D 7.1.2 – "Heat Recovery Steam Generator Functionality"

"Sub WP 7.1: Power Plants"

"Work Package 7: Model component libraries"

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Dynamic heat exchanger model

Summary

Utilisation of logarithmic temperature difference in a dynamic simulation of a heat exchanger, shortens the execution time and facilitates the initialisation, improves the static accuracy and gives acceptable dynamic properties.

These conclusions are based upon comparison with a segmented heat exchanger models utilizing each segments temperature difference for the heat transfer calculation.

Statically the segmented heat exchanger model converges towards the result of the logarithmic model, by increasing number of segments, while the logarithmic model has no such dependence, or in some cases needs a few segments to become indifferent to adding more.

Dynamically the logarithmic model differs to some extent from the segmented, generally having a too slow rise time, and too long transport time. Applying the logarithmic calculation to each segment and increasing their number eliminates these differences at the cost of increasing difficulties for initialisation and execution as for any model with many states.

A dynamic simulation of a boiler might well provide valid results with inaccurate component models, as a boiler has controls that force the process to follow desired values. This has been illustrated by comparing the time to reach required steam quality to ST for two different complete boiler models where one had components that all trespassed acceptance criterions of max 10 % rise time deviation, with one where all components fulfilled or where very close to fulfil, the resulting start time only deviated with 1,6 %.

In a supplement has also a comparison with heat exchangers from the ThermoPower library ben done. That shows that this library has faster execution than the logarithmic models but less accurate dynamics.

General remark: All graphs have seconds on the x-axis.

Acronyms

C	heat capacity of coolant or heatant (=specific heat capacity times mass flow rate) [W]
CCPP	combined cycle power plant
Dead time	the time to rise from initial value to 10 % of the final value.
ΔT	temperature difference [K]
ΔT_{ln}	logarithmic average temperature difference [K]
DelT	model that uses ΔT
LnT	model that uses ΔT_{ln}
HB	heat balance
HRSG	heat recovery steam generator
NA	not applicable
Rise time	the time for any changing variable to rise from 10 to 90 % of the change.
TBD	to be defined
TP	ThermoPower, a free library from Milano polytechnic high school, Casella et al.

Contents

1 Task

Simulation offers a power full tool to design power plants that are capable of handling all operating events, and it also minimizes time from order to commercial operation and could provide support for the operator decisions and supervisions.

Making a simulation model is a challenging task that involves balancing the level of details to the accuracy needed with the constraint that the simulation should executable within an acceptable time frame. The mathematics used must be robust as the limited CPU capacity prevents infinitely small time steps, unlike nature that works fluently and simultaneously in all time scales.

This paper presents a mathematical handling of the logarithmic mean temperature difference (denoted LnT in the following) that is numerical robust and decreases the CPU load substantially compared with conventionally modelled heat exchanger based upon splitting into many segments (denoted DelT) in order to have the correct physical properties.

Thereby the LnT method is a candidate to also dimensioning heat exchangers instead of the epsilon-NTU method as it handles the logarithmic average temperature difference by differential equations instead of cumbersome static iterations, which have been the driver for the ε-NTU method. However this is not studied in this report, it is left as an idea to be further studied.

The report verifies and clarifies the usability of the LnT approach by comparison the DelT by in both cases applying as many nodes (segments) as necessary to have a converged solution (i.e. the result of the model will not change if more nodes are added).

2 Background

2.1 Equations

The steady state heat transfer in a heat exchanger is given by Equation 1.

Equation 1 Steady state heat transfer

$$Q = k \times A \times \Delta T_{ln}$$

where

Q power exchanged [W]

k the overall heat transfer coefficient [$W/m^2/K$]

A heat transfer area [m^2]

T temperature [ºC]
ΔT temperature differences [K]
index
ln notifies that it is the logarithmic temperature difference according to Equation 2

The logarithmic temperature difference is given by Equation 2:

Equation 2 Logarithmic temperature difference

$$\Delta T_{ln} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$$

where index
1 temperature difference between heating and cooling fluids at one end of the heat exchanger
2 the corresponding temperature difference at the other end of the heat exchanger

This formula is rarely used in dynamic simulations as numerical problems arises whenever any of the temperature differences becomes zero or equal, as if ΔT_2 equals zero the logarithmic argument becomes infinite, and if ΔT_1 becomes zero the logarithm is undefined and finally if they are equal the denominator becomes zero and Q becomes infinite. In a dynamic simulation it is rather impossible to avoid passages of such situations resulting in numerical problem that stops the simulation. Major restrictions upon the operating dynamic range for the simulation must be introduced to avoid this. Simulations covering from start to nominal operation, or including huge transients are rather impossible to simulate without making a mathematical fence that takes over the ΔT_{ln} calculation at the critical points.

Another problem is that the outlet temperature must be known when calculating the heat transfer, which is no problem in a steady state situation, but not at hand when inlets are varying. It is wrong to apply Equation 2 in a dynamic situation. The question is how big will the error be, and whether steady state accuracy and dynamic controls could compensate for the dynamic errors introduced.

Normally heat exchangers are instead divided into several segments whereof each temperature difference T_{hot}-T_{cold} is used as ΔT without taking the temperature variation over the segment into account (Equation 3).

Equation 3 Temperature difference

$$\Delta T = T_h - T_c$$

where index
h heatant

c coolant

The corresponding heat transfer for the segmented pipe (DelT) is given by Equation 4:

Equation 4 Heat transfer of segmented pipe

$$Q = \sum_i k_i \times A_i \times \Delta T_i$$

where index
i runs over all segments from end to end of the pipe

This makes the calculations numerical robust and they handles easily shifting heat transfer directions, and by having many segments the solution closes in to the real heat transfer given by Equation 1 and 2. The drawback is that each segment adds 4 states (two each for heatant and coolant) to the simulation and could give numerical problems by the share size of the equation system for the simulator to solve. For the purpose of building full scale nuclear or combined power station simulations, there is a need to keep down the number of states to have executable models.

Another option is to apply the NTU method but it only gives the steady state heat transfer based upon the maximum possible heat transfer for the actual input data and does not involve any dynamics. These have to be added by associating the heat transfer with volumes (nodes) and pressure losses, giving the dynamics of mass and energy flows. However to have a proper transport time impact upon the dynamics in combination with the correct steady state properties requires a number of nodes (the latter requires a very high number if not NTU or LnT methods are used). As the author of this paper has no experience of the NTU method it is not further analysed in this paper.

2.2 Theoretical and basic aspects of the equations

2.2.1 Static properties

DelT with too few nodes gets a steady state deviation that could be decreased by increasing the number of nodes. Then it converges towards the result of the corresponding heat balance calculation. LnT always gives the same steady state result as the heat balance calculation in cases where there is no phase shifts. If there are a few additional nodes are needed in the range from 2 to 8.

2.2.2 Dynamic properties

Theoretically a segmented pipe with consecutive volumes and flow paths is a multiple low pass filter. Such filter has the following step response (y(t)) for n nodes:

$$y(t) = 1 - e^{-t/T} \times \sum_{i=0}^{n-1} \left(\frac{t}{T}\right)^{i} / i!$$

It has the limit value of zero for any time point when n increases towards infinity, as the summation then becomes the serial expression of $e^{t/T}$. At lower numbers of n the summation is limited and $e^{-t/T}$ dominates and makes y(t) start from zero when the step initiated and becomes one when t is larger than n times T. The transition from zero to one becomes more abrupt with an increasing number of nodes. The dead time increases, while the time to settling decreases, making half the rise time added to the dead time approximately the same as the transport time, see Table 1.

Table 1 Simulated step response for a pipe split into different number of nodes

nodes	*10 % time [s]*	*90 % time [s]*	*Rise time [s]*	*Transport time [s]*
2	6,23	45,41	39,18	25,82
10	14,46	33,62	19,16	24,04
20	17,01	30,53	13,52	23,77
50	19,38	27,92	8,54	23,65
100	20,60	26,65	6,05	23,62
200	21,46	25,76	4,3	23,61

The pipe is 25 m long and has an inner diameter 0,035 m with pure water (1000 kg/m^3) and at the inlet the temperature is raised with a step from 2,13 to 4,52 ºC. The water flow is 1,061 m/s (1 kg/s) which makes the traveling time for the water through the pipe equal to 23,57 s.

The step response for Table 1’s last line with 200 nodes is given in Figure 1, that shows how the temperature increases as a function om time at different positions, (expressed as [nod number] within the 200 nodes pipe).

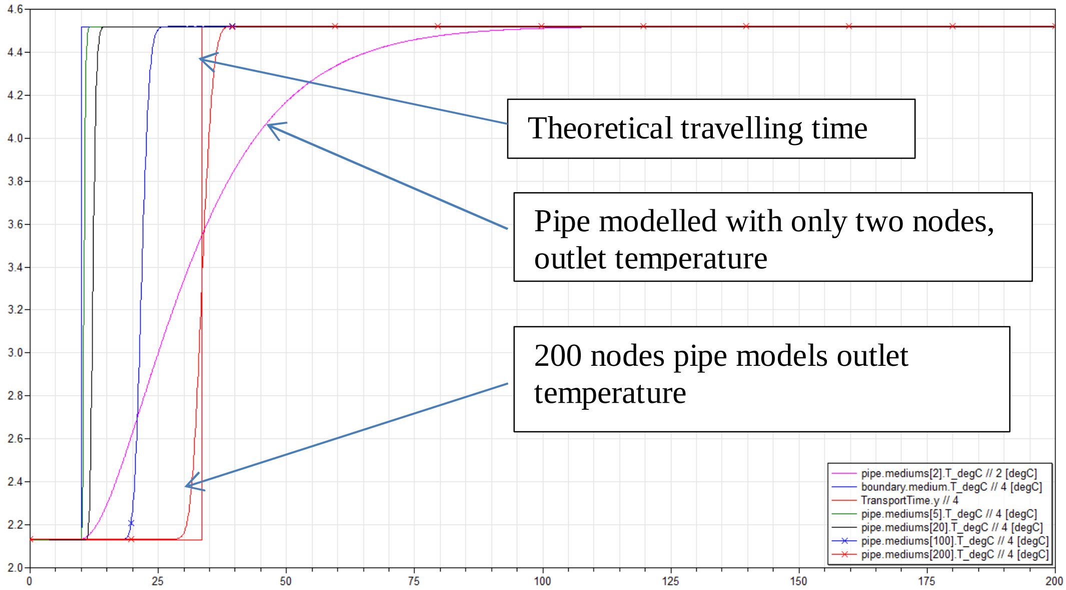

Figure 1 Temperature [°C] propagation along the pipe modelled with 200 nodes at step change at inlet. For comparison a 2 node version of the same pipe (lilac) and the theoretical transport time (red) is added.

In Figure 1 the travelling time from inlet to outlet for the mass flow is market with a red line at 23,6 s (25 m at 1,06 m/s with the step initiated at 10 s), and the good agreement with the real traveling time and the simulated for a 200 nodes pipe is clear, and that a model with only two nodes does not at all capture the traveling time. The increasingly diffused input steps travelling time could be given as the average time of the 10 and 90 % times, see Table 1. This measure of the traveling time is rather independent of the number of nodes, but there is a minor increasing agreement with the number of nodes. The problematic property is the rise time, which is very important for calculating dynamics. It shows a significant improvement as the number of nodes is increased, from 2 nodes (40 s) up to 200 nodes (4 s). This makes it rather necessary to calculate with as many nodes as possible to have reliable dynamics.

A conclusion must then be that a segmented pipe consisting of consecutive volumes with flow elements in between (to capture the pressure losses), requires a considerable number of segments to be dynamically realistic.

An LnT based heat exchanger will only have one segment in order to have fast execution and easy initialization. Hence the transport dynamics will be much too smoothed to be realistic. On the other hand for a heat exchanger the heat transfer impact by altering temperature differences adds to the dynamics, and here the LnT could be expected to be too fast as the actual inlet and outlet temperatures are used without awaiting the propagation of the changed inlet values. This phenomenon acts compensatory for a too slow rise time in some cases, but the outcome is complex depending upon coupling and size of changes.

A simple test for at heat exchanger water to water with where the heatant has a step change from 21,2 to 45,1 °C in one second is shown in Figure 2.

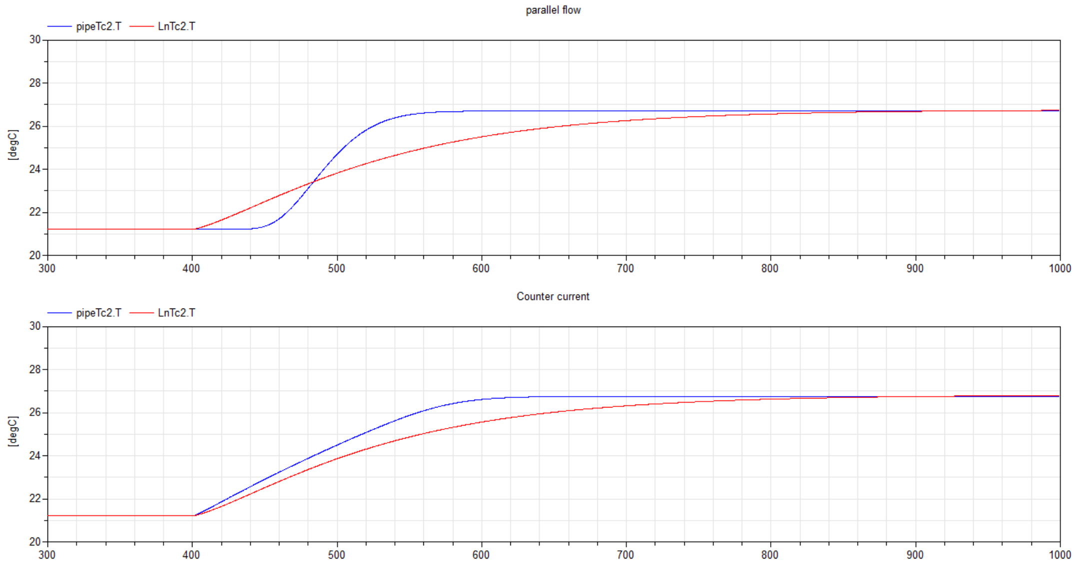

Figure 2 Step change for parallel and counter flow for DelT and LnT models

The LnT model has only one node while the DelT has 20. The lack of transport time in the parallel flow for LnT is apparent, while in a counter flow the response curves are more similar. The transport time is 120 s on the coolant side and 64 s on the heatant. The resulting temperature response for DelT has a transport time of 96 s while LnT has 150 s. Apparently is that for a parallel flow arrangement LnT deviates a lot from a DelT, while for a counter current the deviation is less but still obvious.

If the change is slower than the slowest transport time the differences diminishes (Figure 3), but it is still apparent.

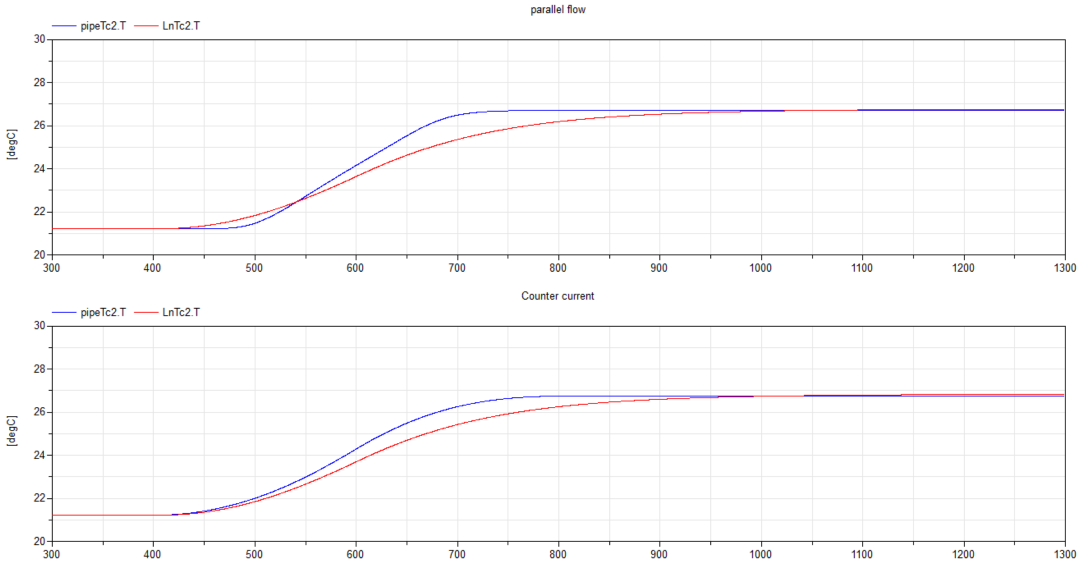

__Figure 3 Ramp change, slower than the slowest transport time__

A final example that shows rather overall good agreement is given in Figure 4, while the transport time delay is still clearly visible.

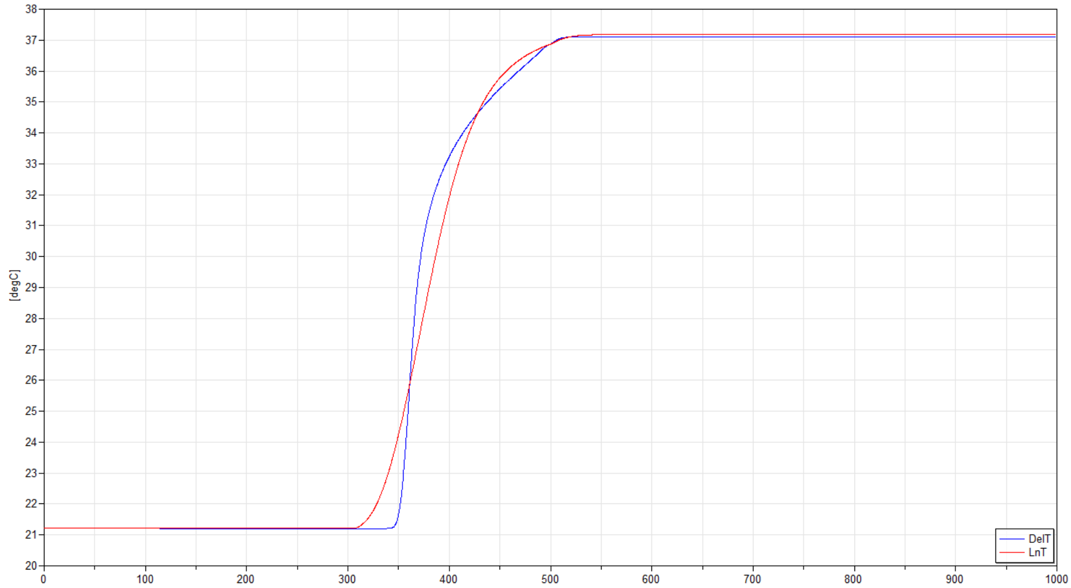

__Figure 4 Short traveling time compared to change duration, parallel flow__

In Figure 4 the traveling time for the coolant is 2.9 s and for the coolant 12,5 s, while the input changes takes 200s. The LnT starts as expected immediately while DelT catches up and is then again passed by LnT to finally reach the final value nearly exactly. The outcome for different cases is numerous, and in case of boiling phenomena the single node LnT is surely disqualified, and not even the assumption that LnT gives the correct steady state is valid according to Figure 5 where boiling occurs on both sides of the heat exchanger.

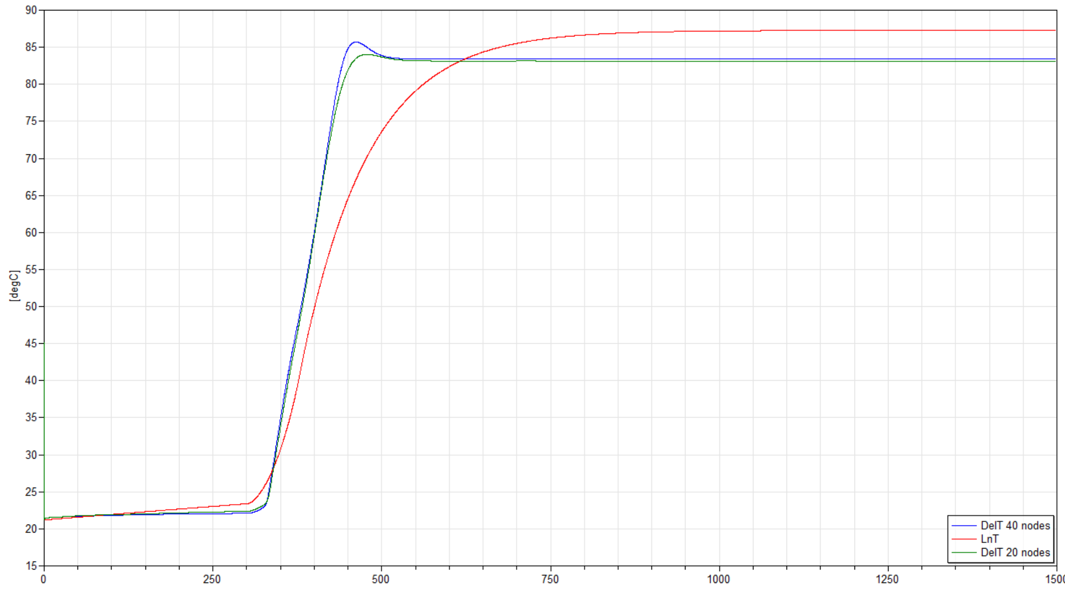

Figure 5 Heat exchanger outlet temperatures, parallel configuration

The DelT converges towards a lower temperature than LnT gives. This is caused by that the heat transfer of all heat to the LnT volume will not give the same result in the steam properties as in a real pipe where the pipe end experiences totally different properties compared to the inlet end. Figure 6 gives the huge differences in the mass flows in and out of the heat exchanger.

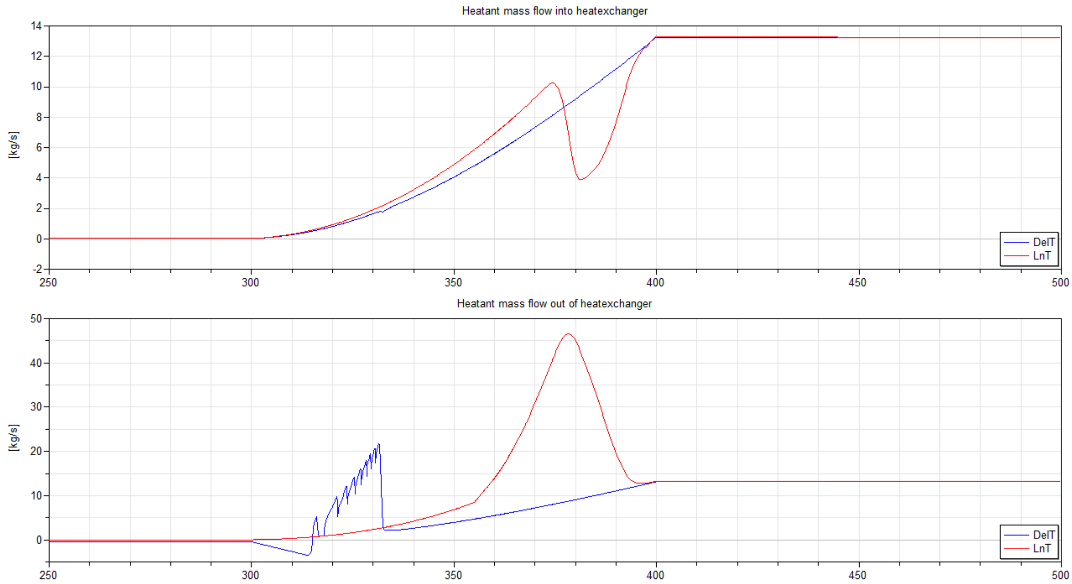

Figure 6 Mass flows in and out of the heat exchanger

The oscillations in flow for DelT is caused by the boiling, where the higher number nodes gives nodes with expanding and condensing steam giving pressure pulses that influences the mass flows. For LnT fewer nodes give a much calmer flow, but apparently a huger part of the pipe gets heated to steam, thereby emptying more mass flow to the outlet. Which result that is the more correct could be shown by expanding the number of nodes until more nodes does not change the result. The point is just that LnT and DelT could differ a lot and both methods are dependent upon the number of nodes used.

The only option to picture the transport time is to apply a transport time delay function or by adding sufficient number of nodes. The transport time delay function is not suitable as this will not reflect the continuous heat transfer during the passage of the exchanger. More nodes are the only option.

There is no hindrance in applying LnT to each node if a heat exchanger is split into several. In order to have correct dynamics also the LnT will have to work with several nodes. The question for this report then becomes how many and are there then still executional advantages, as the LnT calculation is a bit more complicated than the DelT. The difference in execution times will be presented in the continued investigation.

With the above shown variation in outcome, how will an LnT catch a real HRSG boiler dynamics? Apparently it will not be identical, but with the short travelling times on the flue gas side the dynamics might be acceptable and the gain in initialisation effort and execution time considerable.

2.2.3 Heat exchangers dynamic properties

For the interest of simulating complete combined power plants only heat exchangers working with flue gas as heatant and water/steam as coolant will be studied in this report. Characteristics of a HRSG are banks with many parallel tubes for the coolant and a cross flow of flue gas over the bank. The passage time of the flue gas for each bank is nearly zero as the speed is 10 to 20 m/s, while the length in the flow direction is only in the range of one or two meters. The coolant tube length could be in the order of 50 to 500 m and the water velocity could range from a few m/s up to the steam speed that could be 20 m/s. The passage time is than for the coolant in the range a several hundred seconds down to a few seconds.

Dynamically changes on flue gas side immediately affect the whole tube bank, while changes on the tube side could have a considerably settling time.

Both concurrent and counter current arrangements of the tubes are used, i.e. the change could start from both sides of the heat exchanger. Another phenomenon is the varying properties of the coolant as it is heated from sub cooled water to super-heated steam, making the velocities and heat capacities vary a lot. These influences need simulations to see the outcome on the use of LnT or DelT.

2.2.4 Discriminating between the methods

This report will investigate some realistically dimensioned heat exchangers for a HRSG to compare LnT and DelT by execution time and accuracy.

When results differ it is assumed that DelT is always dynamically more correct (if it shows static convergence with number of nodes) than the LnT, and vice versa for steady state properties, with the exception in cases where phase shifts occurs during the passage of the heat exchanger. This is not expected as the economiser works only with water in normal cases, will the evaporator works with mixed phase and the super heaters with steam.

The process for the investigation will be a theoretical one with constant heat coefficient, regardless of changing flow conditions and media properties in order to have only differences in the calculations method of LnT and DelT highlighted.

In reality the heat transfer to and from the separating wall is dependent on Reynolds, Prandtl and the heat conductivity of the heatant and the coolant. Those numbers vary dynamically along the flow path and single or few segments (nodes) will deviate from reality, regardless of method used. In this investigation it is assumed that the difference found between LnT and DelT will be valid also if the heat transfer was realistic. Note that the investigation is using reliable heat balance values to calibrate the used constant heat transfer coefficient.

LnT calibrated to give a correct answer in steady state, then reveals how much k deviates at other loads due to change media properties. This is not an aspect of interest for this report.

3 Test description

3.1 Scope of tests

Following test will be carried out:

1. 120 s loading in the gas turbine, from 50 to 100 %, with simultaneous changes of all four input variables. A fairly realistic case.
2. 10 s loading in the gas turbine, from 50 to 100 %, with simultaneous changes of all four input variables. This fast load change is not realistic. It is mostly to provoke the models to see if differences become larger in extreme cases.
3. Test 1 with unloading
4. Test 2 with unloading

5. Test 1 for the economizer with changed input data to have a phase shift of the coolant from water to 2-phase to steam. This case is normal in once through boilers but is a failure in operation for a drum boiler, where the phase shift takes place in the drum, while the evaporator should only work with 2 phase water at boiling temperature. The economiser should only handle sub cooled water.

The 4 first tests will be carried out for following components
1. Economiser
2. Evaporator
3. Super heater 1
4. Super heater 2

By applying tests 1 to 4 on the above components a variation in geometrics will catch the importance of coupling (all are counter flow except evaporator), and sizes – thereby covering very short travelling times (super heater 2) to very long (economizer).

4 LnT model description

4.1 Design method

The LnT model will be first run with 16 nodes to set the static reference level for the 50 % load temperature at coolant outlet. This high number guarantees that a model with more nodes will not alter the steady state temperature. The coolant outlet temperature at 100 % load is tuned after the heat balance by tuning the k-value of the flue gases to the tubes, which dominates the overall heat transfer coefficient.

The tuned k-value is kept constant during all transients and all load levels, hence at any other load than 100 % there will be a deviation from the heat balance value. But for this investigation the constant k-value will be accepted as the reality and the LnT coolant outlet temperature at 50 % load will be 100 % accurate.

The steady state criterion will be not to deviate more than 3 % of the 16 nodes LnT temperature change.

The number of nodes for will be chosen as few as possible not to deviate more than 10 % of the dynamic reference set by the DelT model, and of course also the steady state criterion must be fulfilled but that is expected to be fulfilled when the dynamic criterion is fulfilled.

4.2 Model description

Following pictures describes the LnT model. Figure 7 Shows the top level of the test bench with the sources for coolant (water/steam) and heatant (GT exhaust gases).

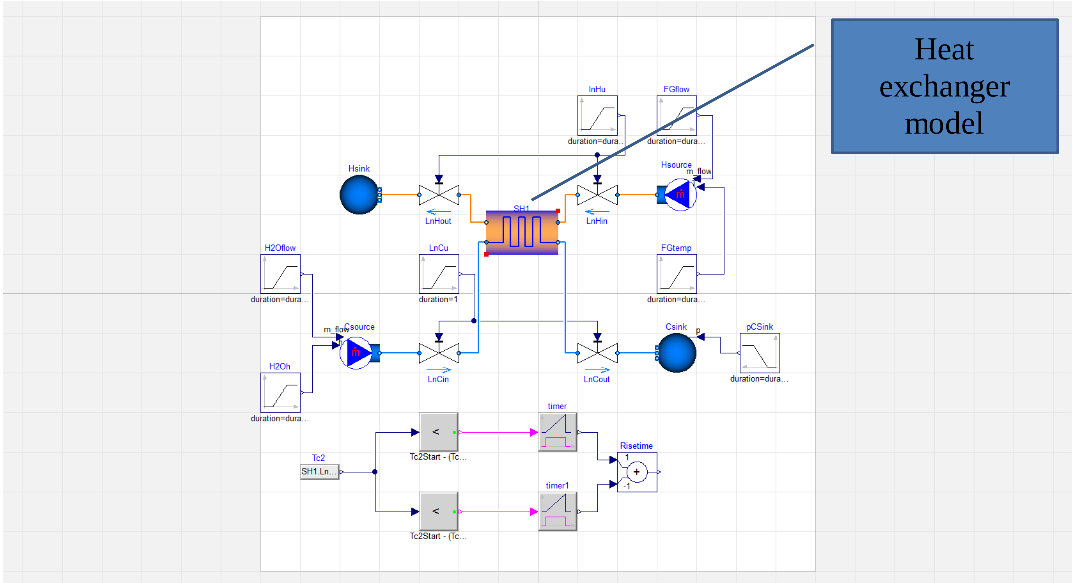

Figure 7 Top level of test bench for LnT model

The heat exchanger connected to the sources and sink of the heat exchanging medias are presented in Figure 8.

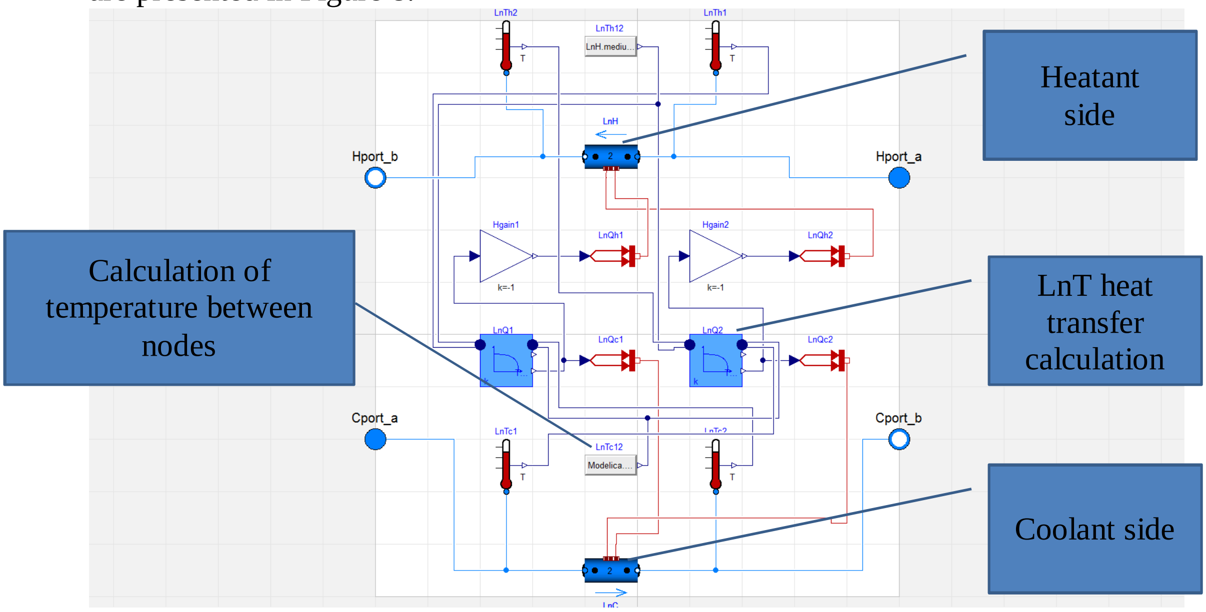

Figure 8 "Heat exchanger model with two nodes in counter current configuration"

All components are from the MSL library except the LnQ1 and LnQ2 that calculates the heat transfer [W]. This component is presented in Figure 9.

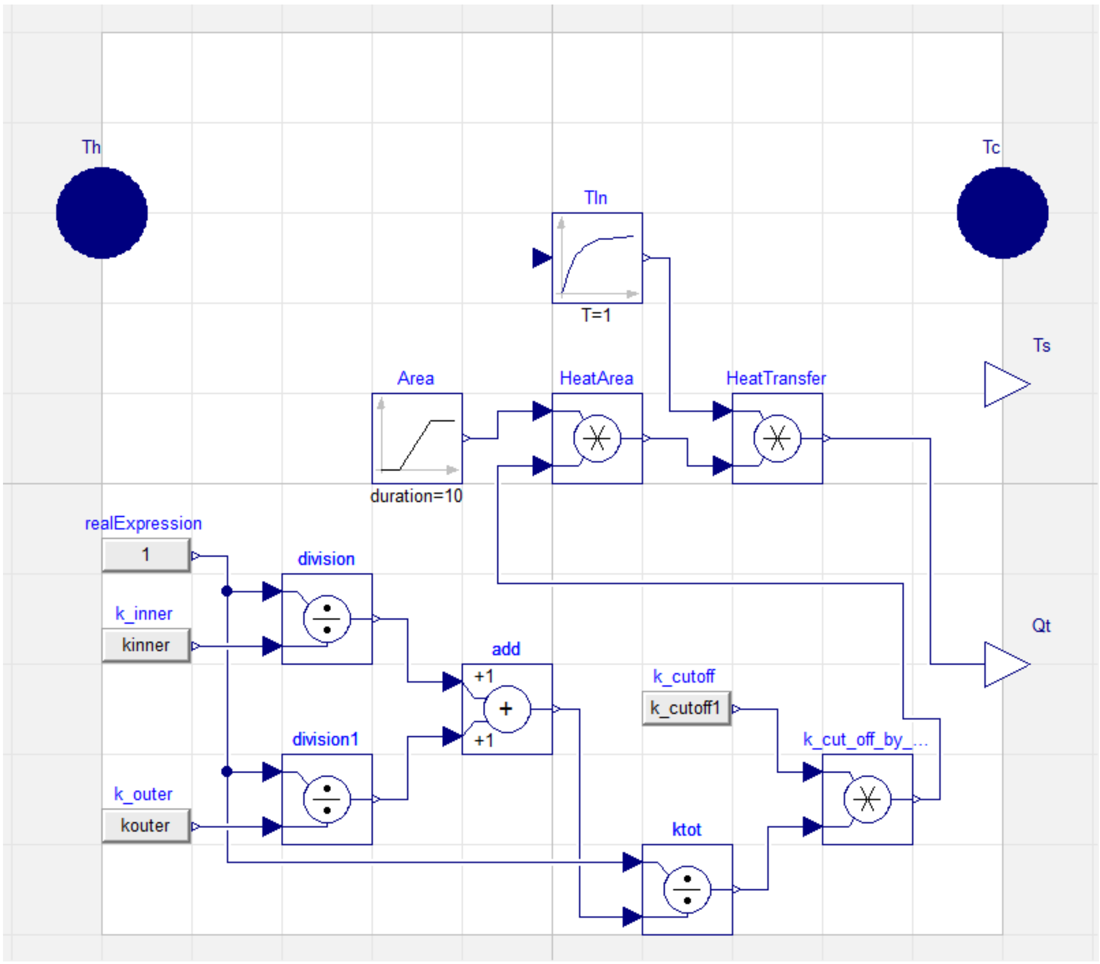

Figure 9 "Graphic view of LnT heat transfer calculator"

All components in Figure 9 are from MSL. The Tln filter has it inputs from the text view. This is a simplified calculation where the heat transfer coefficients (k_inner and k_outer) are constant. In other variants they are inputs from other models that use realistic formulas based upon Reynolds, Prandtl and media heat conductance values.

The text view of the LnT heat transfer calculator contains the following text:

```
model Q_of_lnT_and_k_b "Q_of_lnT_and_k_a with constant heat transfer"
  parameter Boolean cocrnt = true
    "flag for co curent or counter current heat exchanger";
  parameter Real delTlim = 0.1 "switch over point for delT";
  parameter Real delTzero = 0.001 "value of working delT at real delT=0";
  parameter Real b = -log(delTzero) "cut off bias parameter";
  parameter Real a = (b + log(delTlim)) / delTlim
    "cut off proportional parameter";
  parameter Real kouter = 500 "outer heat transfer coefficient";
  parameter Real kinner = 500 "inner heat transfer coefficient";
  Real delT1;
  Real delT2;
```

```
 Real Th1h;
 Real Th2h;
 Real Tc1h;
 Real Tc2h;
 Real delT1h;
 Real delT2h;
 Real k_cutoff1;
equation
 Th1h = Th[1];
 Th2h = Th[2];
 Tc1h = Tc[1];
 Tc2h = Tc[2];
 // selection of cocurrent or counter current formula
 if cocrnt then
  delT1h = Th1h - Tc1h;
  delT2h = Th2h - Tc2h;
 else
  delT1h = Th1h - Tc2h;
  delT2h = Th2h - Tc1h;
 end if;
 delT1 = max(delTzero / 2, min(Modelica.Math.exp(a * delT1h - b), delT1h));
delT2 = max(delTzero, min(Modelica.Math.exp(a * delT2h - b), delT2h));
 Tln.u = SOL3_0.Utilities.HeatTransfer.lnTa(delT1, delT2);
 //Average surface temperature, not used
 Ts = (Th[1] + Th[2] + Tc[1] + Tc[2]) / 4;
//Power cut off function
 k_cutoff1 = max(0, min(1, min(delT1h / delTlim, delT2h / delTlim)));
end Q_of_lnT_and_k_b;
```

The SOL3_0 is the special library developed at the Solutions department at SIT AB. Here only the LnT calculation according to Equation 2 is used to calculate the input to the filter in Figure 9.

The intermediate temperature between nodes on the coolant side (water medium) is calculated with:

Modelica.Media.Water.IF97_Utilities.T_ph(LnC.mediums[2].p, LnC.mediums[1].h)

This formula is used to avoid using the upstream node temperature as inlet temperature to the downstream node, as the pressure loss in between has no enthalpy loss; hence the temperature changes as the pressure decreases. On the heatant side this is not accounted for as the pressure dependence is negligible.

5 DelT model description

5.1 Design method

The DelT is first run with as high number of nodes as possible to set the dynamic reference for the LnT. The rise time of that model will be regarded as the criterion of the true dynamic property. At high number the steady state criterion will be fulfilled (will be checked in each test). In order to have a feasible CPU time consumption that will run in combination with other models to form a complete boiler and still have accurate steady state level, the heat transfer coefficient k of the flue gas side will permitted to deviate 10 % of the value tuned for the 16 nodes LnT reference case.

By allowing this k- value deviation the DelT will provide an acceptable steady state level with considerably fewer nodes, that could make it feasible also as a component in a larger model, but the deviation between the methods will increase.

The 10 % error in k ought to be an acceptable accuracy in many cases and applications. The danger is that this unphysical k-value could in other load points give a deviation both in dynamics and steady state levels that are unforeseen and then call for a further elaboration to follow a schedule that adapts it to all load cases, or eventually also become unnecessary.

5.2 Model description

The model is described by following picture.

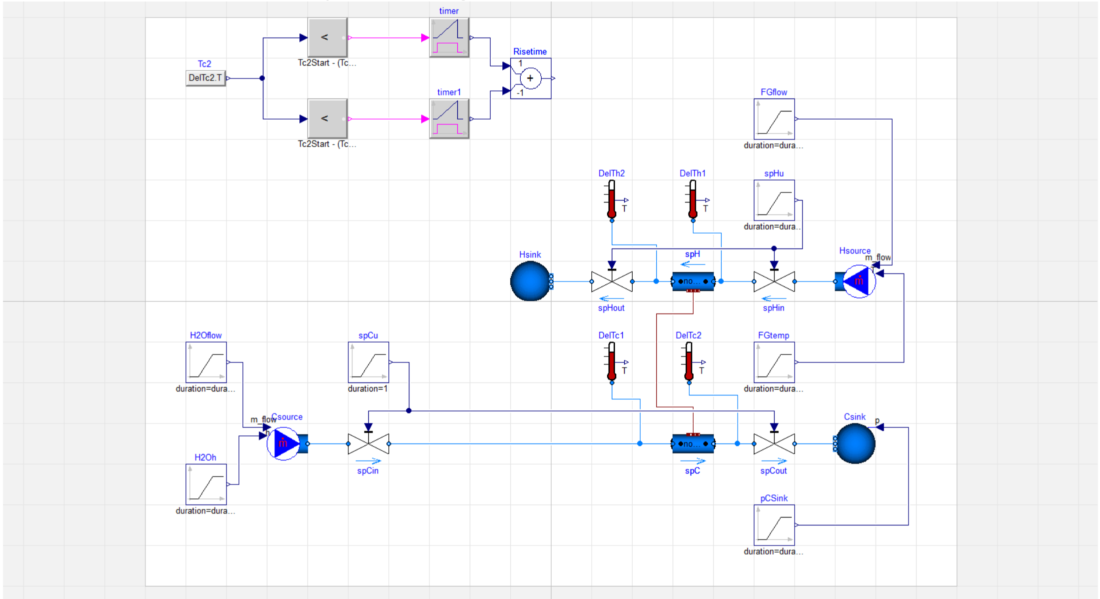

Figure 10 DelT test bench

This model only consist of MSL components and no further details are given (reader is assumed to be familiar with the MSL library.

6 Boiler models data

The used parameters for the different heat exchangers are given in Table 2, identical for both types of models.

Table 2 Heat exchanger geometrics

Heat exchanger	Area [m^2]	Tube length [m]	Outer/inner diameter [m]	Number of parallel tubes	Coupling	Coolant tube smoothness [m]
Eco	7845,0	537,4	0,038/0,0316	15	Countercurrent	3,3e-5
Eva	6577,7	134,9	0,051/0,0446	40	Concurrent	1,035e-4
Sh1	1398,8	57,8	0,051/0,0446	20	Countercurrent	3,31e-4
Sh2	871,6	35,8	0,051/0,0446	20	Countercurrent	2,15e-4

All data in Table 2 are from a heat balance calculation for a drum boiler at 57,7 MW, except the tube smoothness that is used to calibrate the pressure drop over the heat exchanger. As constant heat transfer coefficient is used the staggering, fins geometry and longitudinal and transversal spacing of tubes are of no importance. For the flue gas side geometrics are used that give approximately 10 mbar pressure drop over the tube banks at 100 % load, as the c_p value is not sensitive to the pressure, only to the temperature.

Media properties are by NASA for the flue gases and IAPWS/IF97 for water.

7 Evaluation criteria

The evaluation is based upon the CPU time consumed by LnT respectively DelT for the minimum number of nodes that fulfil the criterions.

8 Results

8.1 Economiser

8.1.1 Load change in 120 s

Figure 11 gives the trends for the economiser where the GT load is changed in 120 s, which corresponds to the final part of a fast GT start.

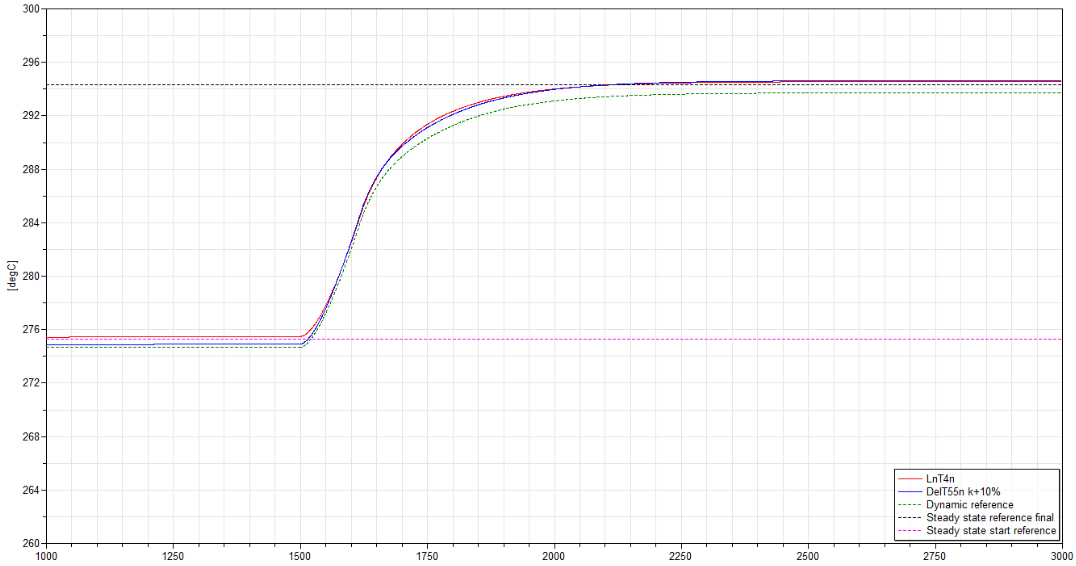

Figure 11 Economiser at GT load change from 50 to 100 % GT in 120 s

The deviations from references are due to a minimizing CPU time for both LnT and DelT.

Figure 12 gives the correspond curves for unloading with the same rate.

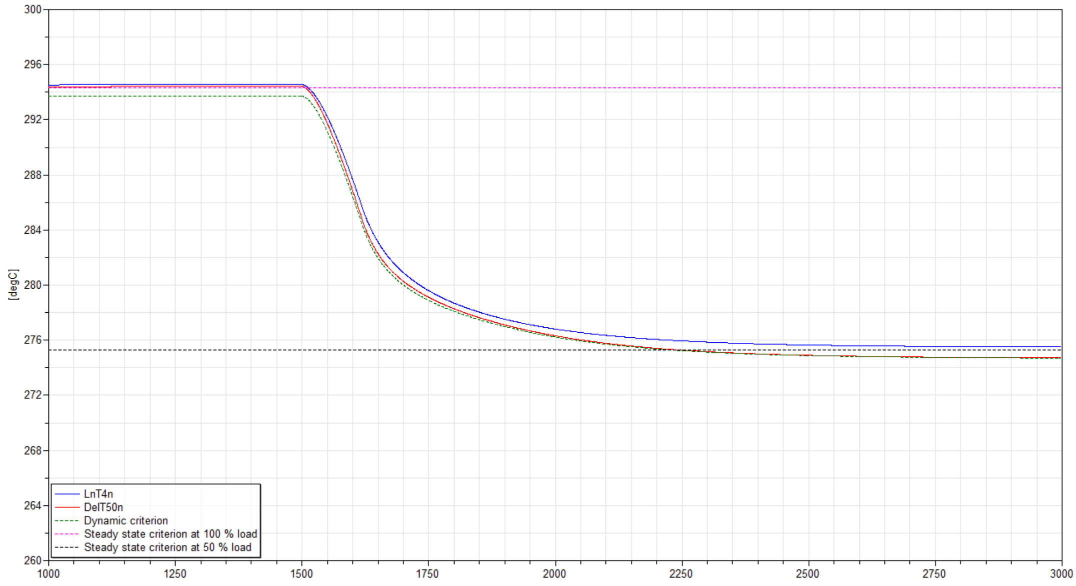

Figure 12 Economiser at GT load change from 100 to 50 % in 120 s

There are differences due to the fact that both models are chosen to give as low CPU load as possible under constraints given by steady state criterion (black and magenta dotted lines) and dynamic criterion (green dotted line). In Table 3 the evaluation figures of the economiser test are given.

Table 3 Evaluated Economiser properties at a 120 s load change

	Criterions			LnT				DelT			
	Rise time	Min Rise time [s]	Max dev [K]	nodes	Max Dev [K]	Rise time [s]	CPU [s]	nodes	Max Dev [K]	Rise time [s]	CPU [s]
Loading	295,9	266	0,57	4	0,257	277,5	5,3	$50_{k+10\%}$	-0,613	296,1	31,4
Unload.	407,1	366,4		4	0,257	370,5	6,2	$50_{k+10\%}$	-0,603	410,7	37,6

In Figure 11 there is an deviation of the dynamic criterions own steady state levels and the steady state criterion of -0,619 [K]. An explanation could be that still more nodes in DelT are needed to reach the LnT steady state level. This has been possible to investigate by improving the initialisation, permitting still more nodes to be simulated. A cumbersome investigation presented in Figure 13 shows how DelT converges toward the LnT level by increasing number of nodes, both the 50 % and the 100 % values. However it's not apparent that an infinite number nodes will give complete convergence - it could also settle at a slightly (~0,2 K) lower value.

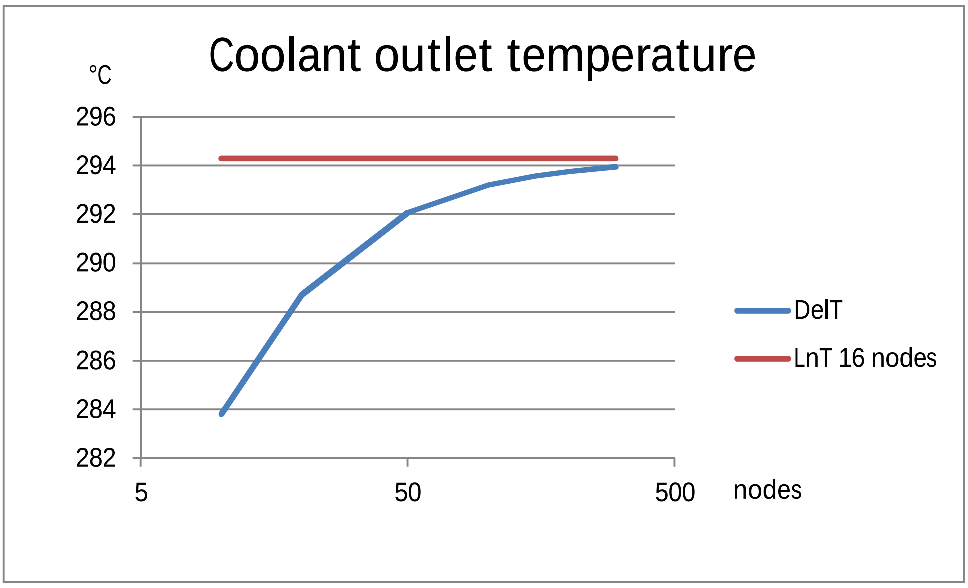

Figure 13 Convergence of LnT (16 nodes) and DelT as function of nodes

A mathematical analysis of the filtering of the segmented pipe gives that every adding of a node also ads a increment of temperature that will have zero as limit when nodes increases towards infinity, but as long as they are not infinity there is a value larger than zero, i.e. by increasing accuracy one will always find that the accuracy will improve by adding another node. Like Achilles and the turtle aphorism, this reasoning does not reveal the limit value, only confirms that infinite accuracy requires infinite number of nodes. Hence it could be ruled out that the limit value for DelT deviates from the LnT and extrapolating manually Figure 13, 0,2 K seems likely to be the limit value for infinite number of nodes. From simulation point to have a 0,2 K difference in the steady state output at 100 % load is a minor problem as there are many other variables constituting the heat transfer, that requires calibration of larger magnitude, like impact of fins, geometrics, turbulence, pressure losses and fouling etc. As also LnT do have some a small trend towards DelT it is possible that total agreement could be reached for more than 16 LnT nodes and more than 500 DelT nodes. A reason for this high sensitivity for the number of nodes (at lower temperature changes not more than 20 DelT nodes are needed to have high accuracy) could be the inherent water properties that make the mathematical description none linear and sensitive to how the model is built.

Also to be noted is that the calibration of k to have correct 100 % value with fewer DelT nodes gives unsymmetrical result as the deviation does not decrease equally much at 50 % load. This could be solved by a load dependent k-value.

8.1.2 Load changes in 10 s

A change to 10 s GT load change makes the same type of result and the same magnitude of the possible CPU load reduction by LnT for loading (Figure 14).

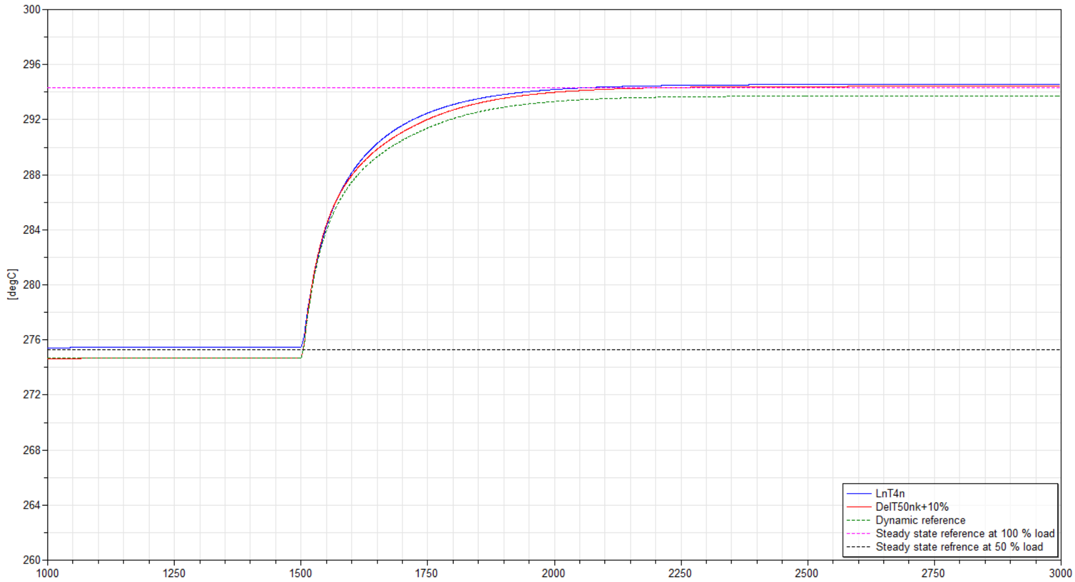

Figure 14 Economiser at GT load change from 50 to 100 % in 10 s

For unloading an interesting phenomena occurs that reveals the sensitivity in simulating steam and water processes. As the DelT has a tendency of requiring numerous nodes to reach up to the same temperature level as the LnT, it reveals a different temperature trend due to the start from a lower temperature. Figure 15 shows a typical display of the differences for the selected models for LnT and DelT at unloading.

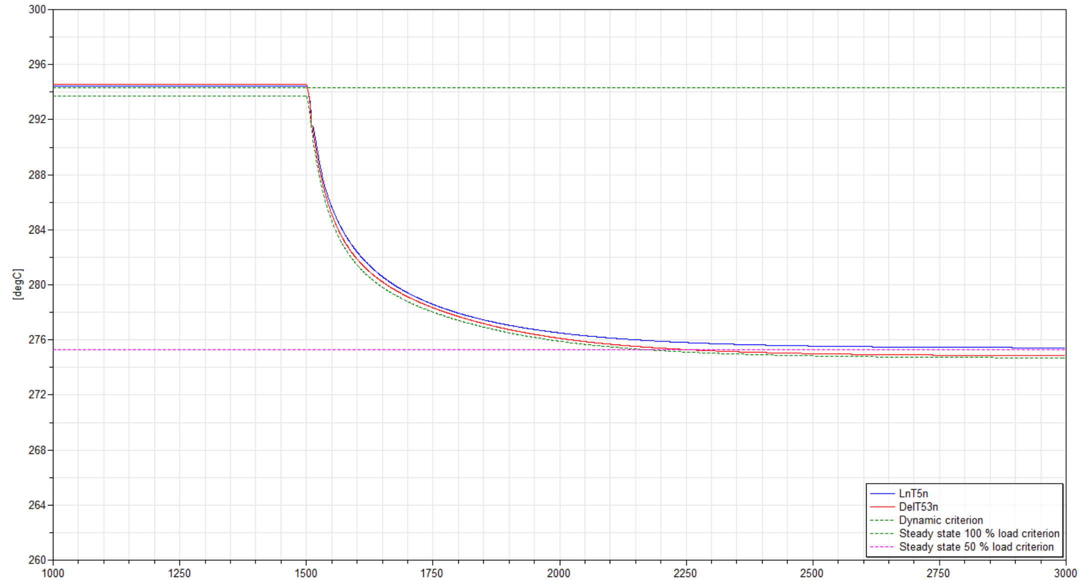

Figure 15 Economiser at GT load change from 100 to 50 % in 10 s

A blow up of the event is shown in Figure 16.

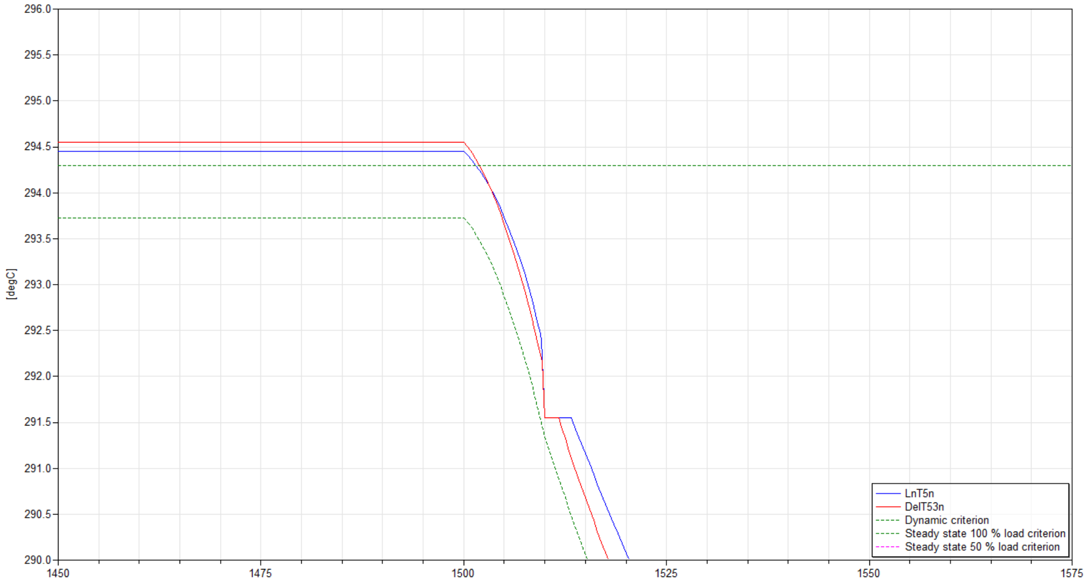

Figure 16 Detail of Figure 15

What happens is that in both LnT (5 nodes) and DelT (53 nodes + 10 % higher heat transfer coefficient) the last segment goes into boiling for a short while. This does not happen with the dynamic criterion simulation with 200 nodes. The reason is that the 200 nodes DelT simulation happens to avoid the phenomena by having a lower temperature at 100 % load. A test with 100 nodes (200 nodes is a bit cumbersome to execute) and raising the heat transfer coefficient for the flue gas side from 61,1 to 64 W/K/m^2 the boiling occurs also for the DelT calculation. For separating between LnT and DelT this is not significant, but it is for selecting parameters of the model (calibrating the heat transfer for the case with necessary accuracy). The LnT with 4 nodes give the approximately same result but the CPU time increases dramatically as the temperature at 100 % is a bit higher.

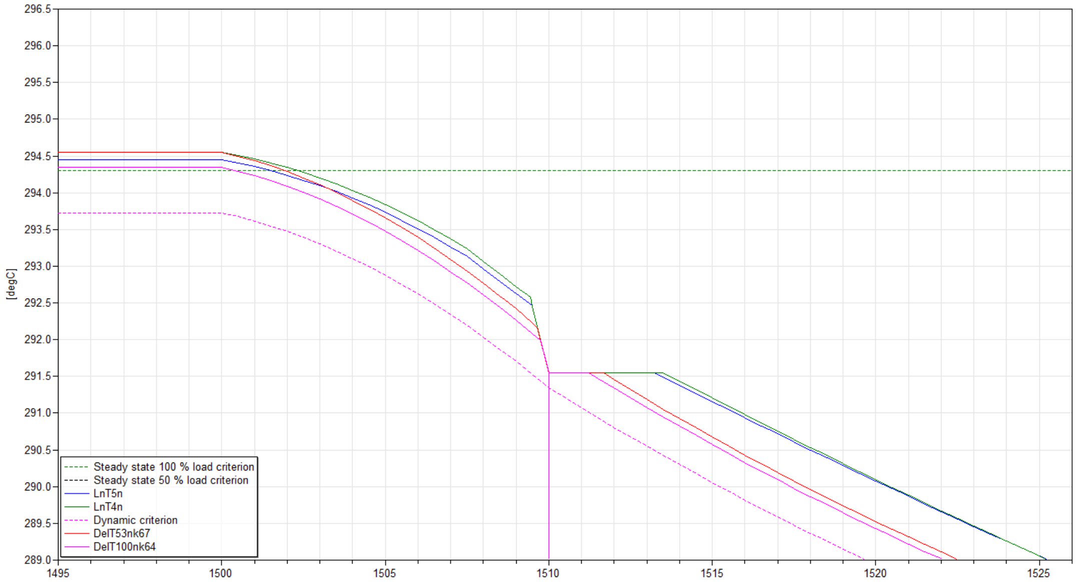

Figure 17 Detail from Figure 15 with adding of LnT with 4 nodes and DelT with 100 nodes and k=64

In Figure 17 one can observe a spike that in fact decreases down to 18 °C and returns in 0,5 ms which illustrates the numerical problem that could arise in boiling phenomena. The overall impact of this is how ever minor. The evaluation data is given in Table 4 for the unloading figures.

Table 4 Economiser data for 10 s load change

	Criterions			LnT				DelT			
	Rise time	**Min Rise time [s]**	**Max dev [K]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**
Loading	270,4	243,4	0,57	4	0,228	252	6,205	$50_{k+10\%}$	-0,614	270,0	32,7
Unload.	382,3	344,0		16	0,003	372,3	17,1	200	-0,614	382,3	230,9
				5	0,151	357,3	7,9	$53_{k+10\%}$	-0,461	385,1	42,6
				4	0,257	384,6	53,6	$100_{k+5\%}$	0,304	384,5	126,2

For the unloading Table 4 gives that having DelT with a too high k-value (illustrated by last line) will bring up the DelT CPU time (the spike alone consumes 33 CPU seconds) but the deviation and rise time is acceptable. The same thing will happen at any number of nodes that are brought up to steady state criterion at 100 % load. 100 nodes are chosen to exemplify this.

For LnT 5 and 4 nodes gives acceptable overall result but 4 nodes due to a higher temperature runs harder into the boiling and consumes more CPU time than any LnT with higher number of nodes (tested up to 32 nodes consuming 39,9 CPU s). Also the rise time deviates from the expected trend of reduction by number of nodes. Hence for sensitive cases the number of nodes are limited downwards also by CPU, not only by accuracy.

8.1.3 Load change for once through boiler

A once through boiler heats water to steam directly in the pipes without using a separating drum. To see how the DelT and LnT handles the same load change from 50 to 100 % GT load is used but the incoming flue gas temperature is raised to 600 °C. The coolant inlet temperature is 60 °C (not shown) and the outlet temperature increases from 280 to approximately 520 °C. The flow sources are maintained the same as well as the outlet pressure, which is a bit unnecessary as the expected outlet pressure of a once through boiler could be expected rather in the range of 80 than 96 bar.

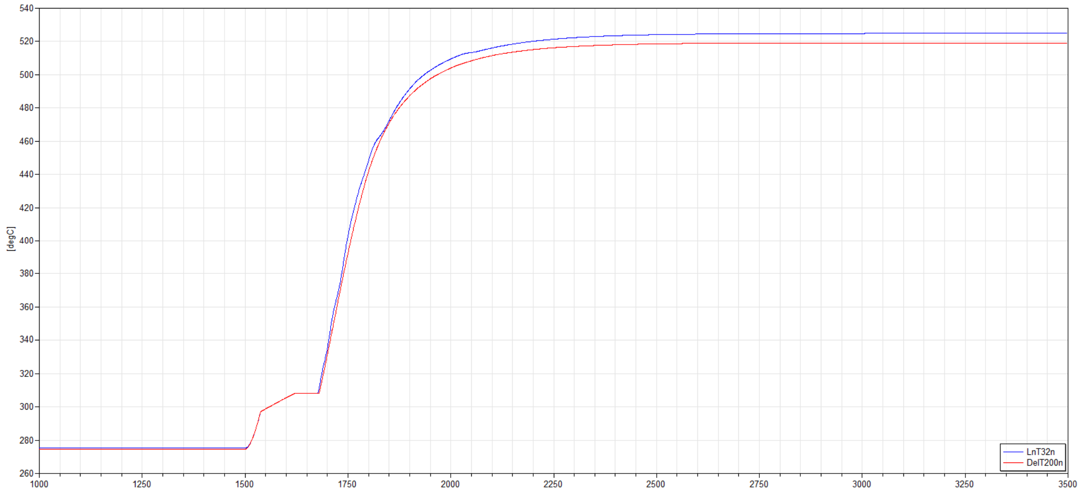

Figure 18 Once through boiler emulation test

In Figure 18 32 nodes are used for the LnT in order to have approximately the same dynamic behaviour as for the DelT, here illustrated by a 200 nodes simulation. Decreasing the high outlet pressure does not decrease the need for nodes to have accurate dynamics with LnT. The high number of nodes (32) one could see as regardless of boiler type the same number of nodes for the complete boiler process is needed (water to steam requires a handful nodes per drum boiler component). There is also a rather high deviation in outlet temperature (6,1 K) between LnT and DelT even at the high number of nodes. But still there is a convergence by increasing the nodes for DelT but not for LnT beyond 16 nodes. This is illustrated in the Figure 19, which presents the power transferred as a function of node number.

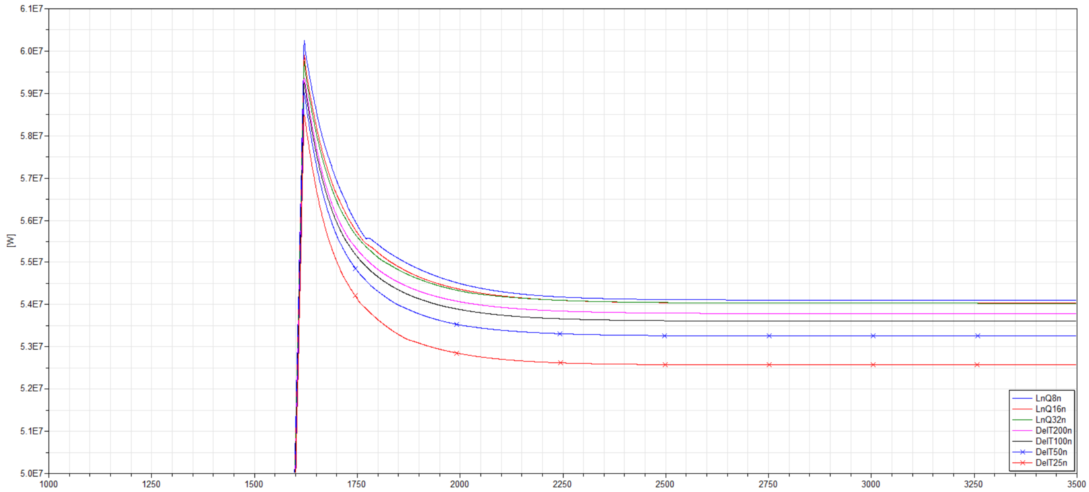

Figure 19 Convergence of LnT and DelT by increase of nodes

However the doubling of nodes for DelT from 100 to 200 indicates that either the complete convergence needs nearly an infinite number of nodes, which is not an entirely implausible conclusion but most likely is that one have to search for another explanation as a remaining difference is indicated by the simulations so far made. Unfortunately it is rather impossible or very time consuming to increase the number of nodes and the convergence looks like it needs many doublings of the nodes to become equal to LnT. One can see that also LnT converges, but from to high temperatures instead. With fewer nodes the outlet temperature and the power transferred increases, but 16 and 32 has the same value and the difference to 8 is minor, while it increases with 4. But the 16 and 8 nodes LnT solution reveals that too few nodes give a difference in behaviour (Figure 20).

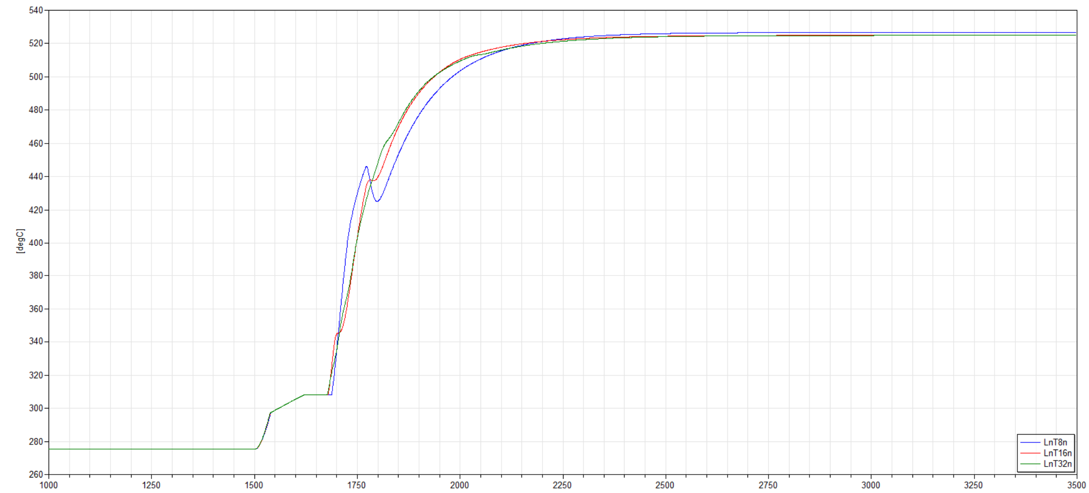

Figure 20 LnT temperature dynamics as function of number nodes used

The oscillation in temperature that is not appearing in DelT or LnT with higher number of nodes could be a result of the lower damping provided by a model with fewer nodes. This is not a boiling phenomenon in the last node as it occurs when that nodes steam already is dry, but boiling is ongoing higher up in the pipe and the fewer nods the more the mass flow and temperature oscillates. It is likely that a small volume that goes into boiling and fast expansion will influence flow less of the neighbouring nodes, than a large node experiencing the same. On the other hand a small volume is more sensitive to changes of the surroundings than a large one. The phenomenon is damped with a higher pressure. In this case the pressure has infinite potential as an ideal flow source is used. A simulation with a fixed pressure source will from this reason be more sensitive and is likely to get numerically stuck if boiling occurs.

The CPU cost for the once through boiler test is given in Table 5.

Table 5 CPU consumption for once through boiler emulation

LnT			**Del T**		
nodes	Steam Temp [°C]	CPU [s]	nodes	Steam Temp [°C]	CPU [s]
4	542,1	7,3	25	490,4	27,3
8	526,6	10,7	43, k+10 %	524,3	54,7
16	524,9	20,4	50	506,6	69,3
20	525,1	42,0	100	514,9	244
32	524,9	85,9	200	519,1	1290

To have the correct steady state level 16 nodes must be used for LnT. Permitting 10 % calibration of the k-value for DelT would permit the use of only 43 nodes, but still this is a CPU factor 2 in favour of using LnT. An argument for using DelT is that 16 nodes show a small (false) oscillating temperature and flow in the boiler. To avoid this 20 nodes are sufficient which only gives a 75 % CPU time reduction in favour of LnT (unfortunately the 20 nodes model has a another division of nodes (16+4) which is the likely explanation to the 0,2 K higher temperature compared to 16 (and 32).

8.1.4 Discussion

The incorrect dynamics for LnT and DelT (chapter 8.1.2) would lead to an increase of both models number of segments which is clearly to the advantage of LnT that calculates sufficient number of nodes with an increase of only 1,7 s (Table 4) while a corresponding result for DelT requires more than 100 nodes (60, 80 and 100 tested without success although the k-outer factor was a bit too low, i.e. the temperature was lower than it should, thereby less likely to boil) indicating more than 100 s in CPU time is needed.

The LnT cost of reducing number of nodes is that the rise time then deviates more from the criterion, so by 4 to 5 nodes the rise time has reached the permitted 10 % deviation from criterion.

The DelT rise time changes very little with the number of nodes. I.e. using a few nodes could give a quick measure of the expected rise time to evaluate the LnT need of nodes.

In the emulation of a once through boiler (no proper dimensions are used, just the economiser has been provided with 600 °C flue gas), indicates that vaporisation of pure water inside the tubes could need so many nodes also for the LnT that calibration of DelT could become equally efficient (provided that the calibration is made for all load cases). On the other hand if the calibration works well then it could be applied also for the LnT that then has a larger potential for low CPU load.

An alternative here for LnT is to have dynamically assigned number of nodes that follows the boiling zone. I.e. more nodes as long as the acceleration of the mass flow due to vaporization is high (the whole or a fraction of the 2 phase region) but fewer nodes as long as there is one phase water or steam, which also might be an alternative for the DelT method. This is not investigated in this report.

8.2 Evaporator

8.2.1 Load change in 120 s

The evaporator works with 2 phase water where the water/steam temperature is constant, varying only with the pressure. Instead the transferred power will be the measurement to compare LnT and DelT. First step is then to find out the steady state criterion, and according to HB following yields at 100 % load:

- Transferred power: 24,915 MW
- Outlet pressure: 90,52 bar

By adjusting the heat transfer coefficient at the flue gas side to 64,89 J/K/m^2 and the roughness inside the tubes to 1,035*10^{-4}, this is achieved for the 16 nodes LnT model. The outlet temperature is then 300,1 °C. There is no measure of rise time to be taken as the temperature follows pressure that increases in the same way as the flow resistance almost regardless of the heat transfer calculation (all models changes synchronised with the load change). A small delay could be noticed that is identical for LnT with 16 n as for all tests with DelT. Fewer LnT nodes increase the delay which is surprising but the difference is minor: less than 0,5 s (for an event taking 250 s to settle at the new operating point). The reason is that the load increase performed simultaneously on both coolant and heatant sides gives in fact a power reduction in the beginning of the heat exchanger and the more aggressive LnT with few nodes picks this up and it gives a small initial power decrease, which is not occurring on the DelT.

Figure 21 shows the power convergence by the number of nodes for LnT and DelT.

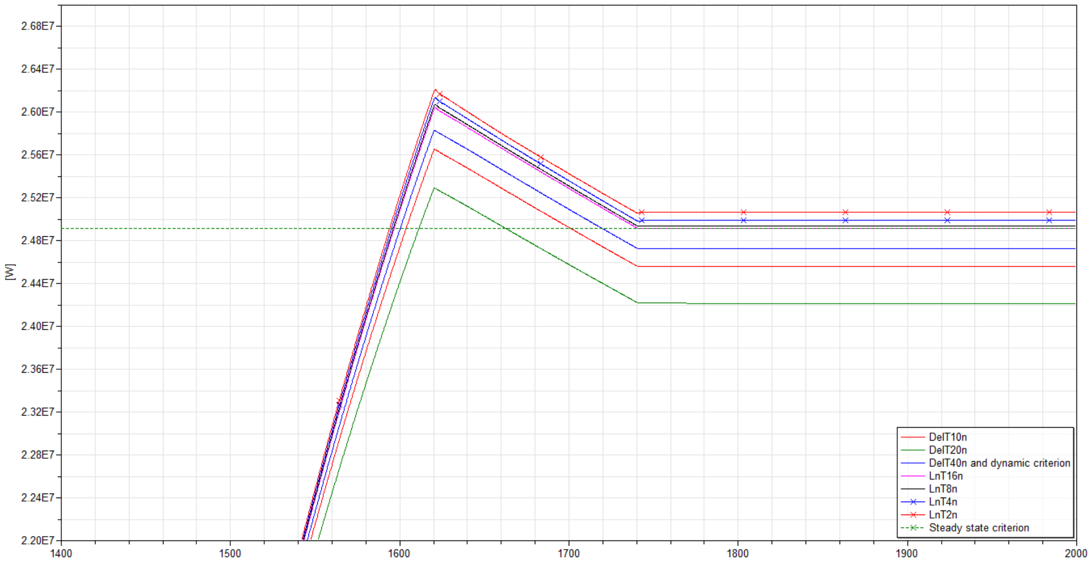

Figure 21 Evaporator load change in 120 s

The evaporator shows the same convergence as noted for the economiser. It indicates that with an infinite number of nodes DelT heat transfer converges towards that of the LnT. Data is given in Table 6.

Table 6 Comparison of evaporator load change in 120 s

LnT			**DelT**		
nodes	CPU [s]	Max power step deviation [%]	nodes	CPU	Max power step deviation [%]
2	7,57	2,68	10	13,7	-11,90
4	9,89	1,30	20	23,2	-6,02
8	14,2	0,39	40	43,5	-3,16
16	23,4	0	80	98,2	-1,76
			20[a]	23,4	1,08

[a]Heat transfer coefficient increased with 10 %

Table 6 reveals that for the evaporator the same number of nodes gives approximately the same CPU time, where LnT has a bit higher value. But to have the same static accuracy the LnT only needs 2 nodes while DelT needs 40. Minimizing the DelT CPU-time by calibration of the heat transfer value, 20 nodes are more than sufficient, as maximum calibration of the k-value brings deviation to pass from negative values to positive. Extrapolating the 7 % improvement at 20 nodes, only 14 nodes should be sufficient to reach – 3 % by allowing 10 % k-value deviation, and hence a CPU time of about 18 s, hence about double CPU time consumption for a k-value calibrated DelT and approximately a factor 5 for a none calibrated DelT.

The dynamics, save the static levels, are identical for both power and temperatures when load changing in 120 s in the 2 phase region (Figure 21).

The initialization part of the CPU consumption increases with the number of nodes. By manipulating the initial equations this could be mitigated to some extent. Simulation without such actions makes any simulation with more than 30-50 nodes impossible. Figure 22 shows the present situation for the DelT and LnT CPU curves when simulation the 120 s unloading. Here both methods utilizes a technique where the heat transfer coefficient start value is zero and increases to full value at a steady pace in 20 seconds. A problem for the comparison is that an optimal initialization might look differently between the both methods. But this will not impact conclusions as Figure 22 shows that the CPU consumption after initialisation (say after the first second) is significant higher with many nodes.

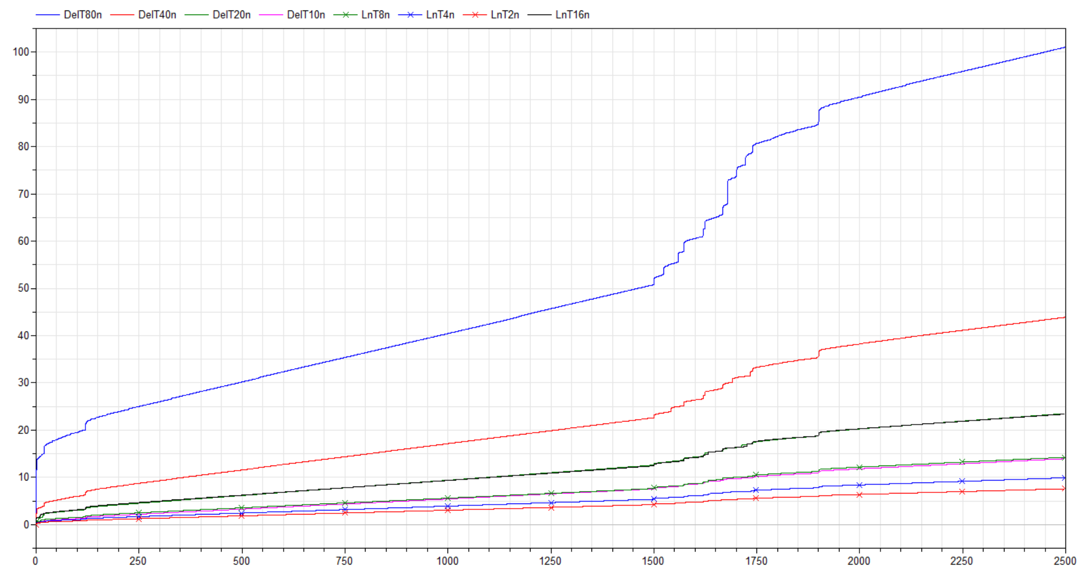

Figure 22 CPU times for 120 s load increase

An unloading in 120 s from 100 to 50 % load gives resembling results with the explicit figures given in Table 7.

Table 7 CPU consumption and power deviations for 120 s evaporator unloading

LnT			DelT		
nodes	CPU [s]	Deviation [%]	nodes	CPU	Deviation [%]
2	7,10	0,69	10	13,5	-5,48
4	9,32	0,41	20	22,5	-2,79
8	14,0	0,14	40	41,1	-1,58
16	25,06	0	80	97,5	-1,01

For the unloading it looks like only 10 nodes would be necessary if k-value calibration is applied, while about 20 nodes are needed without calibration (assuming the same 7 % improvement as for loading with 20 nodes).

8.2.2 Load change in 10 s

For load changes in 10 s there is a difference in dynamic behaviour of similar kind for both loading and unloading (only unloading is shown in Figure 23).

Figure 23 Unloading evaporator 100 to 50 % in 10 s

However the duration of the transient is practically identical and the maximum deviation compensated for the static error is 2 %. Taking also into account that this 50 % to 100 % load change in 10 s is very unlikely to occur, the significance of the dynamic error is negligible in the choice of calculation method.

8.3 Super heater 1 loading test

8.3.1 Load changes in 120 s

At loading from 50 to 100 % the SH1 temperature decreases due to the flue gas temperature from the GT decreases, and the power increases only with 30 % although mass flow increases with nearly 50 %.

SH1 only works with steam and the traveling time is in average 15 m/s both at 50 % and 100 % load, and the traveling time is about 3 seconds. I.e. most load changes has longer duration than the travelling time and the heat exchanger outlet temperatures will to a higher extent be under change simultaneously as the inlets, compared with the economiser and the evaporator. This is believed to contribute to the more akin transients of the DelT and LnT calculations as presented in Figure 24.

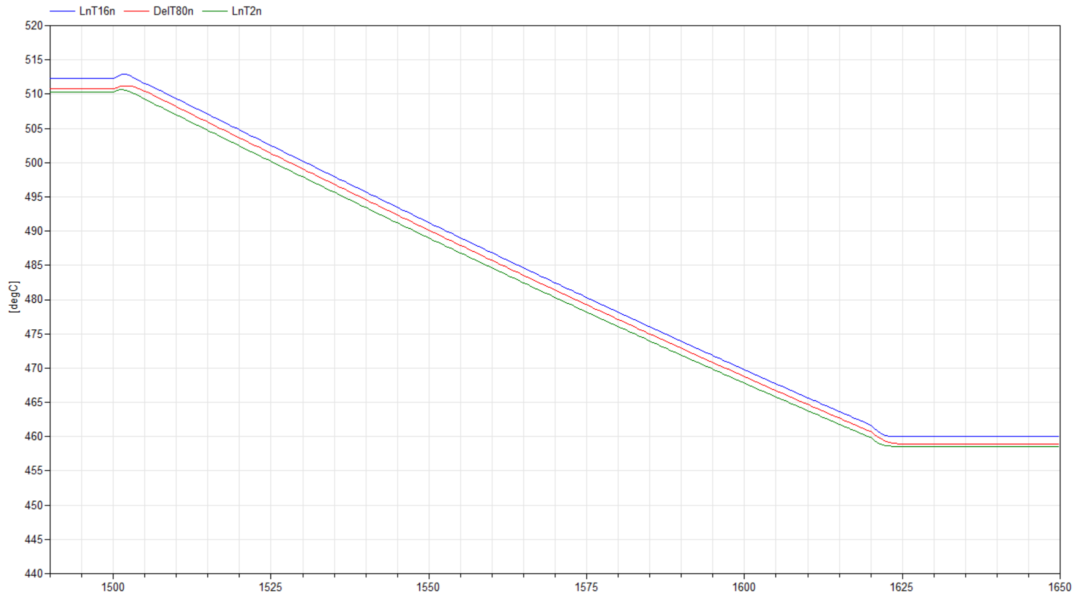

Figure 24 SH1 loading 50 to 100 % in two minutes

Figure 24 show that the dynamics are the same regardless of number of nodes for LnT or DelT, but they cause a steady state deviation. This deviation from the heat balance calculation and CPU consumption is given in Table 8.

Also the unloading gives a similar result (Figure 25)

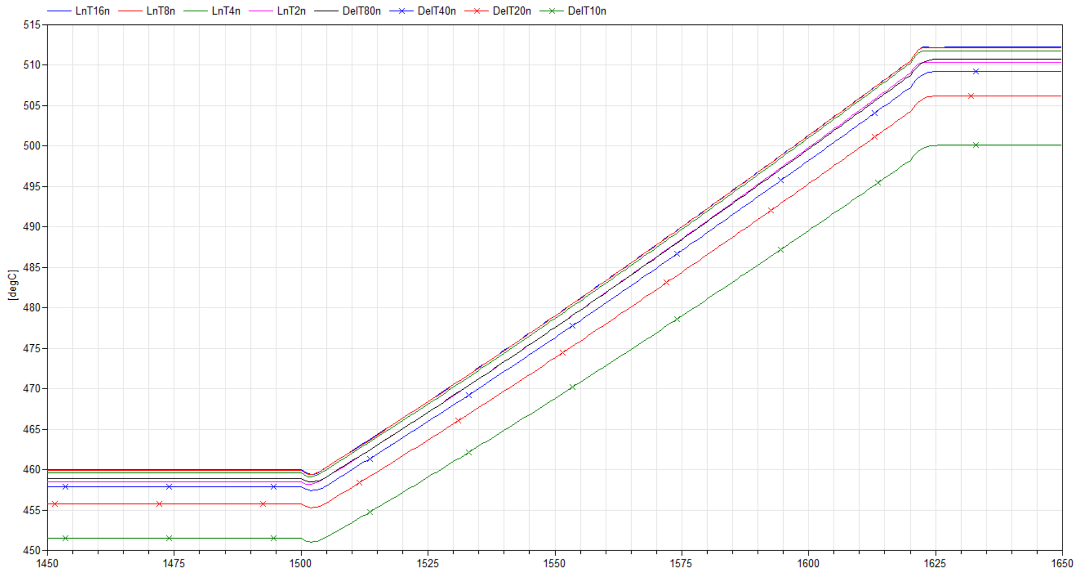

Figure 25 SH1 unloading 100 to 50 % in two minutes

The 16, 8 and 4 nodes LnT coincide dynamically and statically. LnT with 2 nodes gives a too high steady state deviation. For DelT 80 nodes are needed to have acceptable steady state error, while use of fewer needs additional calibration. Table 8 shows the data for LnT and DelT comparison.

Table 8 Super heater 1 comparison data for 120 s load change

	Criterions			LnT				DelT			
	Rise time	**Min Rise time [s]**	**Max dev [K]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**
Loading	95,3	85,8	1,57	2	-1,92	96,2	3,7	10	-12,1	95,8	25,9
				4	-0,480	96,1	5,2	20	-6,00	96,0	19,9
				8	-0,085	96,0	7,6	40	-2,98	95,7	29,3
				16	0,007	96,0	13,0	80	-1,48	95,3	75,9
Unload.	95,4	85,9		2	-1,92	94,9	3,8	10	-12,1	95,4	12,8
				4	-0,480	95,0	5,8	20	-6,00	95,4	16,4
				8	-0,085	95,1	7,9	40	-2,98	95,4	27,3
				16	0,007	95,1	14,5	80	-1,48	95,4	83,7

The rise time is decided by the load change duration as the passage time of the heat exchanger is shorter than that. The aftermath lasts only for 5 seconds after the inlet changes has ceased, and looks identical with the time perspective of the whole event.

A worrying problem for DelT is besides the need for calibration to reach same executional speed as LnT, is that different numbers of nodes requires different initial values. 40 and 80 nodes has the same initialisation while that applied to 20 nodes gives 57,6 s instead of 16,4 s for the unloading. One can also see that 10 nodes loading, that by all experience should have faster execution than 20 nodes (as for unloading), has the result of 25,9 s indicates that more work should pay off to find a better initialisation. Some examples how the CPU time is spent is given in Figure 26.

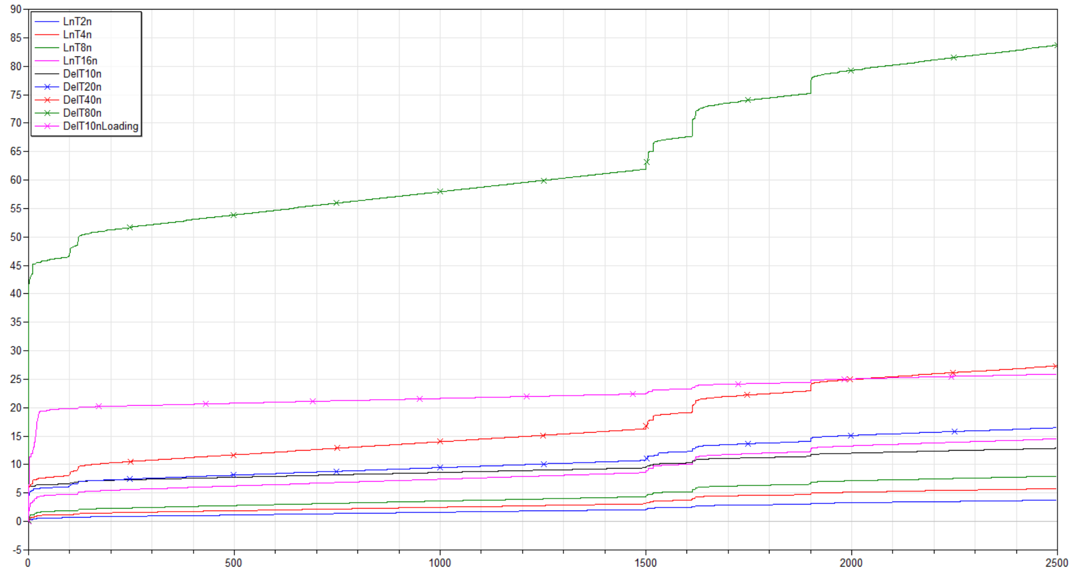

Figure 26 Consumption of CPU-time for SH1 unloading

In Figure 26 CPU curves for the unloading in 120 s is given, but also the deviating 10 nodes loading curve (star marked magenta), that clearly shows that the initialisation is very sensitive for the DelT model and this will be further investigated in chapter 11.5. The impact of number of nodes is twofold:

1. The CPU time gradient increases with the number of nodes (states)
2. The initialization becomes harder and requires more precise values or sophisticated handling

Looking at the CPU time gradients it is clear that it increases monotonously with the number of nodes. The 45 s start time of the 80 nodes DelT simulation could possibly be shortened at lot as well as for the “failed” 10 nodes initialisation at load increase test. However considerably higher effort has already been spent for both compared with the LnT. Using the same initialisation as for LnT will not work for many of the DelT cases, and instead requires some systematic testing to find suitable start values. The application of homotopy operator has not been tested. Worth mentioning here is that also a 16 nodes LnT is more sensitive than a 2 nodes, and in no case the initialisation could be set randomly, and requires homotopy approach by manipulating the properties of the model at the start. This is done alike for both DelT and LnT as a starting point.

Calibration of DelT gives that loading with 18 nodes k increased with 7,1% fulfils criterion both at 50 and 100 % load, with a CPU consumption of 14,5 s. But as noted the simulation initialisation is very sensitive, like changing the pipe start pressure from Krawal value + 10 to +100 pa gives more than 80 s in initialisation time (interrupted). The value will be the same for unloading as here is only the steady state of interest.

8.3.2 Load changes in 10 s

A fast unloading in 10 s from 100 to 50 % with synchronous changes on all inlets gives differences according to Figure 27. To have the differences more conspicuous presented, only two curves are given. They are the first encountered when doubling the number of nodes that fulfils the steady state criterion.

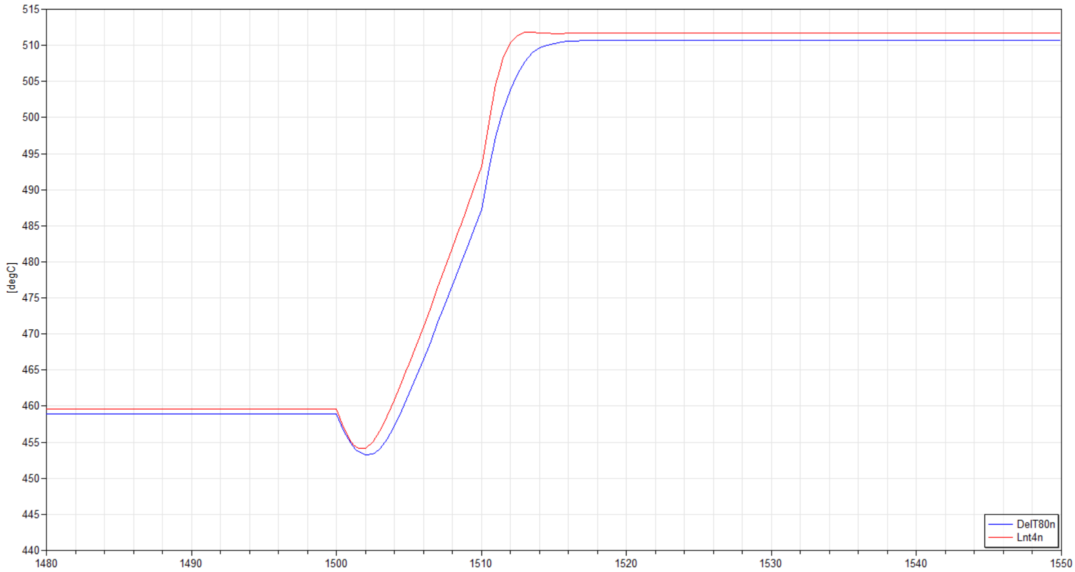

Figure 27 Unloading 100 to 50 % of super heater 1 during 10 s

Remarkably is that without further heat transfer coefficient calibration, 80 nodes are needed for DelT to be within the steady state criterion.

The convergence by applying more nodes is given in Figure 28.

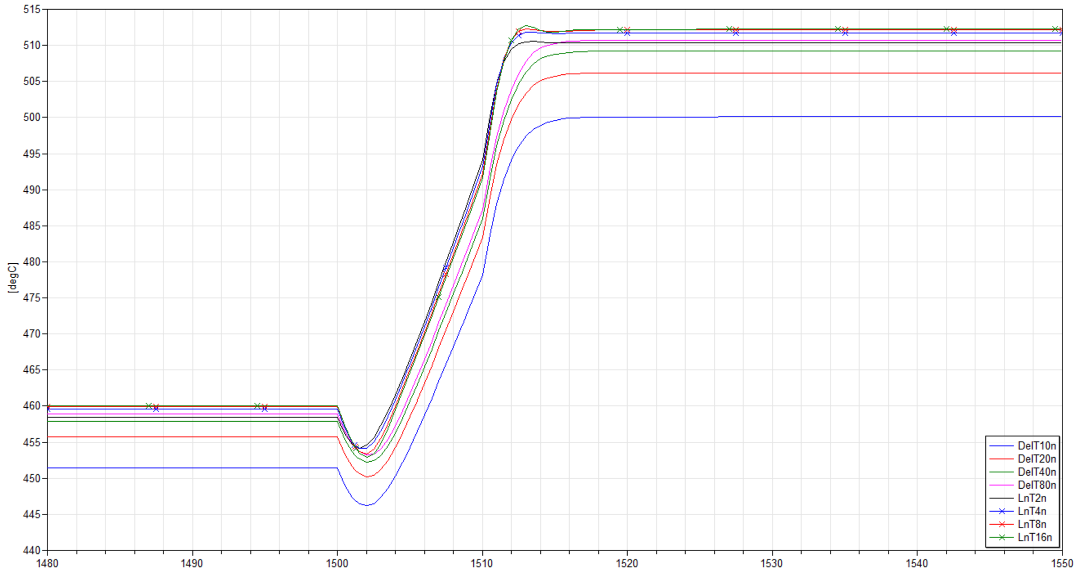

Figure 28 Convergence by node numbers for the unloading in Figure 27

The principal convergence as noted for economizer and evaporator is noted also for the first super heater. A difference could be seen that the settling for the 50 % steady state value does not converge as expected, see data in Table 9, where the unloading rise time for LnT is closer to the dynamic criterion with 2 nodes than with 16 nodes. LnT seems to converge towards a value slightly below 6,3 s, starting at 6,61 s. On the other hand, the appointment of 80 nodes as the dynamic criterion is a bit early as the convergence seems to have a final value much closer, hopefully identical, to that of the 16 nodes LnT. However, even if it should not reach it - all values are within the tolerance limit of the dynamic criterion.

Table 9 Super heater 1 comparison data for 10 s load changes

	Criterions			LnT				DelT			
	Rise time	**Rise time inter-val [s]**	**Max dev [K]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**
Loading	6,95	6,26 – 7,65	1,57	2	-1,92	7,63	3,68	10	-12,1	7,07	9,08
				4	-0,480	7,30	5,03	20	-6,00	7,00	14,9
				8	-0,085	7,08	7,26	40	-2,98	6,97	30,3
				16	0,007	6,98	12,2	80	-1,48	6,95	60,4
Unload.	6,88	6,19-7,57		2	-1,92	6,61	3,70	10	-12,1	6,81	14,0
				4	-0,480	6,44	5,28	20	-6,00	6,84	16,3
				8	-0,085	6,33	7,78	40	-2,98	6,87	27,3
				16	0,007	6,30	13,9	80	-1,48	6,88	72,7

The “none minimum phase” behaviour of the load change (starts with a decrease when the final value is an increase) response is distorting the rise time measure making it less valuable as base for the comparison, and this could be the reason to the differences in convergence for loading and unloading. The transient lasts nearly exactly the same time for all tested model, due to the change duration and passage time relation. By the eye the convergence looks normal.

Also for the 10 s load change the DelT turns out to be very sensitive to start values and each result in Table 9 requires individual values. A minor change of the initial pressure difference over the coolant tubes could prolong the initialization time from a few seconds to hundreds of seconds.

8.4 Super heater 2

8.4.1 Load changes in 120 s

The resulting calculation for loading and unloading is given in Figure 29 and Figure 30.

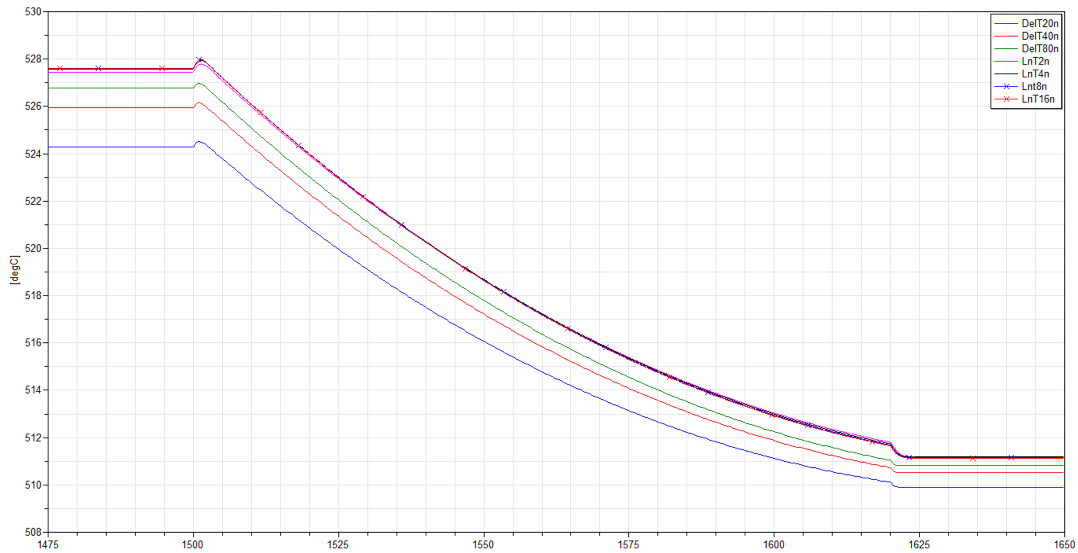

Figure 29 Loading of Super heater 2 in 120 s

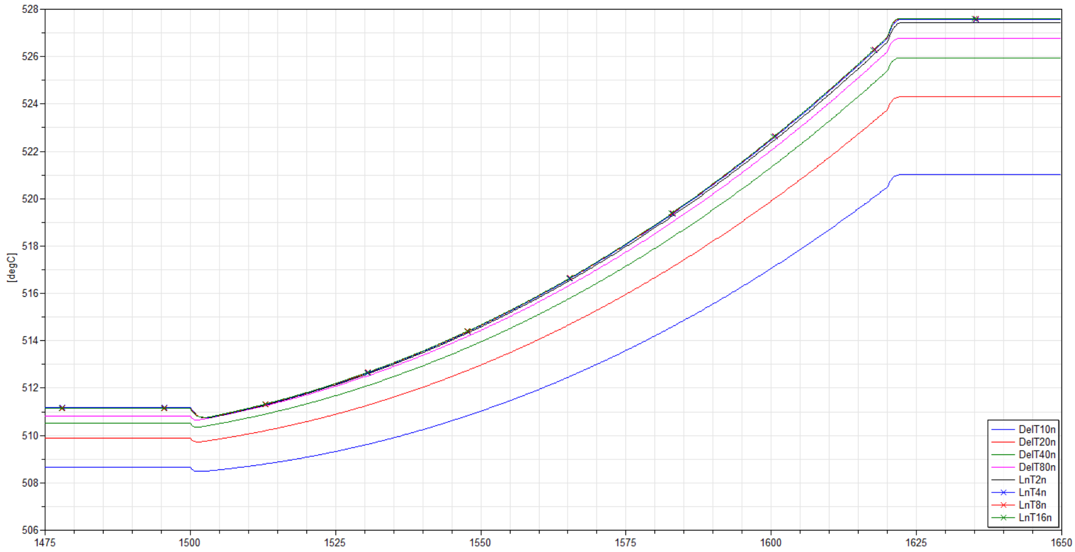

Figure 30 Unloading of Super heater 2 in 120 s

Figure 31 reveals that the 80 nodes simulation could have a shorter initialisation time than the 40 nodes, depending on how well the start values are chosen.

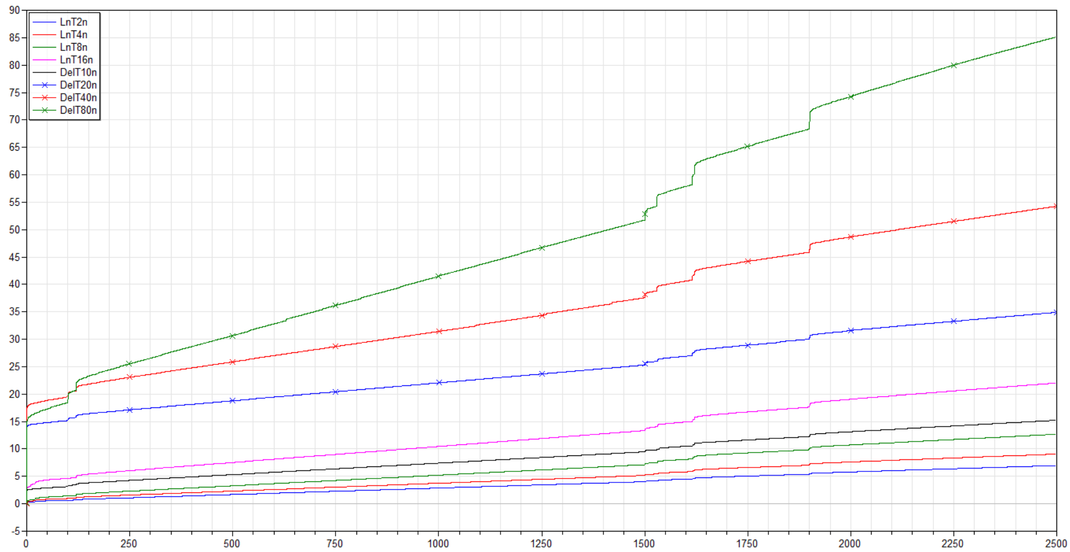

Figure 31 CPU time consumptions for SH2 unloading in 120 s

A complication is that the start values working well for 80 nodes do not work well for the 40 nodes.

The numerical summary of the 120 s load change is given in Table 10.

Table 10 Data for SH2 load changes in 120 s

	Criterions			LnT				DelT			
	Rise time	**Rise time interv. [s]**	**Max dev [K]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**
Loading	88,2	[79,97]	0,49	2	-0,169	91,14	7,04	10	-6,58	85,1	14,2
				4	0,077	91,30	9,23	20	-3,30	87,1	25,1
				8	0,054	91,64	13,9	40	-1,65	87,9	47,3
				16	0,04	92,12	21,2	80	-0,83	88,2	88,0
								20[a]	2,89	89,06	25,9
Unload.	86,1	[78,95]		2	-0,169	83,9	6,95	10	-6,58	81,3	15,2
				4	0,077	84,1	9,02	20	-3,30	84,4	34,9
				8	0,054	84,1	12,7	40	-1,65	85,5	54,3
				16	0,04	84,3	22,0	80	-0,83	86,1	85,1

[a] heat transfer coefficient calibrated within 10 % criterion; not successful for 10 nodes

According to the criterions a DelT with more than 80 nodes are needed to fulfil the steady state criterion. The dynamic criterion is fulfilled without problem for all models, i.e. a 2 nodes LnT is better than an 80 nodes DelT from acceptable accuracy perspective and about 10 times faster. This is valid also if one manages to set the start values perfectly for both to have zero CPU time for initialization (like 6.8 respectively 73 s for loading). On the other hand by calibration of the heat transfer coefficient there is a potential for improvement for both method that will reduce this LnT favour to a factor of 2-3 instead of 10, but this calibration will give cause to fidelity questioning for operating points not calibrated for.

8.4.2 Load changes in 10 s

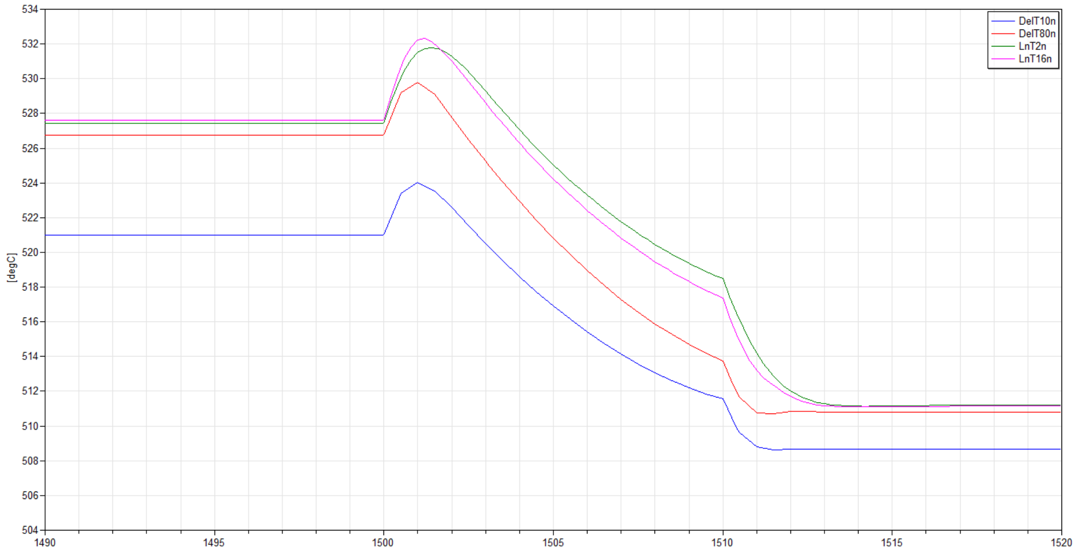

Figure 32 Loading of super heater 2 in 10 s

The convergence looks good but for the dynamics there is no convergence for the amplitude of the DelT – 10 nodes gives the same peak, about 3 K, as 80 nodes. The same is nearly valid also for LnT, but the peak is about 5 K. I.e. to have a steady state convergence of DelT in steady state deviation by applying more nodes, will leave a remaining difference in amplitude of about 2K.

The peak occurs at an earlier time for the DelT but there is a convergence between 2 and 16 nodes and the difference of 0,2 s between LnT with 16 nodes and DelT with 80 nodes would disappear if more nodes where applied for LnT.

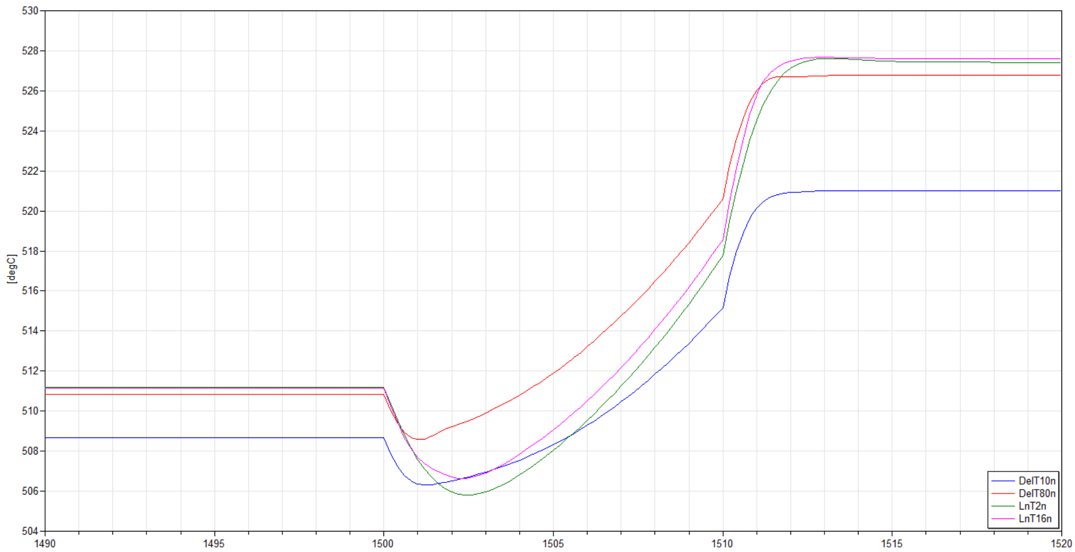

Figure 33 Unloading of super heater 2 in 10 s

For the unloading the result is nearly identical for the peak aspects, but here there is a converging effect also for the peak by applying more nodes but it is not sufficient to eliminate the difference completely. Also the unloading has the difference where the nadir of the transient occurs later for the LnT compared with the DelT, and the only remedy is to increase the number of LnT nodes to make it faster.

Summary of the 10 load change comparison data is found in Table 11.

Table 11 Characteristics of the 10 s SH2 load change

	Criterions			LnT				DelT			
	Rise time	**Rise time interv. [s]**	**Max dev [K]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**	**nodes**	**Max Dev [K]**	**Rise time [s]**	**CPU [s]**
Loading	7,24	[6,5 7,9]	0,49	2	-0,169	6,92	7,09	10	-6,58	7,04	14,3

				4	0,077	6,98	9,14	20	-3,30	7,17	24,9
				8	0,054	7,02	13,7	40	-1,65	7,22	47,1
				16	0,04	7,04	20,4	80	-0,83	7,24	86,8
Unload.	5,31	[4,8 5,8]		2	-0,169	3,52	6,96	10	-6,58	4,32	15,4
				4	0,077	3,62	8,96	20	-3,30	4,92	34,6
				8	0,054	3,68	12,4	40	-1,65	5,19	53,6
				16	0,04	3,70	21,7	80	-0,83	5,31	82,2

For the unloading the dynamic criterion could not be fulfilled by the LnT. But this is only a token of the rise time concept is not the proper for an increase that start with a considerable decrease and shortens the rise time as it only starts to count when the response reached 10 % of the final value, hence the short values of 3,5 to 5,3 s. Defining the time for the 80 nodes DelT coolant outlet temperature to reach 90 +- 10 % as the dynamic criterion instead (10,72 s), then all LnT simulations are acceptable (LnT2n is deviating most, reaching 90 % at 11,34 s or 5,8 % longer time).

Again the steady state criterion needs more than 80 nodes. The rather stable halving of deviation per each doubling of the nodes indicates that 140 nodes would fulfil this criterion.

8.5 Summary of results

In Table 12 are summarised a possible comparison of the CPU time needed for LnT respectively DelT for achieving results fulfilling the steady state and the dynamic criterion.

A summary is that for ECO it takes 6 times, the EVA 2 times and SH1 and 2 about 3 times longer than for corresponding LnT calculation, provided that calibration is successful. Without calibration the factors are tripled or more. However these relations are very dependent upon details in the simulation and how much effort is spent on initialization. In the below table LnT and DelT has been compared with the optimal number of nodes defined as for DelT the number of nodes that required to have the same steady state coolant outlet temperature as for LnT and for LnT the same rise time, with an tolerance of 10 %, as for the DelT with accepted steady state output.

Table 12 CPU time of models fulfilling criterions

		LnT				DelT			
		nodes	**Max Dev [%]**	**Rise time dev [%]**	**CPU [s]**	**nodes**	**Max Dev [%]**	**Rise time dev [%]**	**CPU [s]**
Eco	Load	4	1,35	6,2	5,3	55[a]	2,0	0,0	34,3
	Unload	4	1,35	9,0	6,2	50[a]	3,2	0,7	37,6
Eva	Load	2	0,61	NA	7,6	14[a]	0,7	NA	18
	Unload	2	0,16	NA	7,1	10[a]	0,63	NA	13,5
Sh1	Load	4	0,9	0,8	5,2	80	1,9	0,0	75,9
	Unload	4	0,9	0,4	5,8	80	1,9	0,0	83,7
Sh2	Load	2	1,0	4,4	7,0	80	5,0	0,0	88,0
						20[b]	2,9	1,0	25,9
	Unload	2	1,0	2,5	6,9	80	5,0	0,0	85,1

[a] Heat transfer coefficient calibration with 10 % deviation from real value
[b] Heat transfer coefficient calibrated with 6 % deviation from real value

The DelT column with red figures is not fulfilling the criterion. For the economiser unloading a minor adjustment of the number of nodes is needed and one could conclude that a factor 4 in CPU time consumption is a good measure of the difference in effectiveness of the economiser simulation.

The evaporator has been compared by the transferred power and to have the same accuracy the needed number of nodes is also indicating to need about 40 nodes for loading and a factor 6 more in CPU time. By calibrating the heat transfer a reduction to 20 nodes (giving a factor 2 to 3 in higher CPU time consumption) is possible within a restriction of not adjusting more than 10 % of the real value.

For the super heaters 80 or more nodes are needed for DelT if no calibration of heat transfer coefficient is applied. With such calibration, accepting maximum 10 % deviation in $J/K/m^2$, making approximately 20 nodes sufficient, the CPU time is about 3-4 times higher for those heat exchangers.

9 Accuracy requirements

In order to investigate the importance of correct dynamics for the heat exchangers, a calculation of the ST start time in a CCPP with SGT800 and a one pressure boiler has been carried out with one respectively two nodes LnT models. The reason for not comparing with more nodes or with DelT is that so far complete HRSGs with more than two nodes have failed to execute, i.e. they require more efforts than available, so far, for this report.

Both models have the same drum model and geometrical data. As the models are different their heat transfer has been calibrated for the same nominal load at steady state, but dynamics of the heat transfer are applying the same equations. The result is that the start time for ST differs with 34 seconds for a total start time of 35 minutes (start at 2152 s for one node respectively 2118 s for two nodes), i.e. a difference of 1,6% when boiler is started with 10K/min in the drum, and also the heating of the steam pipes are approximately limited to that value by controlling flow to 0,5 kg/s.

As the one node LnT model will not fulfil the dynamic 10 % criterion in for any component while the 2 nodes does it or is very close to it, it is a bit surprising that the total difference is only 1,6 % for the dynamic question of when ST start conditions are reached. The simple explanation is that the control of the boiler by level, pressure and temperature compensates dynamic inaccuracies to a large extent. So for this random test of dynamic accuracy requirement even a model with components with less than 10 % individual accuracy could provide a combined result far better than 10 %.

10 Conclusion

The LnT delivers acceptable results for all normal cases for the heat exchangers in a HRSG while a DelT model could have problem to achieve correct steady state results, simultaneously as its execution time makes it impossible as component in larger models comprising many heat exchangers.

Both models handles once through boiler (phase shift in the pipes) calculations but require then larger number of nodes.

The LnT has an advantage of consuming considerably less CPU-time due to the ability to have correct steady state levels with fewer nodes. This also gives and advantage for the initialisation of the model.

An LnT with too few nodes gives too slow response compared with reality simultaneously as the initial response is faster.

In a real application inaccurate component dynamics may be compensated by the controllers, hence a one node LnT HRSG model may be well suited for dynamic questions in spite components individually trespasses accuracy criterions.

The recommended technique is to always test sensitive results by increasing the number of nodes.

11 Supplement

11.1 General information

In order to see how other libraries models compares to the LnT, the above investigations have also been carried out for heat exchangers from the ThermoPower library (TP) made by Casella et al in Milano Technical high school.

In TP all geometrical data in chapter 6 could easily be applied. There is an option to select shell and tube configuration which has not been utilised instead counter or con current settings where chosen as for DelT and LnT. The heat transfer was, as above, set constant. The heat exchanger was calibrated for 100 % load by a sufficiently high number of nodes that by good margin gave no change in behaviour or levels if further increased. Then the number of nodes where minimised under the constraint not to trespass the acceptance criterions:

1. 3 % deviation in steady state level at each load
2. Maximum 10 % deviation of the sum of the dead time and the rise time, i.e. time from initiation of change until 90 % has passed.

Only one test has been done for each the four heat exchangers in the one pressure boiler. That is to load from 50 to 100 % of nominal load. In this test the power has been compared instead of the temperatures, which should not have any impact upon result.

As above it is assumed that in steady state the LnT with 16 nodes calibrated for 100 % gives the correct power also at 50 % load, and that the DelT with a huge number of nodes (50 to 80) gives the correct dynamic behaviour although it might deviate from steady state levels.

11.2 Economiser

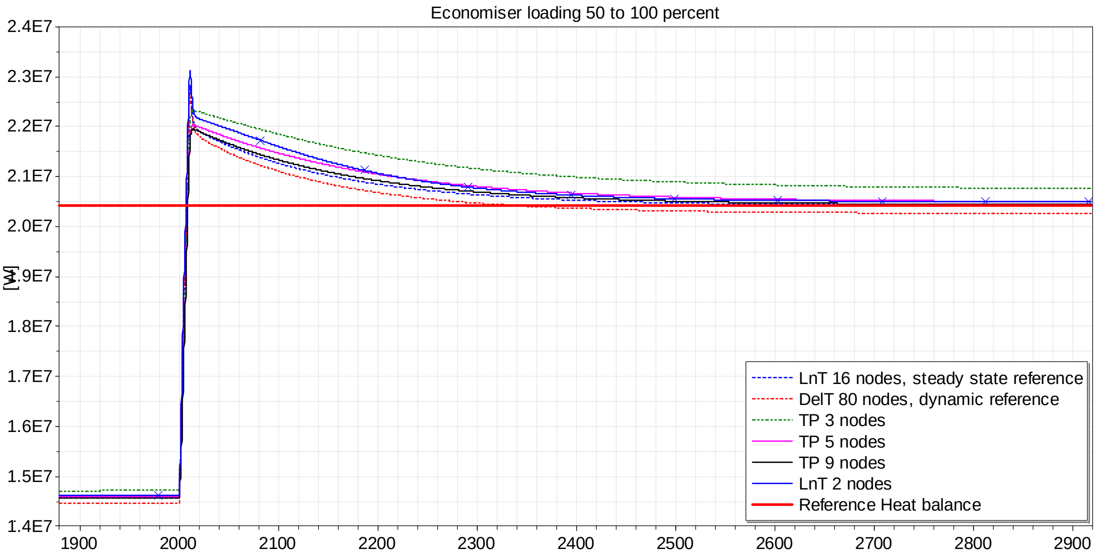

Figure 34 Comparisons with TP for Economiser loading [W]

Table 13 gives the comparison of the acceptance criterions for the test, with following readings from resulting curves:

The heat balance value at 100 % is 20,417 MW and the 50 % value from the LnT 16 nodes is 14,457 MW. This gives acceptance intervals of [19,80 21,03] respectively [14,14 15,01] MW. The DelT with 80 nodes passes the 90 % of the change after 6,44 s giving a time acceptance interval of [5,80 to 7,08] s.

Table 13 Comparison between LnT and TP for Economiser loading

	100 %	50 %	$t_{90\ \%}$ [s]	CPU [s]
LnT 2 nodes	20,50	14,62	6,3	11,16
TP 3 nodes	20,75	14,72	7,9	5,12
TP 21 nodes	20,42	14,57	8,28	43,94

In the table all values within criterions are highlighted green, except in the CPU column where the model with shortest CPU time is marked as the preferred one. For the economiser there is no node number that provides acceptable response time. However the principal responses have some alikeness, but there must be phenomenons in the DelT and the LnT simulations that do not occur in the TP. Figure 35 gives a magnified view of the initial transient for readers' information.

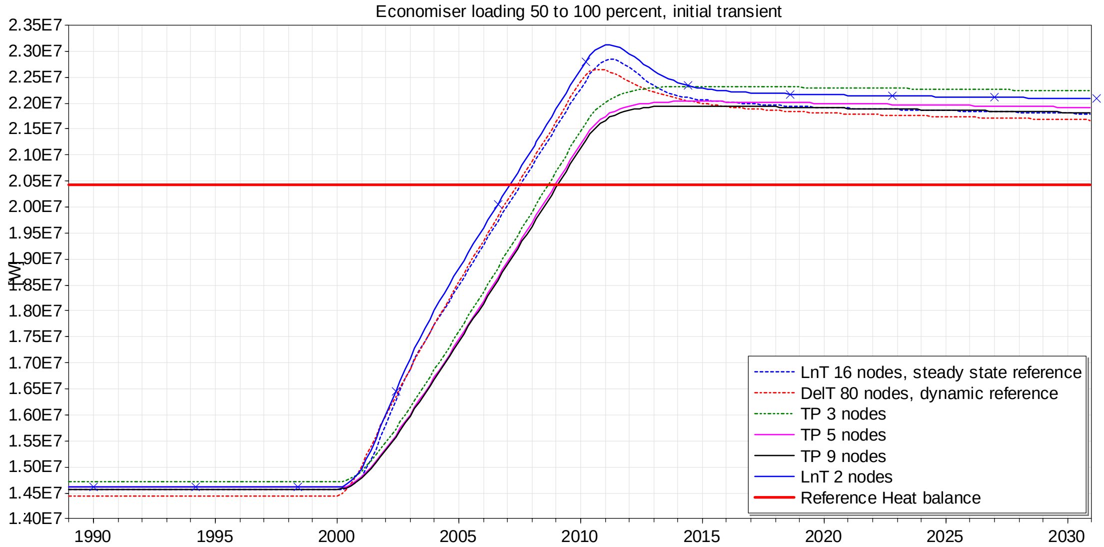

Figure 35 Blow up of economiser loadings initial transient (Obs the LnT 2 nodes curve are with cross marks)

There is a difference as for the LnT and DelT models, the thermal mass of the tube walls have been excluded as they in tests turned not influence the transient in any significant way.

A test of reducing the thermal capacity of the walls in the TP model to one percent does not change the curvature of the power curve, and the peak increases with only 1 % of the step, i.e. enclosure the thermal properties of the wall also in LnT and DelT will not change the result.

The tubes in the economiser are long and it takes rather long time to reach steady state level, which calls for a need to also valuate the settling time. A quick look at Figure 34 shows that these are practically the same, i.e. the differences are well captured by the steady state levels and the rise times.

11.3 Evaporator

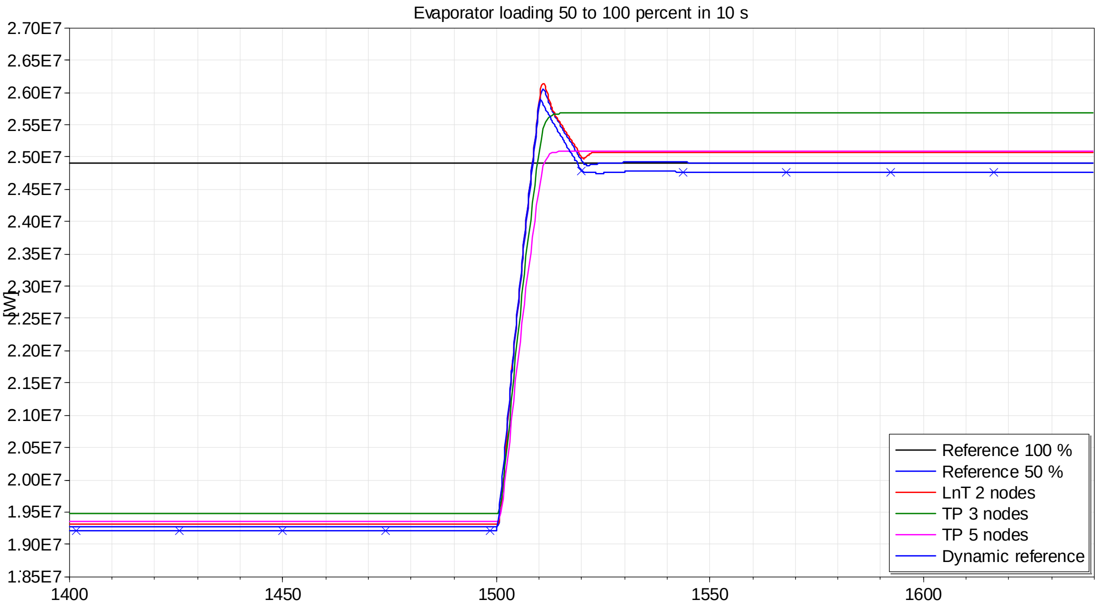

Figure 36 Comparisons with TP for Evaporator (Dynamic reference has a blue cross marked line)

The result is the basically the same for the evaporator.

The heat balance value at 100 % is 24,92 MW and the 50 % value from the LnT 16 nodes is 19,27 MW giving an acceptance interval of [24,17 25,67] respectively [18,69 19,85] MW. The DelT with 80 nodes passes the 90 % of the change after 7,3 s giving a time acceptance interval of [6,57 to 8,03] s. Table 14 gives the criterions data from the simulations, with green colour marking as for the economiser.

Table 14 Comparison between LnT and TP for Evaporator loading

	100 %	50 %	$t_{90\,\%}$ [s]	CPU [s]
LnT 2 nodes	25,07	19,32	7,5	7,38
TP 3 nodes	25,69	19,47	9,01	3,28
TP 5 nodes	25,10	19,36	10,14	4,85

Also for the evaporator there is no setting of the node number that provides acceptable response time for TP. From the response curves in Figure 37 its clear that the physics in the models are not the same as there is no overshoot by the TP models. The reason for that will not be a topic of this report, but it raises the question if the assumption for this report that Modelica standard fluid libraries pipe models applied for a heat exchanger will have the correct dynamics, founded by that they convert towards heat balance value given the same heat transfer coefficient as the LnT, and that the error made by taking the temperature difference between connected nodes is assumed eliminated by letting the number of nodes increase towards infinity (very high number used). Thereby they provide a high credibility, at least in the eyes of the author of this report.

11.4 SH1

Corresponding loading test for SH1 is given in Figure 37.

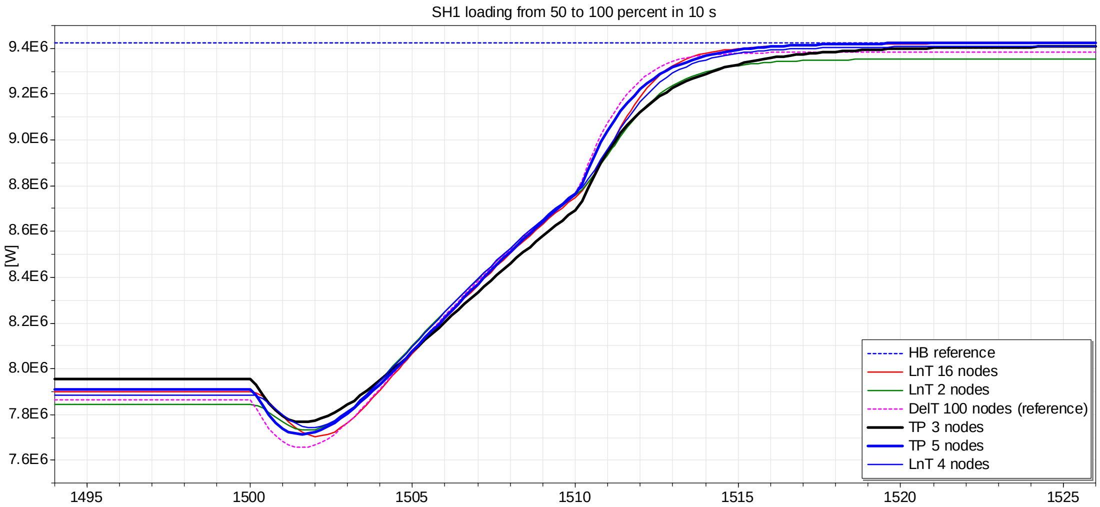

Figure 37 Comparisons with TP for SH1

Figure 37 shows rather similar dynamics for all model types. DelT with 100 nodes has 11,8 s as reference for the acceptance interval is 10,6 to 13,0 seconds. With LnT 16 nodes as reference for the 50 % value (7,899 MW) and heat balance for the 100 % (9,422 MW) power value the acceptance interval for 100 % load is [9,14 9,70] MW and the 50 % load [7,66 8,14] MW.

Table 15 Comparison between LnT and TP for SH1 loading

	100 %	50 %	$t_{90\ \%}$ [s]	CPU [s]
LnT 2 nodes	9,35	7,84	13,5	7,8
LnT 4 nodes	9,41	7,89	12,8	13,6
TP 3 nodes	9,41	7,95	13,6	3,3
TP 5 nodes	9,42	7,91	12,4	4,7

For SH1 the TP model with 5 nodes has the fastest execution time and fulfils both the static and dynamic criterions.

11.5 SH2

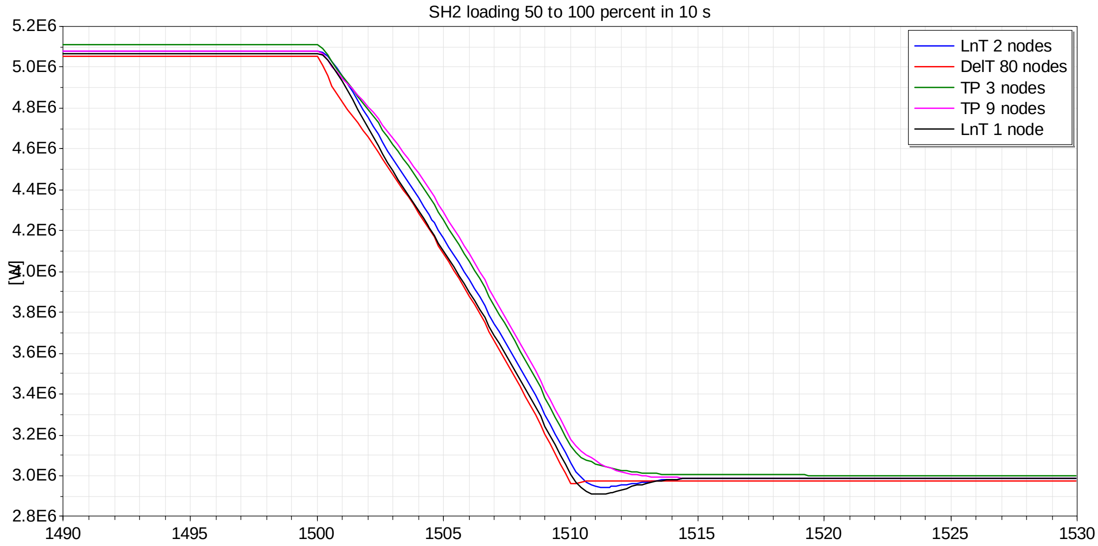

Figure 38 "Comparison with TP for SH2"

The heat balance reference for 100 % is 2,986 MW which gives an acceptance interval of [2,90 3,08] MW and LnT 16 nodes calibrated for 2,986 MW at 100 % load gives [4,93 5,23] MW acceptance interval at 50 % load. The 80 nodes DelT passes the 90 % after 9,1 s giving an acceptance interval of [8,2 10] s.

Table 16 Comparison between LnT and TP for SH2 loading

	100 %	50 %	$t_{90\ \%}$ [s]	CPU [s]
LnT 1 node	2,99	5,06	9,2	7,27
LnT 2 nodes	2,99	5,08	9,4	8,01
TP 3 nodes	3,00	5,11	9,8	3,23

All models have are within the acceptance criterion and the TP model is the fastest. The CPU gain for LnT to have only one node is surprisingly low and the probable explanation is that the LnT algorithm takes its toll.

11.6 Conclusion for the TP comparison

Following conclusions are at hand now, based upon above component tests:

1. TP executes faster than LnT
2. LnT has better dynamic properties

Analyse the cause of the dynamic difference between TP at one hand and LnT and DelT on the other, remains to be done. In the light of the 1,6 % difference between 1 and 2 nodes LnT models (chapter 9) and that the dynamic discrepancies between TP and the dynamic reference are less, the outcome of a corresponding investigation by

TP would also be a minor differences that might be sufficiently accurate. To find out the building a complete TP boiler model has so far failed, and requires further efforts, still awaiting funding.