycle is not detected within a defined period, then this routine could force a heating cycle to be completed. This ensures that minimum delivery temperatures and daily Legionella sanitation is maintained for small thermal loads, whilst not adversely impacting the energy savings for larger load consumers that do not need to force a regular daily heating cycle.

Another application is to force a regular heating cycle to an alternate target temperature, such as a weekly Legionella sanitation cycle. The distinguishment of this type as opposed to a simple timer in this application, is that the duration of the heating cycle once commenced is not dependent upon time, the control of this type will remain active until the heating cycle is completed.

Given that this type can be used to control multiple heating logics within the same simulation, the source code has been written with the inclusion of S-array unit storage, allowing each instance of this type to be independently assessed.

7.5 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.

7.6 Moving average TYPE84

This routine has a similar function to that of Type84 in TRNSYS 16 and subsequent releases of TRNSYS. The average of an input is assessed over a number of defined timesteps as shown in equation 7.6.1.

$$\bar{X} = \frac{\sum_{n-p}^{n} Input}{p} \qquad (7.6.1)$$

Where p is the number of timesteps, n is the number of timesteps from the start of the simulation, and the input is a variable to be time-averaged. The maximum value of p is 10,000.

Where the n is less than p (at the commencement of the simulation), the average is assessed over the reduced timestep as shown in equation 7.6.2.

$$\bar{X} = \frac{\sum_0^n Input}{n} \qquad (7.6.2)$$

7.7 Sanitation conformance TYPE180

This routine assesses the Legionella sanitation conformance to AS3498 of thermal storage tanks. Type180 is designed to assess stored water temperatures at various levels in the storage tank. In solar-thermal applications Type180 tracks water volumes and hold times above a temperature threshold so that additional compliance checks to Table 1 of AS3498 can be made. As stipulated within AS3498 section 7.2 there are a number of methods that can be used to inhibit the growth of Legionella bacteria in potable water.
The four compliance methods assessed within Type180 are: -

- At least 45% of the volume of the storage tank is heated to 60°C daily (see AS3498 section 7.2 (b)),
- At least 90% of the volume of the storage tank is heated to 60°C once a week and held at this temperature for at least 32 minutes (see AS3498 section 7.2 (a)),
- All water that exits the tank has been heated to at least 55°C and has been in the tank for at least 6hrs within 7 days before passing through the heated water outlet (see AS3498 section 7.2 (c)).
- Where a preheat storage tank is employed with an inline instantaneous water heater, the inline booster shall heat the water to a minimum of 70°C when the inlet water temperature to the inline booster is <55°C (AS3498 section 7.2 (f)).

The first two compliance methods are used in all water heating applications; the third compliance method is only evaluated for Solar-thermal applications with the fourth compliance method only applicable where inline instantaneous boosters are used.

There are no parameters that the user enters – it is internally determined within the source code. The modes are: -

- Mode = 1 for thermal storage tanks Type160, Type138, Type145 and Type104 for heat pump heating.
- Mode = 2 as per Mode 1 for simulations of solar-thermal heating & PV powered elements. Mode 2 is not to be used with heat pump applications.
- Mode = 3 as per Mode 2 with the addition of inline instantaneous boosting (gas or instantaneous electric)
- Mode = 4 for applications without solar-thermal & PV and inline instantaneous boosting.

There are two or four inputs being: -

For mode 1: -

- Tank temperature at 45% volume from the top of the storage tank (T45, °C)
- Tank temperature at 90% volume from the top of the storage tank (T90, °C)

For mode 2: -

- Tank temperature at 45% volume from the top of the storage tank (T45, °C)
- Tank temperature at 90% volume from the top of the storage tank (T90, °C)
- Volume of fluid that has been heated to ≥55°C (San_vol, m^3)
- Time that San_vol has been ≥0 within the storage tank (San_time, hr).

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For mode 3: -

- Tank temperature at 45% volume from the top of the storage tank (T45, °C)
- Tank temperature at 90% volume from the top of the storage tank (T90, °C)
- Volume of fluid that has been heated to ≥55°C (San_vol, m^3)
- Time that San_vol has been ≥0 within the storage tank (San_time, hr).
- Inlet temperature of fluid to inline instantaneous booster (Tinlet, °C)
- Outlet temperature of fluid from inline instantaneous booster (Toutlet, °C)

For mode 4: -

- Tank temperature at 45% volume from the top of the storage tank (T45, °C)
- Tank temperature at 90% volume from the top of the storage tank (T90, °C)
- Inlet temperature of fluid to inline instantaneous booster (Tinlet, °C)
- Outlet temperature of fluid from inline instantaneous booster (Toutlet, °C)

The outputs for all modes are: -

- Net sanitation compliance :- San_fail (1 = fail, 0 = pass)
- Time of net sanitation fail :- San_ftime (hr)
- Daily sanitation compliance :- Daily_fail, (1 = fail, 0 = pass)
- Weekly sanitation compliance :-Weekly_fail (1 = fail, 0 = pass)

Additional output for modes 2&3 are: -

- San_vol sanitation compliance :-Sanvol_fail (1 = fail, 0 = pass)

Additional output for modes 3&4 are: -

- Inline boosting sanitation compliance :-Boost_fail (1 = fail, 0 = pass)

The net sanitation compliance (San_fail) is set to 1 when ***all*** of Daily_san, Weekly_san, Sanvol_fail (only for modes 2&3) and Boost_fail (only for modes 3&4) are concurrently 1. Where this condition is made, San_fail is locked at 1 and the time at which this occurred is recorded as San_ftime.

In all modes of Type180, the daily compliance check is assessed. In the event that the daily compliance check is passed (Daily_fail = 0), the weekly assessment is omitted. The daily assessment commences at 6 am and occurs daily for the duration of the simulation. The daily sanitation compliance check is set to fail (Daily_fail = 1) where T45 has not reached 60°C in the preceding 24 hrs. The daily sanitation compliance will be reset (Daily_fail = 0) at any point in the simulation where T45 ≥ 60°C.
In the event that the daily compliance check fails (Daily_fail = 1) then the weekly sanitation compliance check commences (for a duration of 6 days as one day has already lapsed in the daily sanitation compliance check that has failed). If at the end of the 6 days, T90 has not been ≥ 60°C for ≥ 32 minutes, the weekly compliance sanitation check has failed and Weekly_fail = 1. The weekly sanitation compliance check is reset (Weekly_fail = 0) when T90 ≥ 60°C for ≥ 32 minutes.

For modes 2&3 the volume of fluid within the thermal storage tanks that has been ≥ 55°C is tracked (San_vol) along with the simulation time since San_vol = 0 m^3 (denoted San_time). The San_vol sanitation compliance is assessed continually in the simulation such that Sanvol_fail can be set to 1 by: -

- San_time is less than 6 hrs at the time that San_vol reduces to 0 m^3, or
- San_vol has not increased > 0 m^3 within 7 days

San_vol sanitation compliance check is reset (Sanvol_fail = 0) when San_time > 6 hrs
For modes 3&4 the inlet and outlet temperature of the inline instantaneous water heater is monitored, where the inlet temperature is less than 55°C and the outlet water temperature is

less than 70°C then Boost_fail is set to 1. Boost_fail is reset to 0 at any point where the inlet water temperature ≥ 55°C or the outlet let water temperature ≥ 70°C.

7.8 Compressor on/off differential controller with minimum/maximum on/off times TYPE182

This routine commences analysis of inputs in a similar manner to type 2 (on/off differential controller). The binary output of this differential temperature assessment is then assessed for minimum and maximum on/off time limits for the compressor which are defined as parameters. An example of the application of this type is to control a heat pump compressor such that the following compressor constraints are incorporated:-

- Upper temperature input:- this is the equivalent to input 1 for type2. An example of its use would be to set the HP to a maximum of 60°C after which the compressor is turned off.
- Lower temperature input:- this is the equivalent to input 2 for type2. An example of its use would be to detect the stored water temperature (output 12 from type104 for instance)
- Upper deadband temperature difference: - this is equivalent to input 5 for type2. An example may be to have a fixed deadband of 12°C whereby where the stored temperature is detected to fall to 60°C – 12°C = 48°C the compressor would commence operation.
- Lower deadband temperature difference: - this is equivalent to input 6 for type2. This would not be used for the example above and would be set to 0°C.
- Input control function: - this is similar but not identical in function to input 4 for type2. An example may be that a time limitation of HP operation could be a binary input See the mathematical representation of control logic in Table 7.8 for further detail on how the input control function is used.

Note whilst the above inputs are used to determine the binary output of the on/off differential controller, the result can be over-written by the minimum/maximum on/off times as detailed below.

- **minimum off-time:-** used to ensure that a compressor is not restarted before there has been sufficient off-time for the refrigerant circuit to unload by equalizing high and low side refrigerant pressures and so that oil can drain back to the compressor.
- **minimum run-time :-** used to ensure a compressor operates for a minimum time period after each start so that adequate thermal delivery is achieved per heating cycle and the impact of startup loss is minimised.
- **maximum run-time** :- used to limit the run-time of a compressor when the heat pump is failing to meet the required load and boost elements may need to be turned on to complete the heating cycle.
- **maximum off-time** :- used to keep a refrigerant system lubricated so that moving parts such as the rotor and/or compressor do not “stick“ locked during long standby times (this feature would seldom be used).

The routine is limited to control one compressor, and it can only be used once in the deck file for each simulation (parameters are not held in the S-array).

There are 4 parameters

Parameter 1 - Min_ton Minimum on-time (hrs)

Parameter 2	- Max_ton	Maximum on-time (hrs)
Parameter 3	- Min_toff	Minimum off-time (hrs)
Parameter 4	- Max_toff	Maximum off-time (hrs)

There are 5 inputs

Input 1	– T_H	Upper input temperature (°C)
Input 2	– T_L	Lower input temperature (°C)
Input 3	– ΔT_H	Upper deadband temperature difference (°C)
Input 4	– ΔT_L	Lower deadband temperature difference (°C)
Input 5	– γ_i	input control function (binary)

Note – the number of oscillations of the differential on/off controller in a timestep after which the output ceases to change is 7 (which is equivalent to parameter 1 of type2 being 7).

There are 10 outputs: -

Output 1	- Signal_out	Control signal that satisfies the differential temperature control (output 10) and compressor minimum and maximum runtime limits limits (0=OFF,1=ON))
Output 2	- On-time	Duration of current ON event for signal_out (hrs)
Output 3	- Off_time	Duration of current OFF event for signal_out (hrs)
Output 4	- Min_on	Minimum on-time limit is active for signal_out (0=OFF, 1=ON)
Output 5	- Max_on	Maximum on-time limit is active for signal_out (0=OFF, 1=ON)
Output 6	- Min_off	Minimum off-time limit is active for signal_out (0=OFF, 1=ON)
Output 7	- Max_off	Maximum off time limit is active for signal_out (0=OFF, 1=ON)
Output 8	- Starts	Count of signal_out No1 turn-ON events (integer)
Output 9	- Total_hrs	Total ON time for signal_out since start of simulation (hrs)
Output 10	- γ_o	Output control signal from the differential on/off control (excluding compressor minimum and maximum runtime limits)

Example deck descriptions are given in Appendix 19

Table 7.8
Mathematical representation of control logic

Previous output signal	Differential control	Input control function	Revised output signal
$\gamma_o = 1$	$\Delta T_L \le (T_H - T_L)$	$\gamma_i = 1$	$\gamma_o = 1$
$\gamma_o = 1$	$\Delta T_L \le (T_H - T_L)$	$\gamma_o = 0$	$\gamma_o = 0$
$\gamma_o = 1$	$\Delta T_L > (T_H - T_L)$	$\gamma_i = 1$	$\gamma_o = 0$
$\gamma_o = 1$	$\Delta T_L > (T_H - T_L)$	$\gamma_o = 0$	$\gamma_o = 0$
$\gamma_o = 0$	$\Delta T_H \le (T_H - T_L)$	$\gamma_i = 1$	$\gamma_o = 1$
$\gamma_o = 0$	$\Delta T_H \le (T_H - T_L)$	$\gamma_o = 0$	$\gamma_o = 0$
$\gamma_o = 0$	$\Delta T_H > (T_H - T_L)$	$\gamma_i = 1$	$\gamma_o = 0$

$\gamma_o = 0$	$\Delta T_H > (T_H - T_L)$	$\gamma_o = 0$	$\gamma_o = 0$

A minimum/maximum on/off over-ride event is where the output signal is not the same as the input signal γ_o from the differential on/off controller. Once an over-ride event has been applied, there are a number of methods that the over-ride event is reset see Table 7.9

Table 7.9
Resetting of type182 over-ride events

Over-ride event	Control variable	Method for reset
Minimum on-time	Min_on	On-time > Min_ton
Maximum on-time limit	Max_on	$\gamma_o = 0$
Minimum off-time limit	Min_off	Off_time > Min_toff
Maximum off time limit	Max_off	On-time > Min_ton

The max_on reset can be used to allow an alternative energy source (such as an electric element) to replace the heat pump where the heat pump is deemed insufficient to complete the heating cycle. When the maximum on-time limit has been reached, the 5th output changes to 1. The 5th output can be used to turn on an immersion element that completes the heating cycle. When the heating cycle is completed, γ_o (output from the differential on/off controller) = 0, thus resetting the maximum on-time limit, then the heat pump can operate again when called.

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}.

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

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

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

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

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

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

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

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

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

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

For an ambient temperature of 20°C

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

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.

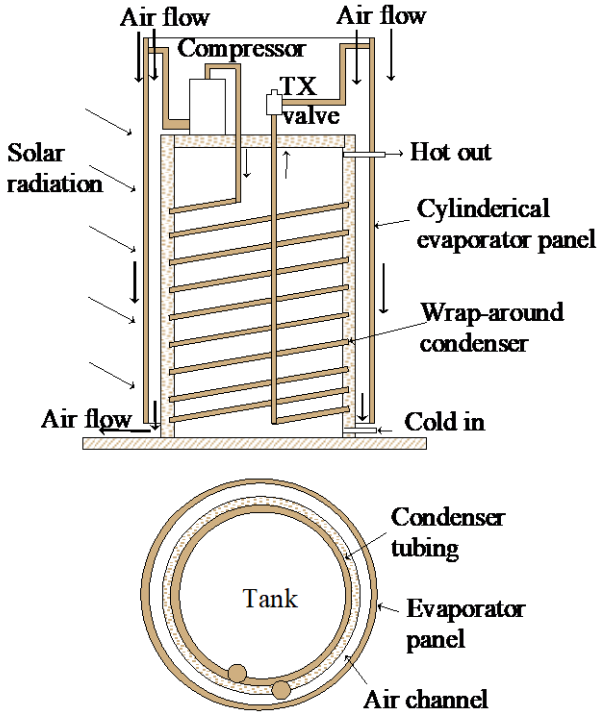


Fig 3. Heat pump water heater with integral evaporator panel around the tank.

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 ≅ 0.25
- $F_{c\text{-}g}$ = configuration factor between the cylindrical absorber and the ground ≅ 0.25
- $F_{c\text{-}w}$ = 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 (e.g. UNIT 1 for a fixed vertical surface and UNIT 2 for a vertical sun tracking surface) and the following equation expression.

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

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. INTEGRAL AIR SOURCE HEAT PUMP WATER HEATERS - TYPE104

The performance of air source heat pump water heaters can be quantified using Australian/New Zealand standard AS/NZS 5125. This Standard specifies the test conditions and test procedures for determining the energy performance characteristics of single circuit air-source heat pump water heaters.
The variation of *COP* and electric power use as a function of operating conditions are determined experimentally so that the results can be used in annual performance calculations of heat pump applications for sanitary hot water supply applications. The measurement and data correlation procedures specified in AS/NZS 5125 apply to both stand-alone heat pump water heaters and heat pumps with the condenser integral with a storage tank.
The performance of a heat pump is determined by operating the product under a range of controlled environmental conditions and measuring the electrical power input and the thermal energy output in the form of hot water. Slightly different test procedures are specified for stand-alone and integral heat pump configurations

9.1 Data correlation

Measured values of *COP* and electrical *Power* are correlated using the functions given in Equations 9.1 and 9.2 (see AS/NZS 5125 for further detail).

$$COP = a_0 + a_1(\overline{T_w} - \overline{T_a}) + a_2(\overline{T_w} - \overline{T_a})^2 + a_3\left(\overline{T_{wet}} - \overline{T_{dp}}\right) \quad (-) \quad (9.1)$$

$$\text{Power} = p_0 + p_1\overline{T_w} + p_2\overline{T_w}^2 + p_3\overline{T_a} \quad (\text{kW}) \quad (9.2)$$

Where: -

a_i and p_i	coefficients determined by curve fitting functions to test data	
Power	overall electric power input averaged over the test point period	(kW)
$\overline{T}_a$	ambient air temperature averaged over test point period	(°C)
$\overline{T}_{dp}$	air dew point temperature averaged over test point period	(°C)
$\overline{T}_{wet}$	air wet bulb temperature averaged over test point period	(°C)
$\overline{T}_w$	*Stand-alone heat pump*— mean of inlet and outlet water temperatures averaged over test point period	(°C)
	Integral heat pump— mass weighted mean of temperature of tank segments adjacent to condenser coil, averaged over the test point period	

9.2 Modelling heat pump water heater load cycle operation

Calculation of the performance of a heat pump water heater and hot water storage tank operating under load cycle condition is specified in AS/NZS 4234 and SA/SNZ MP104.
For heat pumps systems with the condenser integral with the storage tank the energy input to the storage tank can be determined from the AS/NZS 5125 COP and Power performance correlations. To determine the distribution of energy input into the tank over the depth of an integral condenser (thermal stratification in the tank) a model of the heat transfer between the condenser and the water in the tank is needed. As the bulk of the energy transfer occurs in the condensing zone of the refrigerant condenser the heat transfer over the depth of the condenser can be approximated by a constant source temperature on the refrigerant side of the condenser tubing/tank wall system.
The condenser temperature is determined from the AS/NZS 5125 COP and Power and the thermal resistance between the refrigerant and the tank water. The condenser temperature in TYPE104 is modelled for

- micro-channel condensers (Mode = 4),
- wrap-around tube condensers (Mode = 5),
- submerged coil condensers (double walled tube) (Mode = 6).

The total heat transfer (Q) is given by the measured COP (Eqn. 9.1) and Power (Eqn. 9.2) from AS/NZS 5125 for the heat pump/tank system (See Eqn. 9.3).

$$Q = \text{Power} \times COP \quad \text{(kW)} \quad (9.3)$$

The heat transfer is divided between the tank segments by assuming a constant refrigerant temperature (condensing temperature) in the condenser. This model will under-estimate the heat transfer to tank segments covered by the super heat section of the condenser and will overestimate the heat transfer to tank segments covered by the sub-cooling section of the condenser. This modelling approach achieves the correct overall heat transfer but will underestimate the thermal stratification in the tank and hence underestimate the product performance. As the proportion of the heat transfer in the superheat and subcooling sections of the condenser is typically less than 15% of the overall heat transfer the impact of the simplifications in this model will result in only a small error in determining product performance. The condenser temperature is determined from the AS/NZS 5125 test data as a function of the average tank temperature over the depth of the condenser blanket.

For a constant temperature in the condenser (refrigerant condensing temperature T_{cond}) the heat transfer to each segment of the tank is given by Eqn. 9.4.

$$q_i = \frac{(T_{cond} - T_i)}{Ri} \quad \text{(kW)} \quad (9.4)$$

where

q_i = heat transfer to tank segment i
Ri = Thermal resistance between the condenser and the tank contents
T_{cond} = refrigerant condensing temperature
Ti = temperature of tank segment

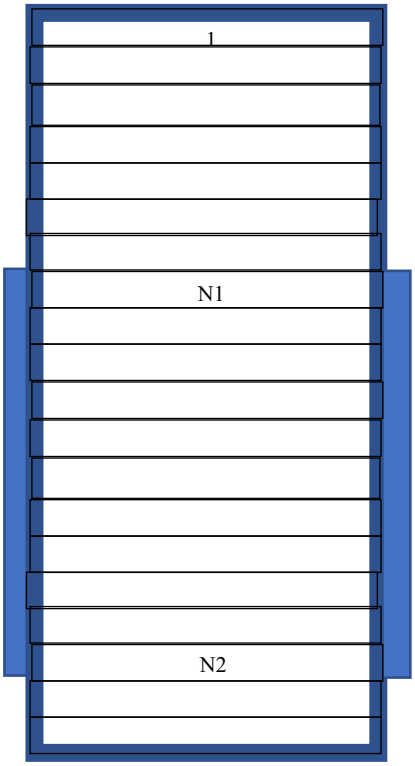


Fig 9.1 Integral micro channel condenser covering tank segments N1 to N2

For a condenser spanning tank elements N1 to N2 the total heat transfer is given by Eqn. 9.5)

$$Q = \sum_{N1}^{N2} \frac{(T_{cond} - T_i)}{Ri} \quad \text{(kW)} \quad (9.5)$$

If the thermal resistance of each segment is the same, the total heat transfer is given by Eqn. 9.6.

$$Q = \frac{(N2 - N1 + 1)T_{cond} - \sum_{N1}^{N2} T_i}{R_i} \quad \text{(kW)} \quad (9.6)$$

The condenser temperature is thus given by Eqn. 9.7

$$T_{cond} = \frac{Q\ R_i}{N2 - N1 + 1} + \frac{\sum_{N1}^{N2} T_i}{N2 - N1 + 1} \quad (°C) \quad (9.7)$$

$$or\ T_{cond} = Q\ R\ \ + \bar{T}$$

where Q is the total heat transfer (COP * Power), R is the thermal resistance of the total heat transfer area and $\bar{T}$ is the average water temperature over the depth of the condenser on the tank.

This model has been implemented in the TRNAUS extension for TRNSYS15 in module TYPE104. Energy is added to each tank segment (Q_i) covered by the condenser using equation 9.8 (as developed by Clift et. al. Oct. 2023).

$$Q_i = \frac{Q \times [T_{cond} - T_i]}{\left[T_{cond} \times N_{Cn} - \sum_{N_1}^{N_2} T_i\right]} \quad \text{(kW)} \qquad (9.8)$$

Where T_{cond} is the condensing temperature, T_i is the temperature of the node in question, N_{Cn} is the number of condenser nodes and N_2 and N_1 are the lower and upper condenser node numbers.

NOTE: TYPE104 determines the condenser temperature from AS/NZS 5125 test results. TYPE104 is not a design tool for determining the impact of changes in the connection of the condenser tubing with the tank. If any changes are proposed to the thermal resistance from the refrigerant to the stored water, then a new AS/NZS 5125 test must be carried out.

The heat transfer (heat loss) from either the stored water or the refrigerant to the environment is assessed using the tested heat loss (e.g. AS/NZS 4692.2) which delivers the thermal resistance from the tested stored water to the environment (UA). In type 104, the driving temperature difference is the greater of the stratified stored water temperature or the condensing refrigerant, to the environment temperature adjacent to the water heater. Therefore for integral condenser tanks where the condenser is on the outside of the tank wall (modes 4 & 5), ***when the heat pump is operating***, the heat loss is calculated using the tank UA and the temperature difference between the condensing temperature and the environment temperature, for tank nodes that are covered by the condenser. In all other nodes and for all nodes ***when the heat pump is not operating***, the heat loss is determined using the temperature difference between the stored water and the environment temperature.

9.3 Micro channel condenser

A micro-channel condenser consists of a series of micro-channel strips (figure 9.2) wrapped around the tank (figure 9.3).

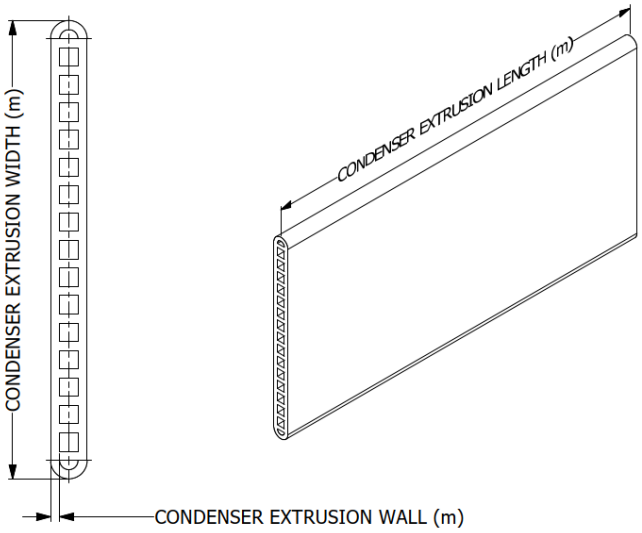


Figure 9.2 Cross section of micro channel refrigerant condenser tubing & typical dimensions



Figure 9.3 Micro channel blanket refrigerant condenser wrapped around a storage tank

The parameters that are required to determine the condenser temperature for a micro channel condenser are:

- Extrusion width
- Extrusion length (in contact with the tank wall)
- Number of extrusions in condenser
- Thickness of condenser extrusion wall
- Thermal conductivity of condenser extrusion wall
- Tank volume above the top of the condenser
- Tank volume above the bottom of the condenser
- Thickness of bond between condenser and tank wall
- Thermal conductivity of bond between condenser and tank wall
- Thickness of tank wall
- Thermal conductivity of tank wall
- Thickness of glass lining of tank (zero if not applicable)
- Thermal conductivity of glass lining of tank

The thermal resistance between the condensing refrigerant and water in the tank consists of a series connection of the following heat transfer stages: -

- Condensation heat transfer inside the micro channels
- Conduction through the walls of the micro channels
- Conduction through the bonding material between the micro channel and the tank wall
- Conduction through the tank wall
- Conduction through the enamel layer on the inside of the tank wall (if used)
- Convection heat transfer between the enamel layer (or tank wall) and the water in the tank

A minimum 0.5mm bond gap between the micro-channel and the tank wall is applied to allow for channel irregularities and tank wall roughness.

For a 1mm bond thickness the typical distribution of overall thermal resistance between the components of the heat transfer path are shown in Table 9.1.

Table 9.1 Typical thermal resistance components for micro-channel on steel tank

Component	Thermal Resistance for 15°C tank temp %	Thermal Resistance for60°C tank temp %
Micro channel	3	5
Bond	7	10
Tank wall	2	2
Enamel	6	9
Convection in tank	82	74

9.4 Wrap-around tube condenser

A wrap-around condenser consists of a refrigerant tube wrapped around the storage tank as shown in figure 9.4.

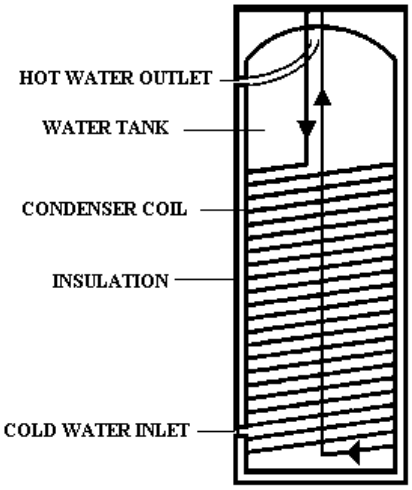
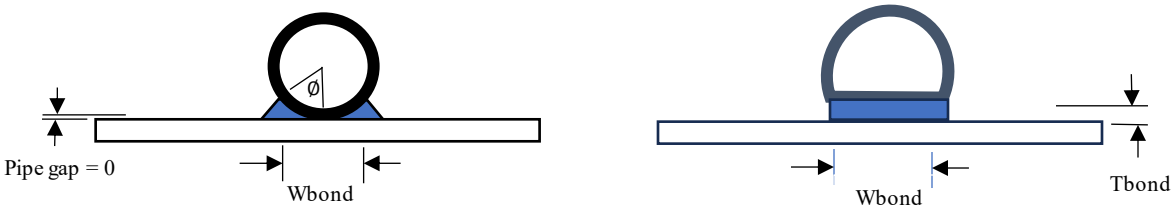


Figure 9.4 Condenser tubing wrapped around a storage tank

The performance of a tank with a wrap-around heat exchanger tube is modelled in TRNAUS Type 104 using the procedure given by Morrison (1994) and Anderson & Morrison (2007) to determine the thermal resistance between the refrigerant fluid and the tank water. The parameters that are required to determine the condenser temperature are: -

- Length of condenser tube in contact with wall
- Thickness of condenser tube wall
- Thermal conductivity of condenser tube wall
- Tank volume above the top of the condenser
- Tank volume above the bottom of the condenser
- Width of contact between condenser tube bond and tank wall (Wbond see Fig 9.5)
- Thickness of bond between the condenser tube and tank wall (Tbond see Fig 9.5)
- Thermal conductivity of bond between condenser tube and the tank wall
- Thickness of tank wall
- Thermal conductivity of tank wall
- Thickness of enamel lining of tank (zero if not applicable)
- Thermal conductivity of enamel lining of tank

The width of contact between the condenser tube bond with the tank wall is shown in Fig 9.5.



(a) (b)

Fig 9.5 Width and thickness of bond between condenser tube and tank wall.

For a round refrigerant tube attached to the outside of the tank wall (see Fig 9.5 (a)) the average thickness of thermal bond is given by eqn. 9.9.

$$T_{bond} = \frac{D^2}{W_{bond}}\left(sin\emptyset - \frac{\emptyset}{2} - \frac{sin2\emptyset}{4}\right) \qquad (9.9)$$

Where Ø is the contact angle at the top of bond paste on the circular tube (Fig 9.5 (a)).
For a round refrigerant tube specify zero for the pipe gap, the average bond thickness is calculated in TYPE104 from the specified bond width (W_{bond}).

A minimum 0.5mm gap between the bottom of the condenser pipe and the tank wall is applied to allow for tube irregularities and tank wall roughness (see Fig 9.5 (b)).

The thermal resistance between the condensing refrigerant and water in the tank is computed from the combination of the following heat transfer stages.

- Condensation heat transfer inside the tube
- Conduction resistance through the tube wall including fin effect of the tube wall
- Conduction through the bonding material between the tube and the tank wall
- Conduction through the tank wall including (a) direct transfer through the tank wall beneath the bonding paste and (2) fin effect of the section of the tank wall between the tube spiral windings.
- Conduction through the enamel layer on the inside of the tank wall (if applicable)
- Free convection heat transfer between the enamel wall and the water in the tank

The thermal resistance due to conduction through the condenser tube wall, including the fin effect of the wall, is given by Morrison (1994) as: -

$$R_1 = 1/(\sqrt{4\, t_t\, k_t\, h_t\, L^2}\ \tanh(m_1\, \pi D/2)) \qquad (9.10)$$

where
h_t = film coefficient of condensing refrigerant inside the tube (W/m^2K)
L = coil length (m)
D = coil diameter (m)
t_t = tube wall thickness (m)
k_t = thermal conductivity of tube (W/mK)
m_1 $=\sqrt{h_t/k_t\, t_t}$

The thermal resistance due to conduction along the tank wall is given by Morrison (1994) as

$$R_2 = 1/(\sqrt{4\, t_w\, k_w\, h_w\, L^2}\ \tanh(m_2\ S/2) \qquad (9.11)$$

where
h_w = free convective film coefficient on the tank wall (W/m^2K)
L = coil length (m)
S = spacing between coil turns on tank (m)
t_w = tank wall thickness (m)
k_w = thermal conductivity of tank wall (W/mK)
m_2 $=\sqrt{h_w/k_w\, t_w}$

The free convective heat transfer coefficient inside the tank is evaluated from the Nusselt number N_u Grashof number G_r correlation (Incropera and deWitt (1990))

$$N_u = 0.59 G_r^{.25} \qquad \text{for Gr} < 10^9 \qquad (9.13)$$

$$N_u = 0.1 G_r^{.33} \qquad \text{for Gr} > 10^9 \qquad (9.14)$$

where G_r $= g\beta(T_w - T_f)\, H_c^3 /\nu^3$
g = acceleration due to gravity (m/s^2)
β = volume coefficient of expansion for water
H_C = depth of tank wall covered by the wrap around coil (m)
T_w = wall temperature °C
T_f = Fluid temperature °C
ν = kinematic viscosity of water (m^2/s)

For a circular 10mm condenser tube and bond width of 5mm, typical distribution of overall thermal resistance between the components of the heat transfer path is shown in Table 9.2

Table 9.2 Typical thermal resistance components for an external spiral coil condenser

Component	Thermal Resistance for 15°C tank temp %	Thermal Resistance for 60°C tank temp %
Refrigerant tube	8	10
Bond	12	17
Enamel	3	4
Conduction along tank wall fin and convection in tank	77	69

Note: The effects of the conduction along the tank wall and free convection inside the tank cannot be uncoupled as in the case of the direct conduction in the micro-channel blanket mode.

9.5 Submerged condenser coil

A submerged tube condenser consists of a refrigerant coil that is within the storage tank as shown in figure 9.6.

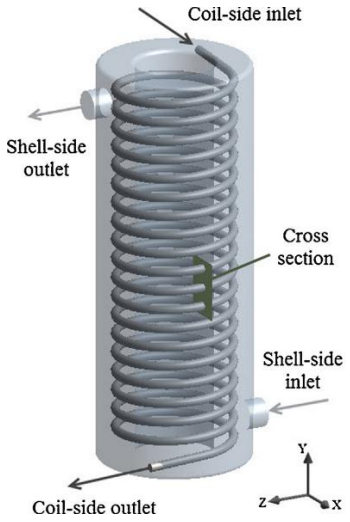


Figure 9.6 Condenser tubing within the storage tank

A submerged condenser coil in contact with the tank water must be double-walled (fig 9.7) if a toxic refrigerant, toxic refrigerant lubricant or a dye is not added to the refrigerant as specified in AS/NZS 2712. A submerged coil heat exchanger may also have an enamel layer on the surface that is in contact with the water in the storage tank.

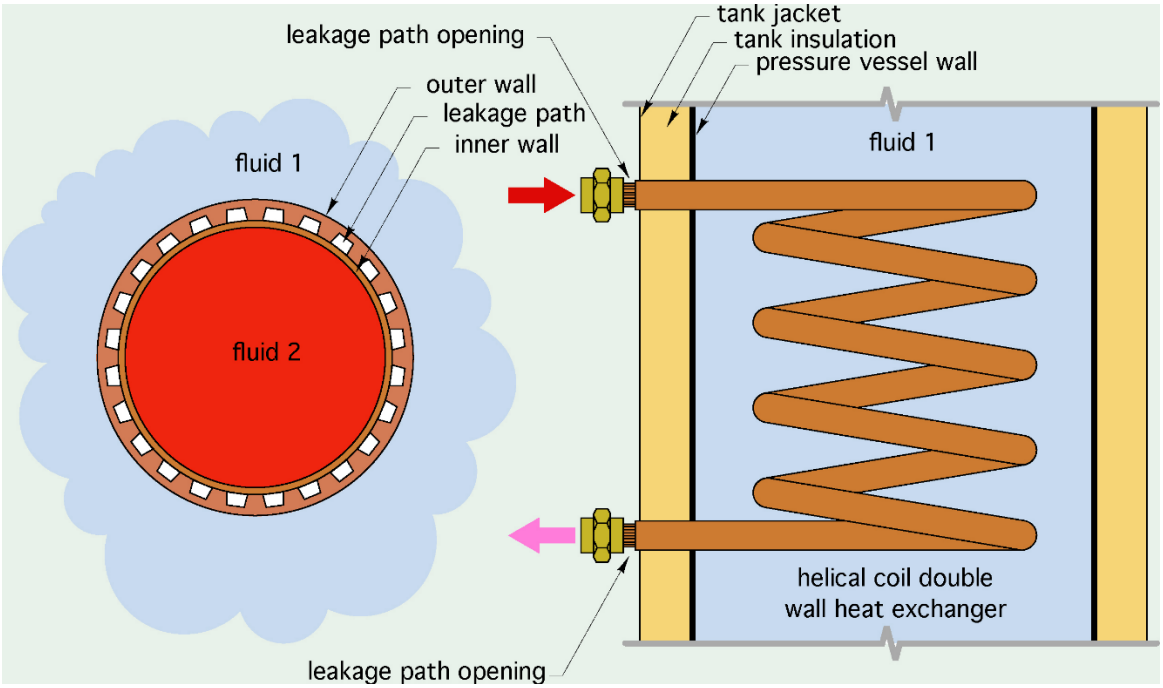


Figure 9.7 Example of submerged, double-wall heat exchanger

The parameters that are required to determine the condenser temperature for a submerged condenser are: -

- Length of condenser tube in contact with water
- Condenser tubing external diameter (outer layer of double-wall HX)
- Thickness of inner layer of condenser tubing wall (0 if only single wall HX)
- Thermal conductivity of inner layer of condenser tubing
- Thermal resistance of the join between the inner and outer tubes
- Thickness of outer layer of condenser tubing wall
- Thermal conductivity of outer layer of condenser tubing
- Thickness of enamel lining on outer surface of condenser tube (zero if if not applicable)
- Thermal conductivity of enamel lining of condenser tube

The parameters that are required to determine the conduction heat transfer from adjoining nodes are: -

- Thickness of tank wall
- Thermal conductivity of tank wall

The thermal resistance between the condensing refrigerant and water in the tank consists of a series connection of the following heat transfer stages: -

- Condensation heat transfer inside the condenser tube
- Conduction through the inner wall of the condenser tube
- Conduction through the connector between the inner and outer tubes
- Conduction through the outer wall of the condenser tube
- Conduction through the enamel layer on the outer wall of the condenser tube (if applicable)
- Convection heat transfer between the outer face of the enamel layer (or HX outer wall) and the water in the tank

The distribution of thermal resistance of a copper double wall coil with a co-extruded copper tube assembly is shown in Table 9.3.

Table 9.3 Typical thermal resistance components for submerged double wall coil

Component	Thermal Resistance for Twater = 15°C %	Thermal Resistance for Twater = 60°C %
Condensation heat transfer	7	10
Pipe walls and separator	1	1
Enamel	8	13
Convection in tank	84	76

10. 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 (hr)

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.

11. 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

TRNAUS – TRNSYS15 extensions for solar & heat pump water heaters

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

11.1 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
Locations 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

11.2 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

12. REFERENCES

Anderson T.N and Morrison G.L.
Condenser-Tank Interaction in a Heat Pump Water Heater with a Wrap-around Condenser
IRHACE Conference New Zealand 2007

ASHRAE 93-77 Methods of testing to determine the thermal performance of solar collectors.

AS/NZS 2535. Test methods for solar collectors. Part 1: Thermal performance of glazed liquid heating collectors including pressure drop.

AS 2813. Solar Water Heater-Method of test for thermal performance-Simulator method". Standards Australia

AS 2984 "Solar Water Heaters - Method of test-Outdoor Test". Standards Australia.

AS3498 Safety and public health requirements for plumbing products – water heaters and hot-water storage tanks. Standards Australia

AS 4445.1 Solar heating – domestic water heating system. Part 1: Performance rating procedure using indoor test methods. Standards Australia

AS 4552 Gas water heaters Standards Australia

AS 5125 heat pump water heaters – Performance assessment. Standards Australia

Baur J. M., Klein S. A. and Beckman W. A. (1993). Simulation of water tanks with mantle heat exchangers. Proceedings ASES Annual Conference, Solar93, 286-291.

Clift, Dean Holland, Leerson, Jack, Hasan, Kazi N and Rosengarten, Gary (2023) Maximising the benefit of variable speed heat-pump water heater with rooftop PV and intelligent battery charging. Solar Energy 265, article 112049 (2023)

Close D.J. (1962) The Performance of Solar Water Heaters with Natural Circulation, Solar Energy 6, 33-40 (1962)

Cooper P.I. (1981) Effect of Inclination on the heat loss from flat plate solar collectors, Solar Energy 27,413-420 (1981).

Eames P.C. and Norton B. (1998). The effect of tank geometry on thermally stratified sensible heat storage subject to a low Reynolds number flow. Int J Heat Mass Transfer V41,2131-2142.

Frick R.A, Walsh P.J, Rice S.P and Leadbeater M. (1997). Australian Solar Radiation Data Handbook, National Energy Research Development and Demonstration Council, August 1987.

Furbo S. and Berg P. (1992). Calculation of the thermal performance of small hot water solar heating systems using low flow operation. Thermal Insulation Laboratory, Technical University of Denmark.

Harding G.L, Yin Zhiqiang and McKay D.W. (1985) Heat extraction efficiency of a concentric glass tubular collector. Solar Energy 35, 71-79 1985.

James S.R and Proctor D. (1982) Development of a Standard for Evaluating the Thermal Performance of a Domestic Solar Hot Water System. ANZSES Annual Conference, Brisbane Australia 57-62, (1982).

Klein S.A et al. (1999), TRNSYS User's manual. University of Wisconsin Solar Energy Lab.

Kuhn J.K, vanFuchs G.F and Zob A.P. (1980) Developing and Upgrading of Solar System Thermal Energy Storage Simulation Models. Final Report for U.S. Department of Energy by Boeing Computer Services Co (1980).

Martin M. and Berdahl. P. (1984) Characteristics of Infrared Sky Radiation in the United States. Solar Energy, V. 33, 321-336 (1984).

Mercer W. E., Pearce W. M. and Hitchcock J. E. (1967). Laminar forced convection in the entrance region between parallel flat plates. ASME J of Heat Transfer V89, 251-257.

Mertol A., Place W. and Webster T. (1981). Detailed loop model analysis of liquid solar thermosyphons with heat exchangers. Solar Energy V27,367-386.

Morrison G.L and Braun J.E. (1985) System Modelling and Operation Characteristics of Thermosyphon Solar Water Heaters. Solar Energy 34, 389-405 (1985).

Morrison G.L and Ranatunga D.B.J. (1980). Thermosyphon Circulation in Solar Collectors. Solar Energy 24, 191-198 (1980).

Morrison G.L and Tran N.H. (1984) Simulation of the Long Term Performance of Thermosyphon Solar Water Heaters. Solar Energy 33 No 6 (1985).

Morrison G.L. and Gilliaert.D. (1992) Unglazed Solar Collector Performance Characteristics. ASME. J. of Solar Energy Eng. V. 114, 194-200 (l992).

Morrison G.L and Litvak A. (1988) Condensed Solar Radiation Data Base for Australia. University of NSW School of Mechanical Engineering Report FMT/1/1988

Morrison G.L. (1994) Simulation of Packaged Solar Heat-Pump Water Heaters. Solar Energy V53,249-257, 1994

Norton B and Probert S.D. (1983) Achieving Thermal Rectification in Natural-Circulation Solar-Energy Water Heaters. Applied Energy 14, 211-225 (1983).

Ong K.S. (1976) An Improved Computer Program for the Thermal Performance of a Solar Water Heater. Solar Energy 18,183-191 (1976).

Young M.F and Bergguam J.B (1981) Performance Characteristics of a Thermosyphon Solar Domestic Hot Water System. ASME J. Solar Energy Engineering 103, 193-200 (1981).

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	$\eta = a - b\,(\bar{T}_w - T_a - R)/I - c\,(\bar{T}_w - T_a + R)^2/I$
	-2	$\eta = a - (b + c*V)\,(\bar{T}_w - T_a)/I - d\,(\bar{T}_w - T_a)^2/I$ (unglazed absorber) with wind speed dependent heat loss coefficient and allowance for condensation and long wave radiation
	3	$\eta = a - b\,(\bar{T}_w - T_a + R)/I - c\,(\bar{T}_w^4 - (T_a - R)^4)/I$
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. $\eta = a - b\,(\bar{T}_w - T_a - R)/I - c\,(\bar{T}_w - T_a + R)^2/I$		
6	a	intercept efficiency
7	b	$(\bar{T}_w - T_a + R)$ coefficient kJ/(hr m^2 K)
8	c	$(\bar{T}_w - T_a + R)^2$ 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. $(\eta = a - (b + c*V)\,(\bar{T}_w - T_a)/I - d\,(\bar{T}_w - T_a)^2/I)$		
6	a	intercept efficiency
7	b	$(\bar{T}_w - T_a)$ coefficient kJ/(hr m^2 K)
8	d	$(\bar{T}_w - T_a)^2$ 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. $\eta = a - b\,(\bar{T}_w - T_a + R)/I - c\,(\bar{T}_w^4 - (T_a - R)^4)/I$

6	a	intercept efficiency
7	b	$(\bar{T}_w - T_a + R)$ coefficient kJ/(hr m^2 K)
8	c	$(\bar{T}_w^4 - (T_a - R)^4)$ 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 $\eta = a - b\,(\bar{T}_w - T_a)/I - c*N*(\bar{T}_s - T_a)/I - d*N*\varepsilon s\,(\bar{T}_s^4 - T_a^4)/I$

6	a	intercept efficiency
7	b	$(\bar{T}_w - T_a)$ coefficient per tube kJ/K
8	c	$(\bar{T}_s - T_a)$ coefficient per tube kJ/K
9	d	$(\bar{T}_s^4 - T_a^4)$ coefficient per tube, kJ/K^4
10	N	number of tubes per m^2 of array

Efficiency Modes 7 $\eta = a - b\,(\bar{T}_w - T_a)/I - c*N*(\bar{T}_s - T_a)/I - d*N*\varepsilon s\,(\bar{T}_s^4 - T_a^4)/I$

6	a	intercept efficiency
7	b	$(\bar{T}_w - T_a)$ coefficient per tube kJ/K
8	c	$(\bar{T}_s - T_a)$ coefficient per tube kJ/K
9	d	$(\bar{T}_s^4 - T_a^4)$ 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
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

#Note, this type is not to be used in heat pump applications with integral condensers. Type104 has been developed for heat pumps with integral condensers.

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 **(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)
21	T_th	water temperature in tank at height of active thermostat, C (which ever thermostat is active)
22	T45	The temperature of the fluid in the storage tank at 45% from the top of the tank (by volume) (°C)
23	T90	The temperature of the fluid in the storage tank at 90% from the top of the tank (by volume) (°C)
24	San_vol	The volume of fluid that has been heated to 55°C within the storage tank (m^3)
25	San_time	The time that a positive value of San_vol (output 24) has been within the storage tank (hr)

Appendix 3 TYPE 145 Thermosyphon Solar Water Heater Component Description

PARAMETER		DESCRIPTION
1		**Efficiency Mode**
	1	η vs $(T_i - T_a)/I$
	2	η vs $(\bar{T}_w - (T_a - R))/I$ and $(\bar{T}_w - (T_a - R))^2/I$
	3	η vs $(\bar{T}_w - (T_a - R))/I$ and $(\bar{T}_w^4 - (T_a - R)^4)/I$
	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	$(\bar{T}_w - T_a + R)$ coefficient kJ/(hr m^2 K)
5	c	$(\bar{T}_w - T_a + R)^2$ coefficient kJ/(hr m^2 K^2)
6	R	sky temperature allowance, K
Efficiency Mode = 3		
3	a	intercept efficiency
4	b	$(\bar{T}_w - T_a + R)$ coefficient kJ/(hr m^2 K)
5	c	$(\bar{T}_w^4 - (T_a+R)^4$ 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	$(\bar{T}_w - T_a)$ coefficient per tube
5	c	$(\bar{T}_s - T_a)$ coefficient per tube
6	d	$(\bar{T}_s^4 - T_a^4)$ 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 # absolute value is interpreted, negative values instigates Sanitation assessment and three additional temperature sensors.
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 tested heat exchanger, only single tube is considered , m
47	L_{HX}	length of mantle heat exchanger (used for internal friction evaluation, must equal dimension of tested heat exchanger), 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)
Parameter 26 >0		
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)
Parameter 26 <0		
last – 4	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 – 3	Tt	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)
last – 2	Haux1	Height of 1st aux temperature sensor from the bottom of the tank (m)
last – 1	Haux2	Height of 2nd aux temperature sensor from the bottom of the tank (m)
last	Haux3	Height of 3rd aux temperature sensor from the bottom of the tank (m)

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
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	Qrev	potential heat loss due to reverse flow , kJ/hr (not removed from tank)
20	G	Flow rate through thermosyphon loop (L/hr)
21	T45	The temperature of the fluid in the storage tank at 45% from the top of the tank (by volume) (°C)
22	T90	The temperature of the fluid in the storage tank at 90% from the top of the tank (by volume) (°C)
23	San_vol	The volume of fluid that has been heated to 55°C within the storage tank (m3)
24	San_time	The time that a positive value of San_vol has been within the storage tank (hr)
25	San_fail	Net sanitation pass/fail. 1 = fail, 0 = pass (San_fail)
26	San_ftime	The time that San_fail turned 1 (hr) (San_ftime)
27	D_fail	Daily sanitation pass/fail. 1 = fail, 0 = pass (Daily_fail)
28	W_fail	Weekly sanitation pass/fail. 1 = fail, 0 = pass.
29	Vol_fail	Sanitation volume at time pass/fail. 1 = fail, 0 = pass.
30	Aux1	Temperature of 1st auxiliary temperature sensor (°C) (see parameter Haux1)
31	Aux2	Temperature of 2nd auxiliary temperature sensor (°C) (see parameter Haux2)
32	Aux3	Temperature of 3rd auxiliary temperature sensor (°C) (see parameter Haux3)

Appendix 4 TYPE 137 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
```

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```
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 oscillations 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 (e.g. 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 signal
2	out2	Output control signal value last time step
3	Numstarts	Total number of delay events

Example1 :- Lockout signal to stop boosting in a solar water heater for a specified time period after the solar collector pump turns on.

The following deck sets a control signal (output [77,1]) to OFF (e.g. to delay operation of an electric booster) for 2 hours after the collector loop pump turns on (input 1 [2,1]). The second input to Unit 77 is required for the control function.

```
Constants 1    ! delay timer
delay = 2

unit 77 type 177
parameters 1
delay
Inputs 2
2,1 77,2
 0    0
Equation 1    !Heater control
Heater_ON = [77,1]
```

Example2 : Time delay lockout of heat pump when it starts and total number of start events.
Most heat pumps cannot start when there is a high pressure difference across the heat pump hence, when a heat pump receives an ON signal to start there is usually a time delay before it actually starts to ensure that the pressures in the high and low sides of the refrigerant circuit have had time to adjust.

The following deck sets a control signal (output [77,1] to OFF for 0.25 hours after the heat pump receives a start signal (input 1 [2,1]). The second input to Unit 77 is required for the control function. The third output is the sum of all heat pump start events.

```
Constants 1    ! delay timer
Delay = 025

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

Equation 2    !Heat pump startup delay
HP_ON = [77,1]
Numstart = [77,3]
```

Appendix 9 TYPE 178 Event detection

This type is used to set a control signal to 1 if the first input has not exceeded 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 (hrs)

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 such as the temperature in a tank (e.g. 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 (e.g. 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	□o	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
```

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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

#Note, this type and the unmodified TYPE60 storage tank are not to be used in heat pump applications with integral condensers. Type104 has been developed for heat pumps with integral condensers.

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.
- Internal Legionella sanitation assessment to AS 3498.
- Additional auxiliary temperature sensing locations (that do not change as HX or node counts change)

SPECIFICATION OF MANTLE HEAT EXCHANGER OR FALLING FILM HEAT EXCHANGER

PARAMETER (with height > 0)		**DESCRIPTION**
1 to second last		As for TYPE60
last	hx	0 = ignore this option 1 = collector loop mantle heat exchanger 2 = collector loop falling film heat exchanger

PARAMETER (with height < 0)		**DESCRIPTION**
1 to 5th last		As for TYPE60
4th last	hx	0 = ignore this option 1 = collector loop mantle heat exchanger 2 = collector loop falling film heat exchanger
3rd last	Haux1	Height of 1st aux temperature sensor from the bottom of the tank (m)
2nd last	Haux2	Height of 2nd aux temperature sensor from the bottom of the tank (m)
last	Haux3	Height of 3rd aux temperature sensor from the bottom of the tank (m)

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. Thermostat dead band parameters Tdb1 & Tdb2 are still required to be entered however these parameters are ignored when Tset1<0.
To select Legionella sanitation assessment mode, set parameter 3 (tank height) < 0. The code will compute the height to be the absolute of the entered height. If the tank height > 0 then type160 is backwards compatible with decks developed prior to 2024 release.
Note: Where the deck recognizes that there is an inline booster (type 106 for instance) then the Sanitation checks undertaken within type160 are all set to 1 (fail). This is done as it is assumed that there is no sanitation control within the Type160 tank when an inline booster is present, and as such sanitation compliance is solely checked by the inline booster.

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 (with height > 0)	**DESCRIPTION**

All		As for TYPE60
OUTPUT		**DESCRIPTION**
(with height < 0)		
1 to 21		As for TYPE60
22	San_fail	Net sanitation pass/fail. 1 = fail, 0 = pass.
23	San_ftime	The time that San_fail turned 1
24	Daily_fail	Daily sanitation pass/fail. 1 = fail, 0 = pass.
25	Weekly_fail	Weekly sanitation pass/fail. 1 = fail, 0 = pass.
26	Sanvol_fail	Sanitation by volume and time pass/fail. 1 = fail, 0 = pass.
27	Taux1	Temperature at level of first auxiliary temperature sensor (°C) (see 3rd last parameter)
28	Taux2	Temperature at level of second auxiliary temperature sensor (°C) (see 2nd last parameter)
29	Taux3	Temperature at level of third auxiliary temperature sensor (°C) (see last parameter)
30	T45	The temperature of the fluid in the storage tank at 45% from the top of the tank (by volume) (°C)
31	T90	The temperature of the fluid in the storage tank at 90% from the top of the tank (by volume) (°C)
32	San_vol	The volume of fluid that has been heated to 55°C within the storage tank (m^3)
33	San_time	The time that a positive value of San_vol has been within the storage tank (hr)
For each HX		
29+hxMode*5	Qhx	Rate of energy input from heat exchanger (kJ/hr)
30+hxMode*5	Tout	Temperature of fluid exiting heat exchanger (°C)
31+hxMode*5	Tout_node	Temperature of node containing heat exchanger outlet (°C)
32+hxMode*5	Imtd	Average heat exchanger log-mean temperature difference (°C)
33+hxMode*5	UAhx	Average heat exchanger UA value (kJ/hr-°C)
34+hxMode*5	T1	Temperature of the top of the tank (°C)
35+hxMode*5	Tn	Temperature of the bottom of the tank (°C)
34+hxMode*5+ i (i = node number)	Ti	i = 2 to n-1 Temperature of the ith node (°C) Note this list does not output the top or the bottom node temperatures

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

Appendix 14 TYPE 104 Integral air-source heat pump water heater tank

The TRNAUS Type 104 component was released in 2024. This component is based on the TRNSYS Type 4 component with modifications to allow for the modelling of wrap-around heat pump condensers and internal coil condensers in integral heat pump water heaters. The model uses AS/NZS 5125 heat pump COP and Power performance coefficients to determine overall energy transfer to the tank and a model of the condenser to determine the condensing temperature on the refrigerant side of the condenser. The maximum number of tank nodes in TYPE104 is 20.

PARAMETER NO.	DESCRIPTION
1	Mode (4 or 5 or 6)
2	Tank volume (m^3)
3	Tank inner diameter (m)
4	Tank fluid specific heat (kJ/kg K)
5	Tank fluid density (kg/m^3)
6	Tank heat loss rate (UA) (kJ/hr K)
7	Operation mode of auxiliary heaters 1 = master/slave relationship where bottom element is enabled only when top element is satisfied. Bottom element is the first element in the list below. 2 = both heaters can be on simultaneously
8	Volume of water above the first auxiliary element (m^3)
9	Volume of water above the first thermostat (m^3)
10	Volume of water above the second auxiliary element (m^3)
11	Volume of water above the second thermostat element (m^3)
12	Boiling point temperature of fluid in storage tank (°C)
13	Maximum water temperature in top of tank during AS/NZS 5125 tests (°C) (see stop temperature in AS/NZS 5125.1 section 4.2)
14	Volume of water above the top of the condenser (m^3)
15	Volume of water above the bottom of the condenser (m^3)
16	Volume of water above the first auxiliary temperature sensor (m^3)
17	Volume of water above the second auxiliary temperature sensor (m^3)
18	Volume of water above the third auxiliary temperature sensor (m^3)

For MODE=4	Micro-channel condenser
19	Width of extrusion strip in contact with tank (m) see fig 9.2 for definition
20	Length of extrusion strip in contact with tank (m) see fig 9.2 for definition
21	Number of extrusion strips attached to tank
22	Thickness of condenser extrusion strip wall (m) see fig 9.2 for definition
23	Thermal conductivity of condenser extrusion wall (kJ/hr/mK)
24	Thickness of bond between condenser and tank wall (m)
25	Thermal conductivity of bond between condenser and tank wall (kJ/hr/mK)
26	Thick ness of tank wall (m)
27	Thermal conductivity of tank wall (kJ/hr/mK)
28	Thickness of glass lining of tank m (zero if not applicable)

29	Thermal conductivity of glass lining of tank (kJ/hr/mK)

For MODE=5	**Wrap around coil**
19	Length of condenser tube in contact with wall (m)
20	Condenser tubing external diameter (m)
21	Thickness of condenser tube wall (m)
22	Thermal conductivity of condenser channel wall (kJ/hr/mK)
23	**Round tube** Width of contact between condenser tube bond and tank wall (m) see Fig 9.5 OR **D shape tube** Width of contact between flat side of D tube condenser piping and tank wall (m) See Fig 9.5
24	Separation between condenser tube and tank wall (m) **Round tube** = 0. **D tube** = bond thickness between flat side of D tube and tank wall (m) See Fig 9.5
25	Thermal conductivity of bond between condenser and tank wall (kJ/hr/mK)
26	Thickness of tank wall (m)
27	Thermal conductivity of tank wall (kJ/hr/mK)
28	Thickness of glass lining of tank (m) (zero if not applicable)
29	Thermal conductivity of glass lining of tank (kJ/hr/mK)

For MODE=6	**Coil submerged in tank**
19	Length of condenser tube in contact with water (m)
20	Condenser tubing external diameter (m)
21	Thickness of inner layer of twin wall condenser tubing (m)
22	Thermal conductivity of inner layer of condenser tubing (kJ/hr/mK)
23	Thickness of outer layer of twin wall condenser tubing (m)
24	Thermal conductivity of outer layer of condenser tubing (kJ/hr/mK)
25	Thickness of glass lining on condenser tube (m) (0 if not used)
26	Thermal conductivity of glass coating on condenser tube (kJ/hr/mK)
27	Thickness of tank wall (m)
28	Thermal conductivity of tank wall (kJ/hr/mK)

INPUT NO.	**DESCRIPTION**
1	Temperature of cold load flow (input is bottom of tank) (°C)
2	Mass flow rate of load flow water (kg/hr)
3	Ambient temperature around tank (°C)
4	Total thermal energy transferred from heat pump to storage tank (kJ/hr) (compute from AS/NZS 5125 COP & Power correlations)
5	First thermostat set temperature (°C)
6	First thermostat temperature deadband (K)
7	Heating rate of first auxiliary element (kJ/hr)
8	Second thermostat set temperature (°C)

9	Second thermostat temperature deadband (K)
10	Heating rate of second auxiliary element (kJ/hr)
11	Signal of weekly sanitation cycle (binary, 1 means ***active*** sanitation cycle)

OUTPUT NO.	DESCRIPTION
1	Mass flow rate to load (kg/hr)
2	Rate of energy lost to environment (kJ/hr)
3	Rate of energy removal by load flow (kJ/hr)
4	Internal energy change of the tank from the beginning of the simulation (kJ)
5	Rate at which auxiliary energy is added by the internal heaters (kJ/hr)
6	Rate at which auxiliary energy is added by the first internal heater (kJ/hr)
7	Rate at which auxiliary energy is added by the second internal heater (kJ/hr)
8	Average tank temperature (°C)
9	Average tank water temperature over depth covered by the condenser (Tcoil) (°C)
10	Calculated refrigerant condensing temperature (Tcond) (°C)
11	Rate at which energy is injected to the tank from the condenser (QHX) (kJ/hr)
12	Temperature of first auxiliary temperature sensor (°C) (see parameter 16)
13	Temperature of second auxiliary temperature sensor (°C) (see parameter 17)
14	Temperature of third auxiliary temperature sensor (°C) (see parameter 18)
15	Net sanitation pass/fail. 1 = fail, 0 = pass (San_fail)
16	The time that San_fail turned 1 (hr) (San_ftime)
17	Daily sanitation pass/fail. 1 = fail, 0 = pass (Daily_fail)
18	Weekly sanitation pass/fail. 1 = fail, 0 = pass.
19	The temperature of the fluid in the storage tank at 45% from the top of the tank (by volume) (°C)
20	The temperature of the fluid in the storage tank at 90% from the top of the tank (by volume) (°C)
20+1	Temperature of top tank node (°C)
20+i	Temperature of ith tank node (°C)
20+N	Temperature of bottom tank node (°C)

NOTE: there is no calculation of energy dumped due to overheating. The simulation is aborted within type104 if any of the node temperatures exceed 95 °C.
NOTE: the number of tank nodes N is set by the DERIVATIVE command in the TRNSYS15 deck.

DERIVATIVE N (N = number of nodes used to model tank contents)

DERIVATIVE NO.	DESCRIPTION
1	Initial tank temperature for top node (°C)
i	Initial tank temperature for ith node (°C)
N	Initial tank temperature for bottom node (°C)

Appendix 15 TYPE 238 Stratified Tank (138) with thermostat settings as inputs

TYPE238 is a modification of TYPE138 with the first thermostat set temperature and dead band moved to inputs 8 & 9

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). If par(16) is negative, then the thermostat set temperature is taken as input 8
17	T_{db}	Temperature dead band for auxiliary heater, K If par(17) is negative then the thermostat set temperature is taken as input 9
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

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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 **(NOTE: First element is inactive if second element is active)**
7		enable signal for second auxiliary heater
8		Top thermostat set temperature if par(16) is negative
9		Top thermostat dead band if par(17) is negative

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 overheating, 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 16 TYPE 84 Moving Average

This type is like type 84 that was released in TRNSYS 16 and later versions of TRNSYS. Type 84 determines the rolling average of an input over a fixed number of previous timesteps (maximum number of timesteps is 10,000). Where the simulation has not progressed for the fixed number of previous timesteps, the average is calculated over the number of timesteps from the start of the simulation to the current timestep. The output is the computed moving average. Note TYPE84 for TRNSYS15 does not have multiple variables that can be assessed within the same unit number. If more than one variable is to be assessed, multiple instances of TYPE84 need to be placed within the deck. Please note that the data storage of this type is substantial with 10,000 spaces allocated. It is recommended that no more than 5 instances of type 84 are within a deck. The total storage array for TRNSYS15 has been increased from 12,000 to 120,000 with TRNAUS V24.2 however this total storage array is needed for more units than just type84. If further types are needed the NUMSTR value in the /TRNSYS15/INCLUDE/param.inc file must be increased and the whole TRNSYS Kernel, Types, Dummy and TRNAUS folders must be re-compiled and linked.

PARAMETER		DESCRIPTION
1	N_timesteps	Number of timesteps for the moving average to be assessed over.

INPUT NO		DESCRIPTION
1	x1	Variable to be averaged.

OUTPUT		DESCRIPTION
1	xbar	Moving average of variable.

An example of the application of this routine to determine the moving average of a price is shown below. The input is “Price” as input from a data file.

```
Constants 1

                N_timesteps = 8400 ! the assessment is made over 1 week with 0.02 hr timestep

                unit 84 type 84
                parameters 1
                N_timesteps
                Inputs 1
                Price
                  0
Eqn 1
 Moving_average = [84,1] ! the moving average of “Price” over the past 8400 timesteps
```

Appendix 17 TYPE 179 Delayed event detection with forced heating

The routine determines the lapsed time since input 1 last changed from 0 to a value greater than 0. The lapsed time has two ways that it can be reset to zero, that being that input 1 has changed from 0 to a value greater than 0, or that the monitored temperature has reached or exceeded a defined temperature. Once the lapsed time has reached a defined period (parameter 1) AND the time of day is equal to (or within 2 timesteps) of a defined time (parameter 3) then the output is set to 1. The output stays true until the monitored temperature (input 2) reaches or exceeds the value of parameter 2 at which point the output is set to 0.

PARAMETER		DESCRIPTION
1	Time_period	the time-period over which the controller is monitoring input signal to turn on (hrs)
2	Set_temp	the set point temperature that the routine once turned on will stay on until reached (°C)
3	F_time	the time of the day (in 24hr) that the controller will turn on in the event that the monitored input 1 has failed to come on within Parameter 1 period (hrs)

INPUT NO		DESCRIPTION
1	Control signal	The monitored control signal which is interpreted to change stage when changing from 0 to a value greater than 0.
2	Mon_temp	Temperature that is monitored (°C)

OUTPUT		DESCRIPTION
1	Binary	Output control signal.

An example of the application of this routine is to force a daily heat pump heating cycle on the event that other controls have not independently called a heating cycle to commence. Without this routine, it is typical that water heaters assessed with larger thermal loads whilst passing minimum delivery temperatures and passing Legionella sanitation requirements, will fail these legislated requirements for consumers with smaller thermal loads.

** Daily operation of HP to ensure Legionella sanitation and minimum delivery temp for all loads **

```
eqn 5
Time_p = 16            ! Time that the input signal is watched over (hr)
Set_temp = 60          ! Threshold temperature that must be reached before output of this type is switched off (°C)
F_time = 18            ! Time of the day that the HP is forced on if not already heated (hr)
Comp_sig = [20,1]      ! Monitored temperature from differential temperature controller
HP_control = [104,19]  ! Monitored temperature on heater at ~ mid-point of a stratified storage tank (°C)

Unit 103 Type 179 Time dependent compressor controller (forcing heating cycle at least once per day)
Parameters 3
Time_p Set_temp F_time
Inputs 2
Comp_sig  HP_control
0         60
```

Note in the example above, type 179 will set its output to 1 at 18 hrs in the event that more than 16 hrs has passed since the commencement of the last heating cycle (Comp_sig) or the monitored tank temp (HP_control) has not met or exceeded the Set_temp (60°C) within the past 16 hrs. The output will remain true (1) until the HP_control meets or exceeds the Set_temp.

Appendix 18 TYPE 180 Legionella sanitation conformance

Type 180 monitors 2 or 4 inputs and assesses these over a period to determine Legionella sanitation conformance requirements as specified in AS3498 section 7.2. There are no parameters that are to be listed by the user, however the source code automatically determines which mode to operate in, which is detailed below. If any one of the Legionella sanitation conformance checks is passed, then the net sanitation check is set to pass.

PARAMETER		DESCRIPTION
There are no parameters entered – the mode is automatically determined.	Mode	Mode 1 = for assessments to AS3498 7.2 (a) & (b) only (storage tanks that ***do not*** track sanitation volumes and times that water has been within the storage tank) Mode 2 = for assessments to AS3498 7.2 (a), (b) and (c) (55°C in table 1) only (storage tanks that ***do*** track sanitation volumes and times that water has been within the storage tank) Mode 3 = as per mode 2 assessments that in addition have an inline instantaneous booster that heats the water as per AS3498 7.2 (f) Mode 4 = as per mode 1 assessments that in addition have an inline instantaneous booster that heats the water as per AS3498 7.2 (f)

INPUT NO		DESCRIPTION
1 (for all modes)	T45	The temperature of the fluid in the storage tank at 45% from the top of the tank (by volume) (°C)
2 (for all modes)	T90	The temperature of the fluid in the storage tank at 90% from the top of the tank (by volume) (°C)
3 (only for modes 2&3)	San_vol	The volume of fluid that has been heated to 55°C within the storage tank (m^3)
4 (only for modes 2&3)	San_time	The time that a positive value of San_vol has been within the storage tank (hr)
5 for mode 3 3 for mode 4	Tinlet	Temperature of fluid entering the inline booster (°C)
6 for mode 3 4 for mode 4	Toutlet	Temperature of fluid leaving the inline booster (°C)

OUTPUT		DESCRIPTION
1	San_fail	Net sanitation pass/fail. 1 = fail, 0 = pass.
2	San_ftime	The time that San_fail was set to 1
3	Daily_fail	Daily sanitation pass/fail. 1 = fail, 0 = pass.
4	Weekly_fail	Weekly sanitation pass/fail. 1 = fail, 0 = pass.
5 (only applicable for modes 2&3)	Sanvol_fail	Sanitation by volume and time pass/fail. 1 = fail, 0 = pass.
6 (only applicable for modes 3&4)	Boost_fail	Inline boosting sanitation pass/fail. 1 = fail, 0 = pass.

#Note, Type180. Modes 2&3 are not to be used in heat pump applications.

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Appendix 19 TYPE 182 Compressor on/off differential controller with minimum/maximum on/off times

Type 182 monitors 4 inputs and assesses these against min-max on/off input durations to deliver a binary output. This type is intended to control heat pump compressor operation based on temperature differential and idle durations to ensure HP manufacturer limits of operation are adequately assessed within the simulation.

PARAMETER		DESCRIPTION
1	Min_ton	Minimum time on (hrs)
2	Max_ton	Maximum time on (hrs)
3	Min_toff	Minimum time off (hrs)
4	Max_toff	Maximum time off (hrs)

INPUT NO		DESCRIPTION
1	T_H	Upper input temperature (°C)
2	T_L	Lower input temperature (°C)
3	ΔT_H	Upper deadband temperature difference (°C)
4	ΔT_L	Lower deadband temperature difference (°C)
5	γ_i	input control function (binary)

OUTPUT		DESCRIPTION
1	Signal_out	Output signal (binary)
2	On-time	Duration of current signal_out = 1 event (hrs)
3	Off_time	Duration of current signal_out = 0 event (hrs)
4	Min_on	1= minimum on time is active (binary)
5	Max_on	1 = maximum on time is active (binary)
6	Min_off	1 = minimum off time is active (binary)
7	Max_off	1 = maximum off time is active (binary)
8	Starts	Count of signal_out change from 0 to 1 events (integer)
9	Total_hrs	Total time of signal_out = 1 (hrs)
10	γ_o	Output control signal from the differential on/off control.

An example of the application of this routine is shown below.

```
UNIT 26 TYPE 14
*HP timer to operate from 9am to 5pm daily
PARAMETERS 12
0,0   9,0
9,1   17,1
17,0   24,0
*Output [26,1] average value of the function over the time step (0 or 1 in this case)

eqn 1
*Turn HP off below Taux and use electric element instead
HP_onoff  = GT(Tamb,Taux)*[26,1]   ! HP operation (considering ambient temp and timer restriction)

****   Compressor min/max, on/off time control
eqn 5
Min_ton    = 10/60    ! 10 mins minimum operation time
Max_ton    = 6        ! 6 hrs maximum operation time
Min_toff   = 15/60    ! 15 mins minimum off time
Max_toff   = 8760     ! no limitation on the maximum off time
* T_Control is the HP set temperature of 60°C
* Tsen is the sensor temperature in the tank.
* TDB_HP is the compressor deadband of 12°C
* the lower deadband is 0°C
* in this case, the HP_onoff is dependent upon timer limitations.

Unit 82 Type 182 Compressor differential on/off and min/max on/off time controller
```

Parameters 4
Min_ton Max_ton Min_toff Max_toff
Inputs 5
T_Control Tsen TDB_HP 0,0 HP_onoff
60 60 12 0 1

eqn 9
Comp_on = [82,1] ! 0 = compressor is OFF, 1= compressor is running (binary)
On_time = [82,2] ! the compressor run time for this heating cycle (hrs)
Off_time = [82,3] ! the compressor off time since last shut down (hrs)
Min_on = [82,4] ! 1 = minimum on time is active (binary)
Max_on = [82,5] ! 1 = maximum on time is active (binary)
Min_off = [82,6] ! 1 = minimum off time is active (binary)
Max_off = [82,7] ! 1 = maximum off time is active (binary)
starts = [82,8] ! the total number of compressor starts for the simulation
Comp_hrs= [82,9] ! compressor run time in the simulation (total hrs)
Diff_cont= [82,10] ! the binary control signal of the differential on/off control part of type 182.

Appendix 20 TYPE 106 Inline instantaneous water heater with sanitation detection

Type 106 is identical to TYPE6 with the inclusion of Sanitation detection to ensure compliance with AS/NZS 4398:2020 clause 7.2 (f). There are thus two additional outputs, being the San_fail and the time at which this occurred within the simulation.

PARAMETER		DESCRIPTION
All		As for TYPE6

INPUT NO		DESCRIPTION
All		As for TYPE6

OUTPUT		DESCRIPTION
1-5		As for TYPE6
6	San_fail	Sanitation pass/fail. 1 = fail, 0 = pass.
7	San_ftime	The time that San_fail was set to 1

An example of the application of this routine is shown below

```
Constants 7
*---Instantaneous gas booster
effgas = .800              ! thermal efficiency (frac)
Gascap = 180.0 * 1000   ! gas burner capacity (kJ/h)
*Set point temperature
Tset_gas = 70              ! AS 3498:2009 requires heating to 70 Deg. C when the storage preheat temperature < 55
Deg. C
Ttrig_gas = 55           ! Temperature below which the gas booster gets triggered to boost (Ttrig_gas > 55 Deg. C)
*Note: Setting Ttrig_gas below Tset_gas requires evidence about the gas booster control logic.

eqn 3
Tpre = [23,1]                    ! Outlet temperature from pipe between preheat tank and booster
Flow = [25,2]                    ! Flow rate from the tempering valve
BoostOn = LT(Tpre, Ttrig_gas)  ! Only activate booster if Tpre falls below the booster trigger temperature

Unit 6 type 106 series heater
parameters 4
gascap 4.18 0 effgas
inputs 5
Tpre  Flow  BoostOn  0,0       Tamb
20      0         1       Tset_gas 20

EQN 7
Tout = [6,1]        ! outlet temperature of the inline booster (deg C)
Flow = [6,2]        ! Fluid mass flow rate (kg/hr)
Qaux = [6,3]        ! Required heating (kJ/hr)
Qloss = [6,4]       ! rate of thermal loss to the atmosphere including efficiency effects (kJ/hr)
Qfluid = [6,5]      ! rate of energy delivered to the fluid stream (kJ/hr)
San_fail = [6,6]    ! Sanitation fail (binary)
San_ftime = [6,7] ! The time that San_fail was set to 1.
```