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Alastair McDowell

A Methodology For Calculating The Temperature-Exposure History Of Water In Hot Water Tank Systems For Assessing Risk Of Microbial Contamination

A. McDowell[1], F. McClure[1]

[1]*Energy Analysis and Engineering (EnergyAE), 608 Harris St, Sydney, Australia*
E-mail: alastair.mcdowell@energyae.com

Abstract

An algorithm has been developed to calculate the maximum temperature reached by water drawn from a hot water tank, and the duration of time this hot water spent above a set temperature limit. The algorithm processes tank temperature data to calculate temperature-exposure statistics for each parcel of fluid that is drawn from the tank.

Mixing between layers of fluid in the tank occurs during heating operation when the temperatures of adjacent layers are similar. This mixing phenomenon can cause degradation of temperature-exposure history, and is one of the major complexities dealt with in this new algorithm. Another key complexity of the calculation is how results are rounded to deal with the coarse numerical discretization of the tank.

Applications for this methodology include assessing and reducing the risk of microbial contamination. Tank temperature profiles may be generated from a simulation model or measurements, allowing either real world systems to be monitored, or new systems to be designed. For this paper, a numerical model was used to generate the tank temperature profiles, and the temperature limits were set to 55°C and 60°C, similar to the requirements for legionella treatment as per AS 3498 Clause 7.1 (j) (iii) (Standards Australia, 2009).

Obtaining detailed temperature-exposure history for a specified load profile allows the user to design control strategies to limit unsafe draw-offs, activate boost heating, or limit inlet of a secondary water supply, such as rainwater, to levels and times when it is possible to be adequately treated through heating. These strategies improve water quality and water usage efficiency, allowing secondary water sources to be used in the hot water system while still ensuring water quality for the end user.

1. Introduction

Drinking water supplies are a limited resource in many cities around the world. Implementing water efficiency measures is important in order to conserve this valuable resource. One way to increase the utilization of all water sources is to use rain-water for bathing, showering, cleaning and washing. However, rain-water must be adequately treated before usage, and heating is an integral part of the treatment process, which may also include filtering (ASHRAE, 2000).

Also, water used in aged-care homes or hospitals must meet stringent safety requirements to prevent sensitive patients from becoming infected with legionellosis, caused by the presence of legionella bacteria in insufficiently treated water (Stout, 2007). One treatment method is sterilization to a suitably high temperature for a set period of time. This may be achieved by exposing water to high enough temperatures in the tank for long enough to ensure adequate treatment.

There are complex fluid and thermal dynamics that occur inside the tank during the passage of a parcel of water from the inlet to the outlet of the tank. The movement of water through the tank depends on the hot water demand applied to the tank, convection due to heating operation by the tank heating system, and mixing interactions between adjacent layers of fluid (Han, 2009).

In order to determine the period of time that parcels of fluid have been exposed to above a threshold temperature, a new algorithm has been developed to determine the temperature-exposure history of water in the tank, and to provide data for the algorithm, a hot water system numerical model was created.

This methodology can be applied to various types of hot water heater systems, including electric element or gas heating, air-source heat-pump water heaters, or solar thermal tanks, and can be based on measured tank temperature profile and load draw-off data or data generated using a numerical model.

2. Methods

2.1. Transient simulation model

The Transient System Simulation tool TRNSYS (University of Wisconsin Madison, 1979) is used to simulate the hot water system. TRNSYS is a software package developed by Solar Energy Laboratory, University of Wisconsin-Madison, and Thermal Energy System Specialists (TESS).

TRNSYS software has an extensive library of components that contain a mathematical model for the performance of each part of the system. The inputs and outputs of these components may be linked together to form a complete system, and the performance for this system is simulated for a defined set of environmental conditions.

The core component for this model is the tank, which has a set of boundary conditions applied to the inlets, outlets, and boundaries. Inputs to the model include:

- Tank specifications
- Cold water inlet temperature
- Heating set-point and dead-band
- Hot water usage load profile
- Initial tank temperature profile
- Ambient dry bulb temperature profile
- Ambient wet bulb temperature profile

While TRNSYS offers a user-interface for inputting data, for this investigation an Excel spreadsheet interface is used to input the required data, which is processed behind the scenes by Visual Basic for Applications (VBA) code to be written to the TRNSYS model input file the correct form. The Excel interface is shown in Figure 1.

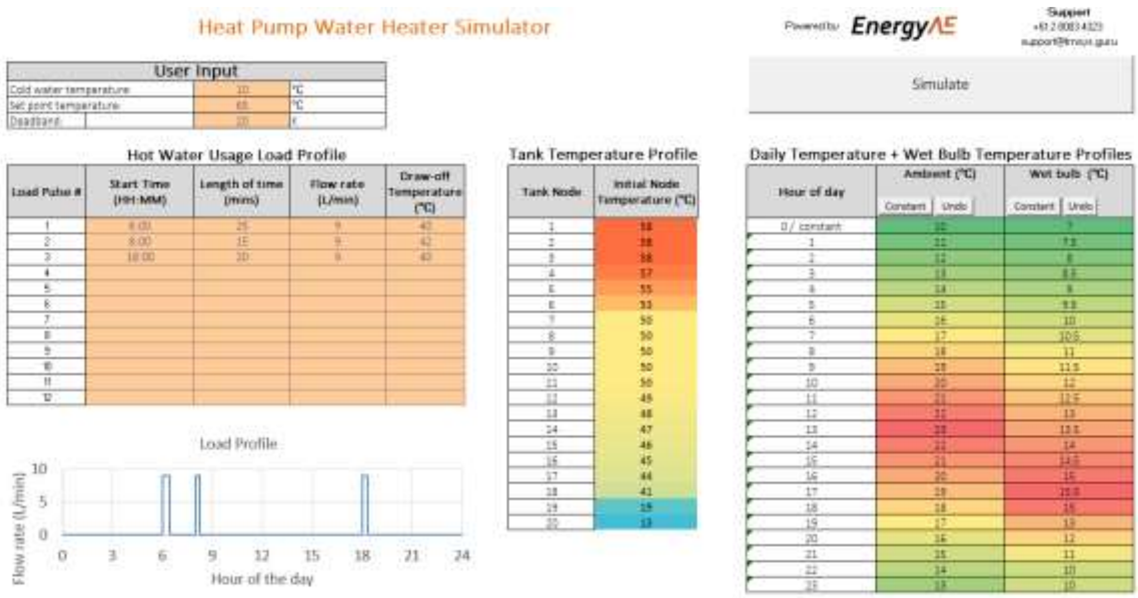

Figure 1. User interface to the TRNSYS model in Excel

The results from the simulation are also imported into the Excel environment for analysis as shown in Figure 4.

The tank is modelled by dividing the 300L capacity tank into 20 equi-spaced imaginary layers called "nodes". The temperature of each of these nodes is determined through an energy balance approach, calculating the temperature of the 15L nodes based on the balance of incoming and outgoing energy through the node boundaries for each time-step. The time-step of the simulation is 1.2 minutes.

The modelling method for heat input from the tank to the water depends on the heating method. Electric elements are modelling by an auxiliary heat input to the node(s) in the tank corresponding to the position of the element. Gas recirculation is modelled by the additional inflow and outflow of hot and cold water. Heat pumps are modelled with a flow heat exchanger that is calibrated to achieve the correct heat transfer. The results in this paper correspond to an integral heat pump tank, modelled with a heat exchanger.

The graphed results and an animation of the nodal tank temperatures provide a visual analysis of the water heater performance. However, these results alone cannot provide a comprehensive indication of temperature-exposure history.

The next stage in the procedure is the post-processing of this nodal tank temperature data to track the temperature-exposure history of individual nodes of fluid through the tank, driven by the applied hot water loads, and thermal mixing interactions between layers.

2.2. Temperature-exposure Algorithm

VBA code is used to develop the algorithm that post-processes the simulation results to determine the temperature-exposure history of each node of water that is drawn from the tank. The algorithm tracks the maximum temperature of each water parcel, the movement of water through the tank due to draw-offs, and degradation of temperature-exposure history due to mixing.

2.2.1. Maximum temperature tracking

This is the basic process that occurs for each time-step, when no draw-offs are occurring, and the conditions for mixing are not met. The algorithm steps through time, and keeps track of the highest temperature that each water parcel has reached. The amount of time that each layer of water has spent above several temperature limits is also tracked. The temperature limits in this paper were set to 55°C and 60°C respectively.

The knowledge of both maximum temperature, and time spent above these two temperature levels are equally important to assessing the temperature-exposure of the eventual water draw-off.

2.2.2. Draw-Offs

During a water draw-off from the tank, hot water is removed through an outlet near the top of the tank, and cold water enters through an inlet near the bottom of the tank.

A "tank node" is defined as a fixed position in the tank, but as water moves throughout the tank, so too does the temperature-exposure history related to parcels of water.

Once one tank node volume of water has been drawn, the temperature-exposure history for that parcel of water is reported in the results table. One tank node volume of cold water is introduced to the bottom of the tank, by initialising the maximum temperature of that water as equal to the cold water temperature, and the time that the water has spent above 55°C and 60°C to zero minutes. The temperature-exposure history of all intermediate nodes in the tank are shuffled upwards in the tank to reflect the movement of this water upwards.

2.2.3. Mixing

During heating, as the temperature of a layer of fluid approaches the temperature of the layer immediately above it, the two layers can roll together. This is due to the buoyancy of the lower layer overcoming the forces separating the two layers. At this point large scale mixing occurs potentially contaminating treated hot water in the upper layer with cooler water from lower in the tank. The mixing mechanisms at work are shown in Figure 2. For domestic scale vertical tanks, the temperature difference between layers at which mixing occurs is typically between 3K and 5K.

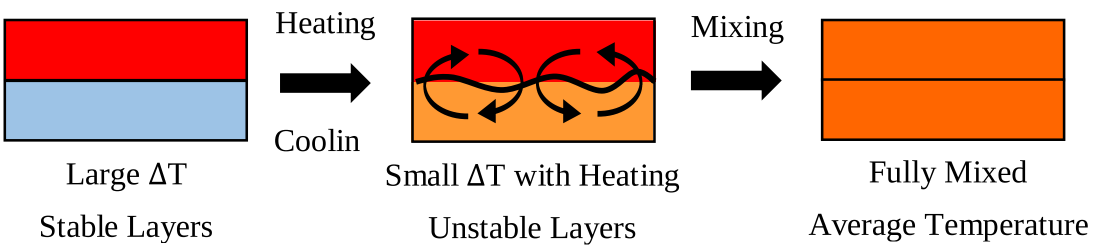

Figure 2. Mixing mechanisms

However, when layers approach this temperature difference, fluid does not always mix completely. It is quite conservative to assume that when two layers mix the temperature-exposure time history of the top layer is completely degraded to that of the lower layer. A dimensionless parameter called the Mixing Coefficient is defined to allow the extent of mixing to be varied, ranging from 0 for no mixing to 1 for total mixing (Davidson et al., 1996).

- A mixing coefficient of 0 is equivalent to the layers not mixing at all, in which case both layers maintain their existing temperature-time history.
- A mixing coefficient of 1 is equivalent to the layers completely mixing, in which case the top layer's temperature-time history is set equal to that of the bottom layer. Note that this may be too conservative in some cases.
- A mixing coefficient of between 0 and 1 results in partial mixing. In this case a new temperature-time history is calculated for the upper layer based on:
  - A mixing coefficient weighted average of the adjacent layers' maximum temperature values, and
  - A selection of either the upper layer's or the lower layer's time above 55°C and 60°C, depending on whether the mixing coefficient is < 0.5 (upper layer) or ≥ 0.5 (lower layer).

2.2.4. Algorithm Description

The algorithm for calculating the temperature-exposure time results is includes the following steps:

- For each time step of a draw-off (or load pulse), the total volume drawn from the tank during that time-step of the draw-off is calculated from the flow rate and temperature data, the cold water temperature, and the hot outlet temperature of the tank.
- The number of tank nodes required to complete each draw-off are then determined, and the fraction of a tank node this corresponds to per time step (draw-offs are often spread over multiple time steps) calculated.
- When a tank node is drawn-off, the temperature-exposure time history of all of the nodes below it are shifted upwards. The temperature-exposure history of the drawn-off node is recorded in the results table, and new cold water entering the bottom of the tank begins with an initialised temperature-exposure time history.
- For each time step where there is no node drawn-off:
  - The maximum temperature of each node is updated if the current tank node temperature is higher than the previous time step's maximum.
  - If the heat pump is operating, and therefore the tank is heating, each node is checked from the bottom up to see if it is about to mix with the layer below it (as defined by Delta T). If it is, then the mixing coefficient is used to:
    - Define a weighted average of the maximum temperatures achieved,
    - Choose between the upper and lower layer's values for time above 55°C and 60°C, and
    - Assign these values to the upper layer.
  - The counters for time spent above 60°C and 55°C are then incremented if the current tank node temperature is higher than these thresholds.
- Once a draw-off is complete, the overall results statistics are calculated, and the percentage of the draw-off that achieve 60°C and the total volume of the delivery are recorded in the results table.

Finally, the overall percentage of water that achieved 60°C for at least one time-step is reported.

2.2.5. Use of Algorithm with Measured Data

In this paper, the temperature-exposure algorithm has been applied to data generated from a mathematical model. This is useful for a theoretical tank to assist in design features of the hot water system. This algorithm may also be used with real measured data as an input. Data from temperature sensors positioned at intervals throughout the height of the tank may be used as an input to the algorithm, allowing water quality as a result of heating and mixing to be determined in real time. This would accommodate the fluctuating hot water loads that a real hot water tank experiences, allowing the tank control system to limit unsafe draw-offs in the event of over-demand causing water to be insufficiently treated.

3. Results and Discussions

In this section, the exemplar load profile in Figure 3 is simulated, and the temperature-exposure results for this case study are analysed in detail.

Hot Water Usage Load Profile

Load Pulse #	Start Time (HH:MM)	Length of time (mins)	Flow rate (L/min)	Draw-off Temperature (°C)
1	6:00	25	9	40
2	8:00	15	9	42
3	18:00	20	9	40
4				
5				
6				
7				
8				
9				
10				
11				
12				

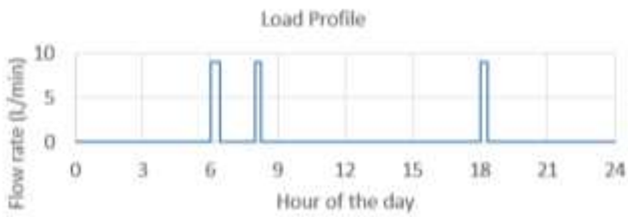

Figure 3. Exemplar load profile

Results of the algorithm are presented in tabular form, as shown in Table 1. For each separate draw-off, the following statistics are shown:

- Volume of water delivered from the tank (L)
- Percentage of the delivered volume that achieved a maximum temperature of at least 60°C
- The maximum temperature of each 15-litre parcel of water that exited the tank (°C)
- The time at which each 15-litre parcel of water spent above 55°C and 60°C (minutes)
- The volume of each water parcel that left the tank (final portions of water delivery are often less than 15L)

Table 1. Temperature-exposure results for a model

Model_1 Temperature Exposure Times - Results

Calculate the temperature exposure time of water draw-offs from the hot water heater system.
Input a value for the mixing parameters below, and click **Calculate.**

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Select a Model: Model_1
Delta T: 1 K
Mixing Coefficient: 0.5

Calculate | Clear all | Write PDF Report

Overall >60C: 93%

Draw-off	Tank volume delivered (L)	Draw Vol % > 60C	Exposure	DN1	DN2	DN3	DN4	DN5	DN6	DN7	DN8	DN9	DN10	DN11	DN12	DN13	DN14	DN15	DN16
1	124	100%	Max Temp (C)	65	65	65	65	65	65	65	65	65							
			Time (mins) above 60C	228	230	231	234	235	237	238	242	243							
			Time (mins) above 55C	267	271	273	277	279	283	285	289	290							
			Volume of draw off node (L)	15	15	15	15	15	15	15	15	4							
2	81	74%	Max Temp (C)	64	64	64	63	58	55										
			Time (mins) above 60C	237	237	236	1	0	0										
			Time (mins) above 55C	387	390	392	6	4	2										
			Volume of draw off node (L)	15	15	15	15	15	6										
3	100	100%	Max Temp (C)	65	65	65	65	65	65	65									
			Time (mins) above 60C	375	378	379	381	382	385	387									
			Time (mins) above 55C	411	415	417	421	423	427	429									
			Volume of draw off node (L)	15	15	15	15	15	15	10									

Table 1 shows the simulation results for 'Model_1'. The animation next to the simulation results plot below in Figure 4 is shown at the start of the simulation, time = 0 hours. The temperature at each node is equal to the initial tank temperature specified in the model setup in Figure 1. In the excel interface, the user may step through the results in time and view the animated changing water temperatures in the tank.

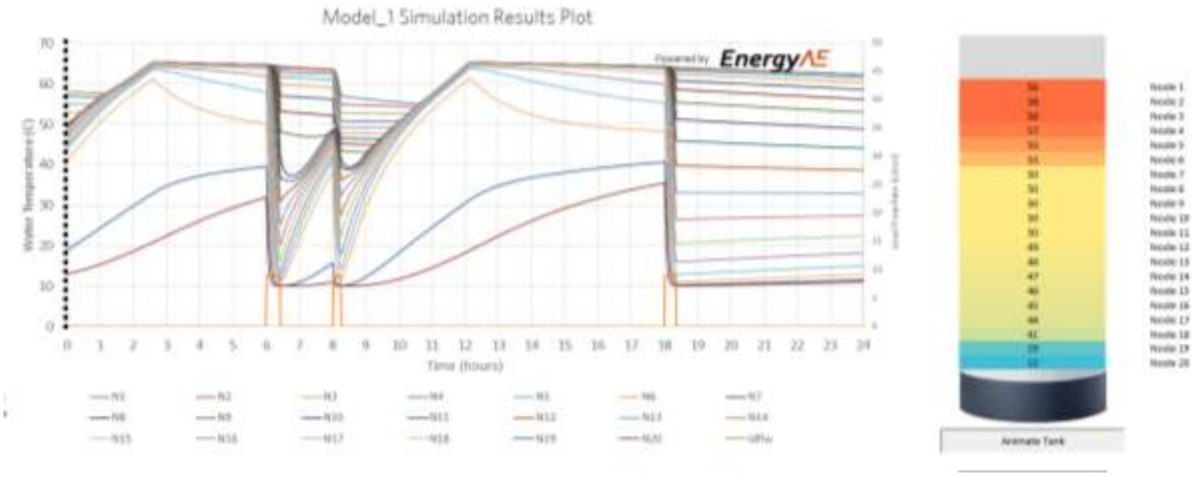

Figure 4. Simulation results plot with animation at time = 0 hours

Moving forward in time to time = 7 hours, a load has just been drawn from the tank, as shown by the orange step function "ldflw" (load flow). The specified flow rate of this load 9L/min for 25 minutes, with a draw-off temperature of 40°C. The actual flow rate and temperature of water drawn from the tank depends on the conditions of the tank outlet, as the flow to the load is tempered by a cold water source of 10°C water in order to meet the required supply temperature and flow-rate.

The tempering valve achieves this by the following equation:

$$\dot{m}_{hot} = \dot{m}_{load} \frac{T_{load} - T_{cold}}{T_{hot} - T_{cold}}$$

Therefore, the actual flow rate from the tank will increase as hot water is drained from the tank and the outlet temperature decreases, and more hot water is required to achieve the same load temperature.

The results in Table 2 show that the total tank volume delivered was 124L. From the graph, the total volume delivered to the load at 40ºC was 9 L/min * 25 min = 225L.

Up until the load was drawn, the top 16 nodes of the tank were above 60ºC about 230 minutes.

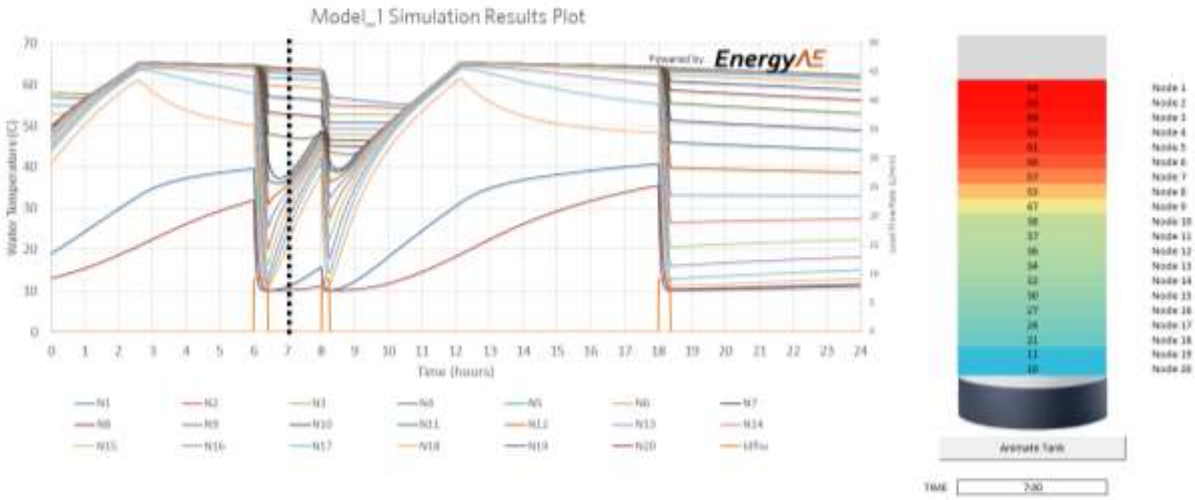

Figure 5. Simulation results with animation at time = 7 hours

This is confirmed by the Temperature-Exposure results table in Table 2. The total volume drawn from the tank was 124L, this equates to eight 15L parcels of water, and one partial 13L parcel. Each of the nine draw-nodes (DN1, DN2, … DN9) display maximum temperatures of 65°C, and approximately 230mins spent above 55ºC and 60ºC, as expected. Since all nine of the draw-nodes have maximum temperatures above 60ºC, the percentage of water drawn that reached at least 60ºC ("Draw Vol % > 60C") is reported as 100%.

Table 2. Temperature-exposure results for the first draw-off

Draw-off	Tank volume delivered (L)	Draw Vol % > 60C	Exposure	DN1	DN2	DN3	DN4	DN5	DN6	DN7	DN8	DN9
1	124	100%	Max Temp (C)	65	65	65	65	65	65	65	65	65
			Time (mins) above 60C	228	230	231	234	235	237	238	242	243
			Time (mins) above 55C	267	271	273	277	279	283	285	289	290
			Volume of draw off node (L)	15	15	15	15	15	15	15	15	4

Draw-offs of partial nodes are dealt with very carefully in the algorithm. At every 1.2-minute time-step, a record of the exact volume that has been drawn from the tank is known. When 15L has been drawn, the statistics for this draw-node are written to the results table, and the temperature-exposure history of all nodes is shifted upwards in the virtual tank.

For the final (partial) node, the statistics for this final portion of fluid is reported regardless, but the temperature-history of all nodes is only shifted if at least 7.5L (half of the 15L parcel) is drawn. This is not the most conservative approach, but is believed to the most reasonable approach, especially in the case where there are many small draw-offs which would cause excessive shifting of temperature-exposure history and produce overly conservative results.

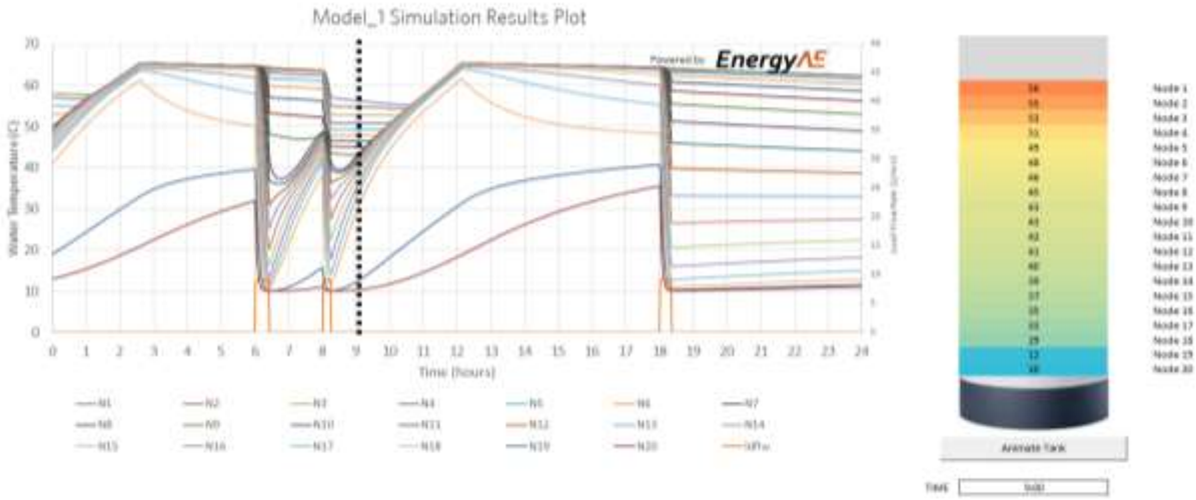

Figure 6. Simulation results at time = 9 hours

Figure 6 shows the state of the tank after the second draw-off. After the first draw-off, sufficient water was drawn from the tank to drop the temperature of the tank below the set-point for the boosting to turn back on. The plot shows the temperature of the lower tank heating up.

At 8AM, the second draw-off begins. As the results in Table 3 show, there is only 60L of water 60ºC or hotter available. After four 15L portions of water (60L) have been drawn, the maximum temperature of subsequent draw-nodes was below 60ºC. Since 60L from a total of 81L has reached a maximum temperature of at least 60ºC, the percentage of water >60C is reported as 74%.

Table 3. Temperature-exposure results for the second draw-off

Draw-off	Tank volume delivered (L)	Draw Vol % > 60C	Exposure	DN1	DN2	DN3	DN4	DN5	DN6
2	81	74%	Max Temp (C)	64	64	64	63	58	55
			Time (mins) above 60C	237	237	236	1	0	0
			Time (mins) above 55C	387	390	392	6	4	2
			Volume of draw off node (L)	15	15	15	15	15	6

A significant amount of time passes before the next draw-off. During this time, the tank continues to heat up until the upper dead-band is reached at 12PM. Heating can also trigger mixing of cooler layers into the warmer layers above due to buoyancy flows driven by the locally heated fluid around the element or heat exchanger.

After this, the tank cools due to tank heat loss, the top layers cool due to tank heat loss and conduction to the layers below, and the bottom layers warm up due to conduction from the layers above, despite tank heat loss.

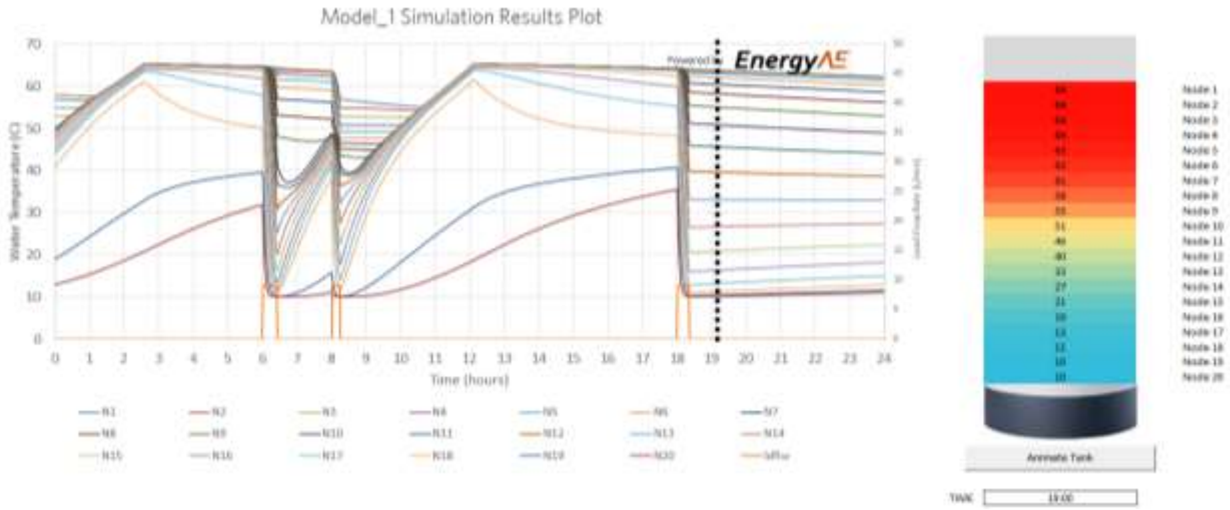

Figure 7. Simulation results at time = 19 hours

At 6PM, the third draw-off begins. Since the tank heated up to the set point temperature 6 hours prior to the load, the tank is fully charged and the 100L, 8-node draw-off has achieved 100% above 60°C for over 370 minutes (6+ hours). This is reflected in the results in **Error! Not a valid bookmark self-reference.**.

Table 4. Temperature-exposure results for the third draw-off

Draw-off	Tank volume delivered (L)	Draw Vol % > 60C	Exposure	DN1	DN2	DN3	DN4	DN5	DN6	DN7
3	100	100%	Max Temp (C)	65	65	65	65	65	65	65
			Time (mins) above 60C	375	378	379	381	382	385	387
			Time (mins) above 55C	411	415	417	421	423	427	429
			Volume of draw off node (L)	15	15	15	15	15	15	10

4. Conclusions

An algorithm has been developed to calculate the temperature-exposure for water passing through a hot water tank.

There are many complex physical interactions that occur inside a hot water tank: heating-induced convection, thermal instabilities causing mixing and internal flows due to draw-offs. Mixing between layers of fluid in the tank occurs during heating operation when the temperatures of adjacent layers are similar. This mixing phenomenon can cause degradation of temperature-exposure history. These processes have been dealt with by a numerical algorithm to estimate the temperature-exposure history of water parcels exiting the tank.

The algorithm tracks the maximum temperature of parcels of fluid, and the time at which they have been exposed to certain temperature thresholds. These statistics help to assess the potability of water in a hot water system.

The algorithm may be applied not only to simulated data, as was done in this paper using a numerical TRNSYS model, but also to measured data from real hot water tanks. This would be particularly beneficial for hot water systems where users are susceptible to legionellosis, thus assisting in meeting the stringent water safety procedures required in hospitals, aged care facilities, and other hot water applications with sensitive users.

The algorithm also has applications in the design of hot water systems that allow secondary water sources that require heat treatment as part of the processing, such as for microbial contamination. The temperature-exposure results can show designers the safe hot water delivery capacity for a tank for a given set of ambient conditions and for a set water load profile. The algorithm would assist in the design of a control strategy to switch between input water sources, control of boost heating and draw-offs.

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