Optimization in twin refiners using temperature profiles and plate clearance information

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Summary

This thesis comprises analysis and optimization of twin refiners used for Thermo mechanical
pulp (TMP)-production in the newsprint paper industry. As each twin refiner consists of two
refining zones (FS and DS), the flow patterns in a twin refiner are unknown. By using a
physical model called the extended entropy model, the pulp consistencies and other variables
from each of the refining zones can be derived. In this paper the extended entropy model has
been used to model unknown variables from two production lines comprising four twin
refiners. The refiners were pairwise connected in series; the first referred to as the primary
refiner and the second as the secondary refiner.

The intent has been to formulate and

- perform a rigorous test procedure to examine how process performance and
  consistency control can be improved.
- propose how to optimize FS and DS by controlling the dilution water feed rates
  individually to reach the same consistency on each side.

Several tests were performed with focus on step changes in dilution water of equal magnitude
but opposite sign on both sides of the refiner. The idea was to affect the consistency in each
refining zone. Responses in plate gap, temperature, acceleration, motor load, consistency,
mass flows and pulp quality to these step changes were analysed.

It is shown that the primary and secondary refiners respond differently to changes in dilution
water in several aspects. For example, the plate gaps change in opposite directions dependent
on which refiner we study. On the primary refiners the position of the maximum temperature
is fairly constant, while it changes considerably for different levels of dilution water on the
secondary refiners.

Two different optimization techniques are proposed, one concerns the stability and power
consumption of the refiners and one refers to consistency control in the separate refining
zones. On the primary refiners, it is concluded that an increased difference in dilution water to
the two sides is purely beneficial (up to an unknown point) in terms of power consumption
and stability. In several instances the standard deviations in temperature (an indicator for
stability) provide different results than the acceleration. This makes the present use of
accelerometers mounted on the static holders questionable to use as indicators for process
stability. While the pulp quality did not seem to deviate much when changing the levels of
dilution water, further research has to be performed to analyze pulp property changes in more
detail.

Finally, it is concluded that the consistency from each refining zone can be controlled through
manipulations in dilution water, if the extended entropy model is implemented in a future
control platform. It is also shown that the consistencies for equal amounts of dilution water on
each side are not strongly correlated to the plate gaps as previously believed while the
temperature profiles inside the refiners seems to have a more important impact on the
outgoing concentration than expected.

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Introduction

The first pressurized Bauer refiner was installed in 1963 at an Anglo-Canadian mill in Québec City and shortly thereafter a pilot plant at Billerud, Jössefors mill in Sweden installed the first pressurized Asplund refiner. The first commercial implementation for Defibrator (a refiner developed by Arne Asplund) was the TMP mill at Rockhammar, Sweden, in 1968 but the breakthrough of the TMP process came 1973 at the International Mechanical Pulping Conference in Stockholm (Lönnberg (2009)).

Several process designs have been proposed during the years but in this section we focus on the TMP process from a simplified perspective, which will be used in the sections that follow. The TMP process can be described as a two stage production line as described in Figure 1. In this process description a preheating screw is feeding a primary refiner with wood chips which are defibrated in the refining zone. Before the cyclone, a NIR-based consistency sensor is sometimes installed but in many processes this is not standard. After the first cyclone there is a secondary refiner for fibrillation of the pulp from the first stage followed by a second cyclone and a pulper. The pulp quality is most often measured by an on-line analyser and in this study we will primarily focus on three variables, Canadian Standard Freeness (CSF)[1], Mean Fiber Length (MFL) and shives.
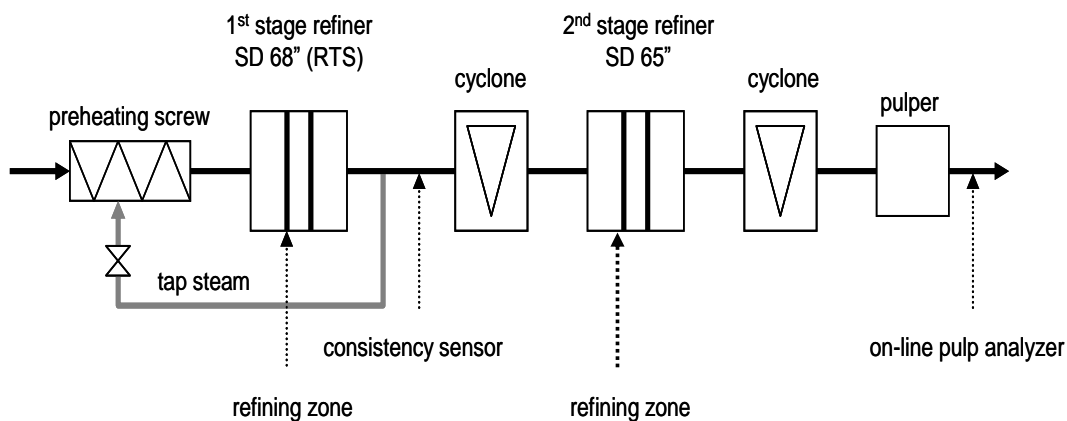

Figure 1: A schematic drawing of a TMP-process comprising serially linked refiners. In this figure the reject refiner is excluded.

Basic principles

In refiners, wood chips are fed in to the refining zones at the centre of the discs and then transported by centrifugal forces, while being defiberized, in the radial direction to the disc periphery. Both the stator and the rotor surfaces are made up of several segments with patterns of bars and grooves. The depth of the grooves and the sizes of the bars differ with respect to radial position.

In Figure 2, a single disc refiner is visualized and as can be seen dilution water is also added to the refining zone. The distance between the segments on the rotor and stator discs is often manipulated by applying a hydraulic pressure on one of the discs. Sometimes a plate gap sensor is used to prevent plate clash and in more sophisticated applications it is also used for control purposes.

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[1] In this presentation we will use the term CSF (Canadian Standard Freeness) when describing on-line measured Freeness even though this is not related to laboratory test procedures.
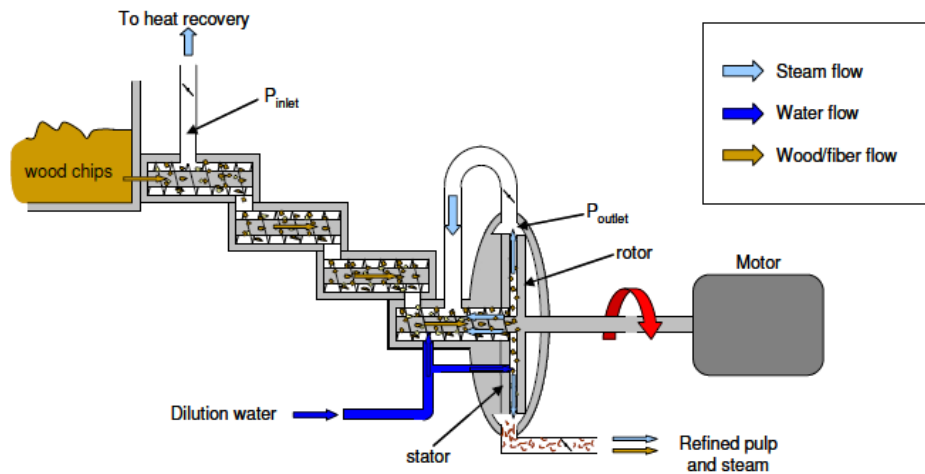
Figure 2: Schematic overview of the feeding system to a single disc primary refiner.

Another type of refiner is the twin-disc refiner which has two refining zones separated by an axially centred rotor (see Figure 3).

Twin refiner

A twin refiner contains two refining zones, the front side (FS) and drive side (DS), which allows for higher production compared to a single-disc refiner (Eriksson and Karlström (2005)). While twin refiners have been used for quite some time, almost no research has been done on the subject of individually controlling each refining zone[2]. A schematic image of a twin refiner can be seen in Figure 3. The chips are fed to the inlet mixing zone using two ribbon feeders, where dilution water (D) is added. The amount of dilution water is usually set to be the same in the two zones, even though the chip feed rates to the zones are unknown. Inside the refiner defibration (separation of the fibres) and fibrillation (delamination of the wood cell walls) occurs as the pulp is grinded between two refining segments, whose function is determined by the segment pattern and taper. The distance between these segments, referred to as the plate gap (g), is an important variable in the control of the refiner. The plate gap is controlled by the hydraulic pressure pushing the segments together (see Figure 3), but it is influenced by other variables as well. Due to the high temperature inside the refiner, most of the dilution water is evaporated. The steam that is produced exit the refiner either through the outlet or back through the inlet, see Karlström and Eriksson (2014a). Another important variable is the temperature profile inside the refiners. In the refiners studied in this paper the temperature is measured using eight sensors at different radial positions. A schematic image of a typical temperature profile can be seen in Figure 4.

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[2] A notable exception to this is the work done by Cocyan, see Cocyan (1993).
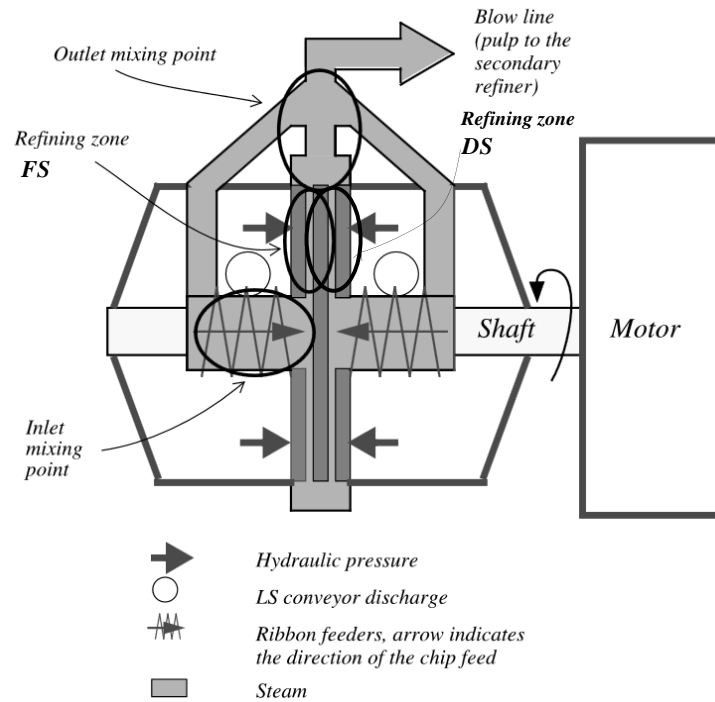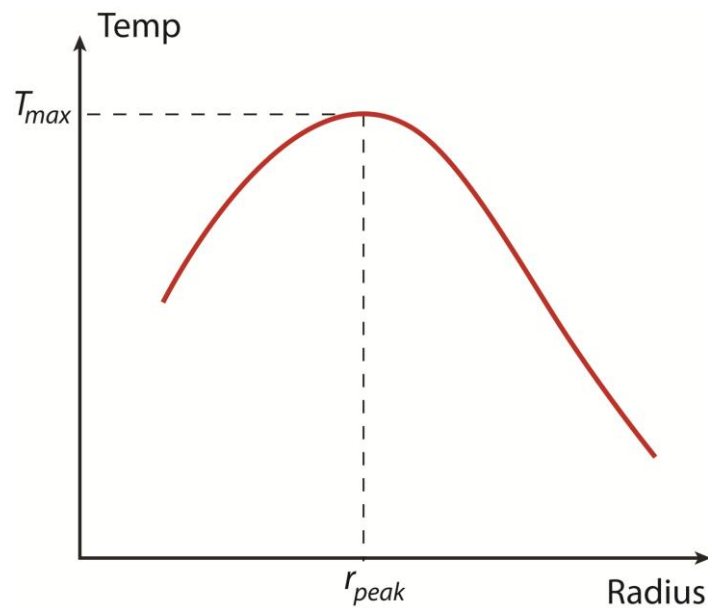
Figure 3: Schematic image of a twin refiner.

Figure 4: Schematic image of a typical temperature profile.

Many important variables (including consistency, mass flows and motor load distribution between the zones) are not known. Because of this Karlström and Ericsson (2014a, 2014b, 2014c, 2014d) developed "the extended entropy model", a physical model that takes the temperature profile and plate gap measurements as input. In this model the position of the maximum temperature (T_{max}) inside the refiner is of great importance, as the pressure gradient is 0 at this point. This position, r_{peak}, is vital in the estimation of backwards and forward flowing steam as well as the velocity of the pulp, see Karlström and Hill (2014a). The taper of the refining segments has an impact on r_{peak}; a large taper will result in a maximum temperature in the outer part of the refiner, while a small taper will result in a maximum temperature closer to the inlet.

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At Stora Enso Hyltebruk the refiners are pairwise connected in series. The first refiner in such a series is referred to as the primary refiner, while the second is referred as the secondary refiner. Due to the different inputs the primary and secondary refiner may react differently to changes in process variables. One example of this is that while r_{peak} may change quite a lot on a secondary refiner, it is fairly constant on a primary refiner due to a build up of chips, shives and large fibre bundles that cannot pass through the narrower parts, see Karlström and Hill (2014a).

The extended entropy model described by Karlström and Eriksson (2014a, 2014b, 2014c, 2014d) was not formulated for a twin refiner, and thus the uneven feed distribution between the refining zones is not taken into account. However, the model has been modified by Anders Karlström and Jan Hill to remedy this. This modification is built upon three hypothesises, as follows:

Hypothesis A: *If the added dilution water feed rate to each zone in a Twin refiner are similar, it is assumed that the fiber mass flow distribution m₁ can be derived using the plate gap measurements g, i.e.*

$$\frac{m_{1_{FS}}}{m_{1_{DS}}} = \frac{g_{FS}}{g_{DS}} \tag{1}$$

Hypothesis B: *The extended entropy model can be used to understand how much work the uneven feed distribution in a Twin refiner will result in on each side.*

Hypothesis C: *Knowing the motor load split in a Twin refiner together with the shape of the temperature profiles, it is possible to estimate the steam and water mass flows iteratively using the extended entropy model.*

Using the modified extended entropy model it is possible to calculate various quantities for the refining zones, such as consistency, motor load and mass flows. In Figure 5 the material and energy balances for a twin refiner are outlined. A nomenclature can be found in Table 1, Table 2 and Table 3.
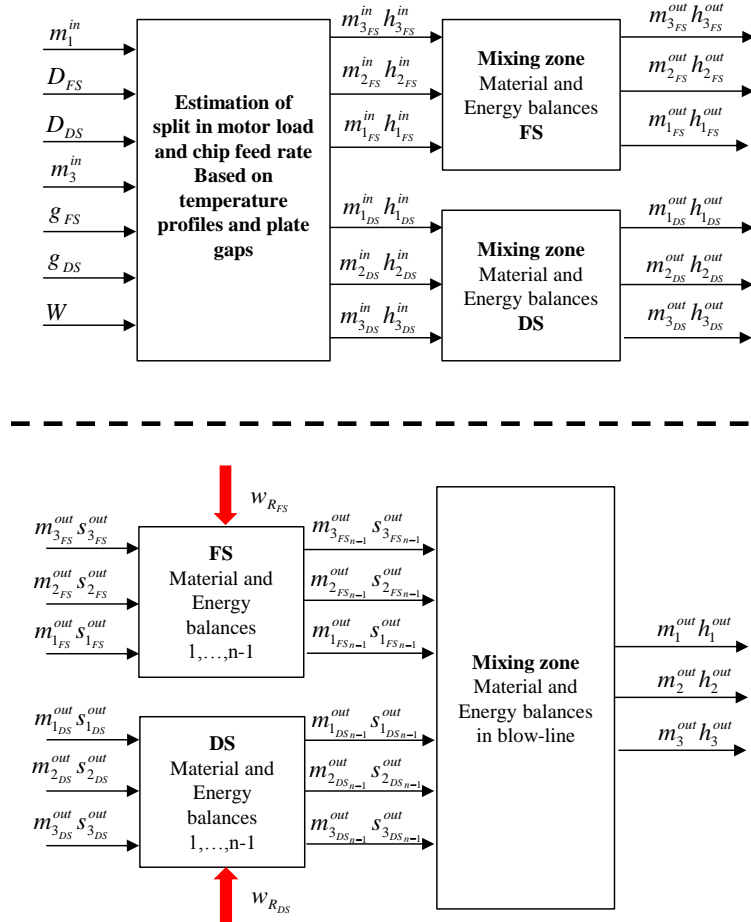
Figure 5: Schematic illustration of the material and energy balances in a twin refiner as described by the extended entropy model. The pulp, water and steam mass flows are represented by m_1, m_2 and m_3 respectively, while h represent enthalpy and s represent entropy.

A block describing the energy balances in a refining zone (FS or DS) according to Figure 5 can be seen in Figure 6. Note that there are n_l such blocks for each refining zone, where n_l is the number of temperature sensors along the radius of the refiner.
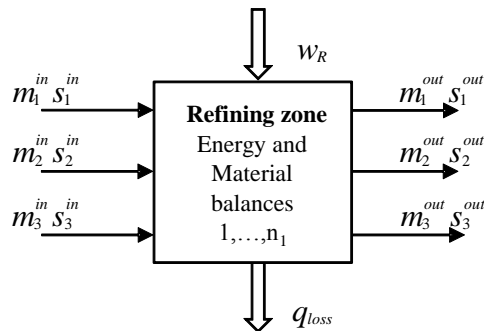
Figure 6: Energy balance for a hypothetical refining zone.

The entropy and enthalpy balances for a refining zone are summarized below, with explanations for the different variables in Table 1, Table 2 and Table 3.

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$$dS(r) = \frac{\delta(r)}{T(r)} \Delta(r) 2\pi r dr$$

where

$$\delta(r) = \mu \left(\frac{r\omega}{\Delta(r)} \right)^2 = \frac{w_R(r)}{\Delta(r)}$$

We also know that

$$dS(r) = m_1 c_p \ln\left(\frac{T(r+dr)}{T(r)} \right) +$$

$$\sum_{j=2}^{3} \left(m_j(r+dr)s_j(r+dr) - m_j(r)s_j(r) \right)$$

$$w_{th}(r)2\pi r dr = m_1 c_p \left(T(r+dr) - T(r) \right) +$$

$$\sum_{j=2}^{3} \left(m_j(r+dr)h_j(r+dr) - m_j(r)h_j(r) \right)$$

which gives

$$\frac{w_R(r)}{T(r)} 2\pi r dr = m_1 c_p \ln\left(\frac{T(r+dr)}{T(r)} \right) +$$

$$\sum_{j=2}^{3} \left(m_j(r+dr)s_j(r+dr) - m_j(r)s_j(r) \right)$$

$$m_2(r) + m_3(r) = m_2(r+dr) + m_3(r+dr)$$

$$w_R \neq 0 \text{ and } q_{loss} \approx 0$$

$$m_1^{in} = m_1^{out} = m_1, \ m_2^{in} \text{ and } m_3^{in} \text{ are known } \Rightarrow$$

$$m_2^{in} + m_3^{in} = m_2^{out} + m_3^{out} \Rightarrow m_2^{out} = m_2^{in} + m_3^{in} - m_3^{out}$$

$$dr = r_{out} - r_{in}$$

Find m_3^{out}, $w_{th_{in}}$ and $w_{def_{in}}$

$$X = \frac{w_{R_{in}}}{T_{in}} 2\pi r_{in} dr - m_1 c_p \ln\left(\frac{T_{out}}{T_{in}} \right) - m_2^{in} \left(s_2^{out} - s_2^{in} \right) -$$

$$m_3^{in} \left(s_2^{out} - s_3^{in} \right)$$

$$Y = m_1 c_p \left(T_{out} - T_{in} \right) + m_2^{out} h_2^{out} - m_2^{in} h_2^{in} + m_3^{out} h_3^{out} -$$

$$m_3^{in} h_3^{in}$$

$$m_3^{out} = X / \left(s_3^{out} - s_2^{out} \right)$$

$$w_{th_{in}} = Y / (2\pi r dr)$$

$$w_{def_{in}} = w_{R_{in}} - w_{th_{in}}$$

Table 1: Latin symbols

Symbol	Description
c_p	Heat capacity
dS	Entropy generation
h_i	Specific enthalpy of component i
m_i	Material flow of component i

q_{loss}	Energy losses per unit area
r	Radial coordinate
s_i	Specific entropy of component i
S	Total entropy
T	Temperature
w_{th}	Thermodynamic work per unit area
w_{def}	Refining work per unit area
w_R	Estimated total work per unit area

Table 2: Greek symbols

Symbol	Description
δ	Viscous dissipation
μ	Dynamic viscosity
ω	Angular speed of the refiner disc
Δ	Plate gap at radius r

Table 3: Indices

Sub- and superscript	Interpretation
1	Wood/pulp phase
2	Water phase
3	Steam phase
in	Refiner inlet
out	Refiner outlet
FS	Front side
DS	Drive side

Prior to this work it was hypothesized that an uneven feed distribution would result in higher consistency of the pulp on the side with the larger plate gap and lower consistency on the other side, and that this could be remedied by increasing the level of dilution water on the side with larger plate gap while decreasing it on the other. It was also believed that a more homogenous consistency distribution would result in better stability and improved pulp quality.

Aim

The aim of this diploma work was to formulate and
- perform a rigorous test procedure to examine how process performance and consistency control can be improved.
- propose how to optimize FS and DS by controlling the dilution water feed rates individually to reach the same consistency on each side.

Method/Experiment

To test the hypothesis proposed by Karlström and Hill several tests were performed on four different refiners at Stora Enso Hyltebruk. The refiners consisted of two primary refiners and two secondary refiners in two separate production lines (L1 and L2). Both L1 and L2 are built

on an almost identical process design with Twin refiners. A total of twelve tests were performed as listed in Table 4.

The experiments were first intended to consist of step changes in three different variables: dilution water, hydraulic pressure (which affects the plate gap) and production. During the course of the work the focus shifted slightly towards a more practical approach; to find results useful in the operation of the refiners. It was deemed that the dilution water was the most important variable to test as it is easy to control and not dependant on other variables, unlike the plate gap. Therefore step changes were made only on the dilution water. All of the experiments had a similar structure; a series of step changes of equal magnitude but opposite sign were performed simultaneously on the two zones of a refiner. This meant that the total amount of dilution water remained the same, limiting the effect on the outgoing consistency. This was necessary as the tests were performed during normal operation. For the same reason the changes in dilution water could not be so large that they threatened the stability of the machines. The difference between the dilution water levels of the refining zones will henceforth be referred to as ΔD, which is defined as positive if the side with the largest initial plate gap (for $\Delta D=0$) has a higher level of dilution water.

$$\Delta D = (D_{FS} - D_{DS}) \frac{g_{FS}(\Delta D = 0) - g_{DS}(\Delta D = 0)}{|g_{FS}(\Delta D = 0) - g_{DS}(\Delta D = 0)|} \tag{2}$$

The reason for using this definition rather than a simpler one (for example $\Delta D = D_{FS} - D_{DS}$) is that the plate gap difference (and by extension the difference in chip feed rate) are different on the different refiners. Dilution water and plate gap values for each test can be seen in Appendix I.

Table 4: Brief description of the tests.

Date	Refiner	ΔD_{max} (l/min)	ΔD_{min} (l/min)	Segments
2014-10-15	Primary L1	60	0	Regular
2014-10-15	Secondary L1	40	0	Regular
2014-11-05	Primary L2	50	-40	Regular
2014-11-11	Primary L2	60	0	Regular
2014-11-11	Secondary L2	40	-40	Regular
2014-11-12	Primary L2	80	0	Regular
2014-11-12	Secondary L2	50	-20	Regular
2014-11-24	Primary L2	20	-10	Low energy
2014-11-24	Secondary L2	20	0	Low energy
2014-11-24	Primary L1	40	0	Regular
2014-11-25	Secondary L2	30	-30	Low energy
2014-12-12	Secondary L1	30	0	Regular

Some of the temperature sensors were not functioning properly[3], which could have had negative influences on the temperature readings and in extension the calculated consistencies, mass flows and motor loads. The malfunctions were handled differently depending on the type of malfunction, and three different types were identified: positive bias, complete malfunction and other reasons for malfunction. The positive bias was likely due to oxidation

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[3] The sensors had been in use for more than eight months for some of the tests.

on the plugs of the sensors and was easily rectified by applying an equally large negative bias. Positive biases were identified during blow cleaning of the refiners, when the temperature was constant along the radius. The completely malfunctioning sensors generally gave a constant value for the temperature which was replaced with a linear approximation from the two neighbouring sensors. The other malfunctions were of unknown origin and did not fit into any of the other two groups. These values were either kept (if they didn't deviate too much from the expected) or replaced by linear approximations.

During the course of the test period new refiner segments were tested on L2. These were so called 'low energy segments' with a different shape and pattern that allowed for lower effects. Some tests were done with these segments, but due to instabilities in the refiners the tests were not nearly as extensive as the tests done with the regular segments.

Most of the tests were done on L2, for two main reasons. The temperature sensors for the secondary refiner on L1 were broken during most of the work, making it impossible to calculate consistency and mass flows. When the sensors were changed there were a lot of problems due to the testing of the previously mentioned low energy segments, which made it impossible to perform any tests for a time.
There was more testing done on the primary refiners than on the secondary. The main reason for this is that the primary refiners were significantly more stable than the secondary, allowing larger changes in dilution water. Due to time constraints (because of the large number of step changes done on the primary refiners) only one test was made with negative (with respect to the initial plate gap difference) changes in dilution water on the primary refiner on L2.
In total there were three tests performed on the primary refiner on L2, one test on the primary refiner on L1, two tests on the secondary refiner on L2 and one test on the secondary refiner on L1. In addition to these one initial test was made for both the primary and secondary refiner on L1, one test was done for the primary refiner on L2 with the low energy segments and two tests were done on the secondary refiner on L2 with the low energy segments, see Table 4. The initial tests on L1 were discarded as the experimental procedure was substandard.

All tests followed a similar procedure, where step changes in dilution water of ± 5 l/min where performed on both the front side (FS) and the drive side (DS). The time between step changes was usually 18-20 minutes, which was deemed sufficient to achieve statistically significant results. All of the relevant variables, except the ones related to pulp quality, were sampled with a sampling period of about one second. The variables related to pulp quality (mean fibre length, shives and freeness) were sampled with a sampling period of about five minutes. In both tests on the secondary refiner on L2 step changes were made in both directions (resulting in both positive and negative values for ΔD). Only one of the tests on the primary refiners tested for negative values of ΔD. Typical dilution water levels during the experiments can be seen in Figure 7 (primary refiner on L2) and Figure 8 (secondary refiner on L2).
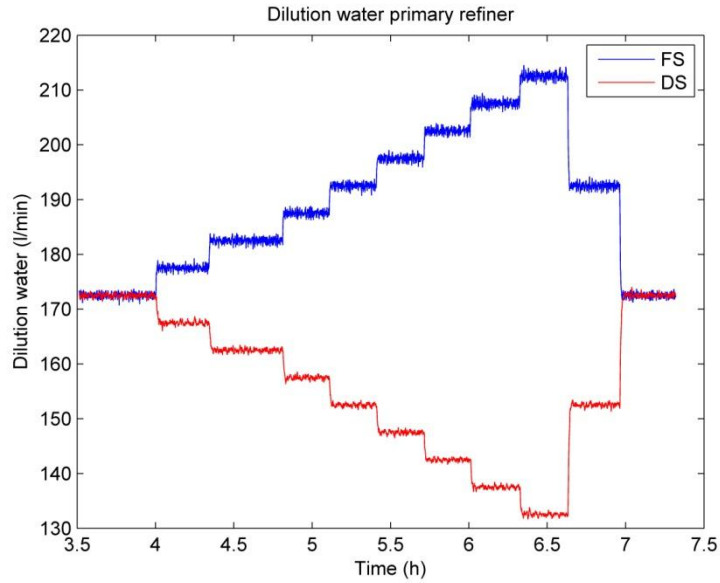
*Figure 7: Dilution water for the primary refiner on L2 during
the test performed 2014-11-12.*
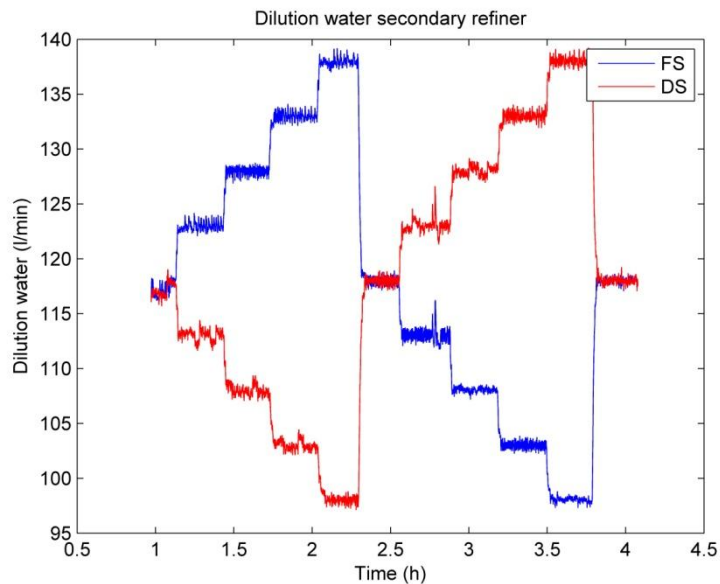
*Figure 8: Dilution water for the secondary refiner on L2 during
the test performed 2014-11-11.*

Results and discussion

In this section, various results are outlined and discussed. The results for the secondary refiner on L1 are presented separately; all other results are for the primary refiners on L1 and L2 and the secondary refiner on L2. The reason for this splitting is that the results from the single test on the secondary refiner on L1 do not correlate with the results obtained for the secondary refiner on L2. These results have thus not been reproduced, which makes them less reliable. The results from the single test on the primary refiner on L1 correlate well with the results obtained from the primary refiner on L2; it is therefore assumed that these results are applicable to both lines. The results for the low energy segments are not discussed due to insufficient data (plots for several process variables are shown in Appendix I).

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Plate gap

The plate gap responds differently to changes in dilution water on the primary and secondary refiners.

Primary: For the primary refiners an increase in dilution water leads to an increased plate gap, see Figure 9. This is likely due to the increased pressure from the larger amount of steam generated which pushes the segments apart. A decrease in dilution water has the opposite effect.

Secondary: For the secondary refiners the relationship is the opposite, an increase in dilution water leads to a decreased plate gap and vice versa, see Figure 10. The reason for this can likely be found in the steam flows inside the refiner. When more dilution water is added the temperature in the beginning of the refiner is lowered while the temperature toward the end of the refiner is increased. This causes the position of the maximum temperature to move outwards, which leads to increased backward flowing steam and decreased forward flowing steam (since the direction of the steam flow depend on the pressure gradient). A reduced amount of dilution water instead leads to a temperature maximum closer to the inlet, and thus more forward flowing and less backward flowing steam. The somewhat unintuitive plate gap changes for the secondary refiner can probably be explained by the change in forward flowing steam, as the steam exerts great pressure on the plates.
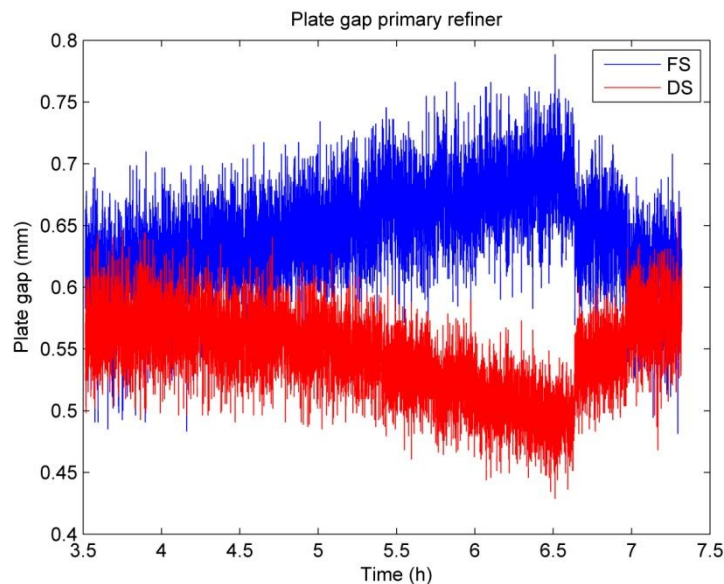
Figure 9: Plate gap for the primary refiner on L2 during step changes in dilution water as seen in Figure 7.

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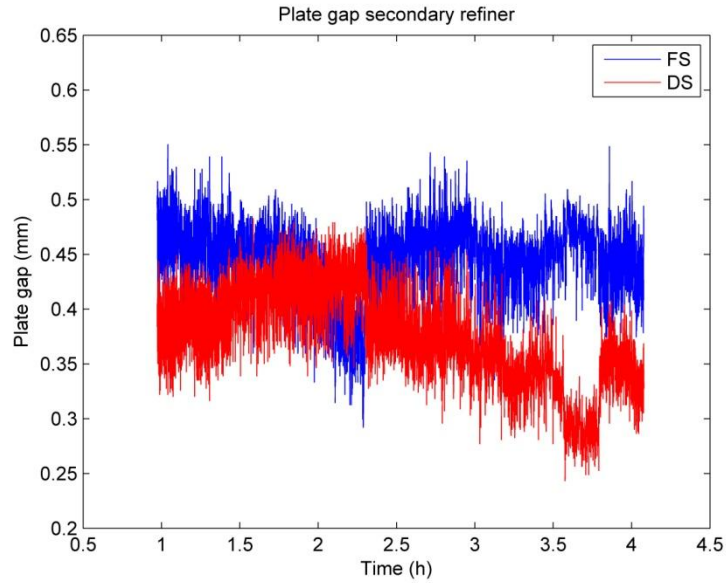
Figure 10: Plate gap for the secondary refiner on L2 during step changes in dilution water as seen in Figure 8.

Motor load

Primary: The estimated motor loads W_{FS} and W_{DS} on the primary refiners decrease with increased dilution water and increase with decreased dilution water, see Figure 11. With the step changes made in the experiments, where the total amount of dilution water remained the same, the zone with more dilution water had a larger decrease in motor load than the corresponding increase on the other zone, resulting in a decrease in total motor load (*W*), see Table 5. While the decrease in motor load only occurs for increases in dilution water, this nonlinearity clearly makes it possible to lower the total motor load without significantly affecting the outgoing consistency. As seen in Table 5 the standard deviation for the total motor load does not vary much during the experiments.

By increasing ΔD on the primary refiners, it is estimated that the energy consumption of the refiners can be significantly reduced. The mean reduction in motor load between the initial $\Delta D=0$ and the largest value of ΔD for the four tests on the primary refiners was 0.4251 MW. It is important to note that the maximum values of ΔD differed between the tests (40, 50, 60 and 80 *l*/min). If more step changes had been made, at least in the tests with $\Delta D=40$ and $\Delta D=50$, the mean reduction in motor load would probably have been higher.

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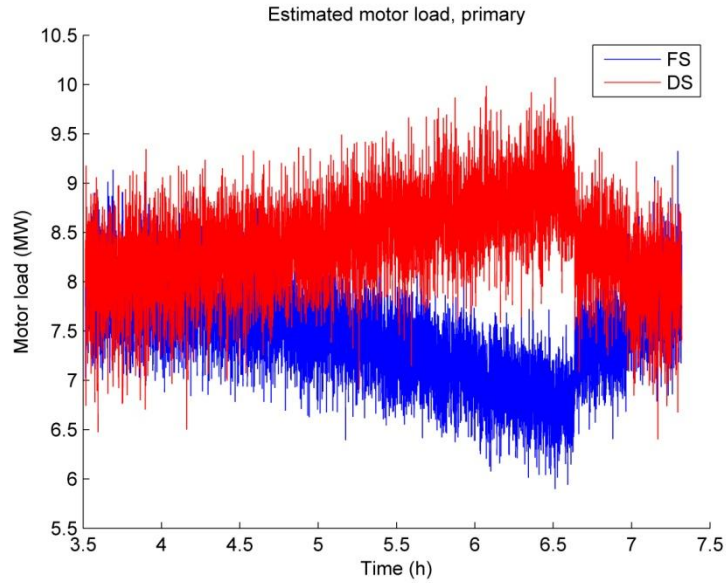
Figure 11: Motor load for the primary refiner on L2 during step changes in dilution water as seen in Figure 7.

Table 5: Total motor load, motor loads for each refining zone and standard deviation for the total motor load for step changes in dilution water.

	ΔD	W	Standard deviation (W)	W_{DS}	W_{DS}
Primary refiner (L2) **Test done on 2014-11-05**	0	15.8181	0.3316	7.4374	8.3805
	10	15.7545	0.3370	7.2629	8.4916
	20	15.7240	0.3284	7.1855	8.5373
	30	15.6920	0.3434	7.0157	8.6773
	40	15.6308	0.3193	6.8457	8.7839
	50	15.5748	0.3119	6.6683	8.9062
	0	15.8322	0.3052	7.4540	8.3782
	-20	15.9279	0.3147	7.7623	8.1657
	-40	15.9763	0.2784	8.2868	7.6901
Primary refiner (L2) **Test done on 2014-11-11**	0	15.1290	0.3063	7.4054	7.7236
	10	15.0572	0.3027	7.2397	7.8175
	20	14.8465	0.3177	7.0324	7.8150
	30	14.6030	0.2900	6.8859	7.7272
	40	14.6055	0.2993	6.7168	7.8993
	50	14.5546	0.3040	6.5953	7.9692
	60	14.3638	0.3321	6.5497	7.8964
Primary refiner (L2) **Test done on 2014-11-12**	0	15.9403	0.2749	7.8795	8.0608
	10	15.9716	0.2689	7.7828	8.1887
	20	15.9157	0.2574	7.6680	8.2477
	30	15.9142	0.2552	7.5666	8.3477
	40	15.9123	0.2804	7.4443	8.4679
	50	15.8577	0.2746	7.2872	8.5705

	ΔD	W	Standard deviation (W)	W_{DS}	W_{DS}
	60	15.7644	0.2807	7.0938	8.6706
	70	15.7260	0.2847	6.9268	8.7992
	80	15.6762	0.2928	6.7860	8.8902
Primary refiner (L1) **Test done on 2014-12-12**	0	16.0286	0.3173	8.8116	7.2170
	10	16.0389	0.3025	8.9344	7.1045
	20	15.9048	0.3111	8.8889	7.0159
	30	15.7992	0.3113	8.8862	6.9129
	40	15.6904	0.3224	8.8714	6.8190

Secondary: The estimated motor loads W_{FS} and W_{DS} on the secondary refiner follow an opposite pattern than that of the primary refiners, they increase with increased dilution water and decrease with decreased dilution water, see Figure 12. This suggests that it is not the dilution water in itself that primarily affects the motor loads. Instead it is likely that the plate gap plays a large role, as an increased plate gap leads to lower motor load and vice versa. This seems reasonable, as it likely requires more work to transport the pulp through a narrower opening between the refining segments than through a wider one. While the total motor load W on the secondary refiner seems to decrease with larger values of ΔD, the results are much more chaotic than the ones for the primary refiners, making them less reliable.
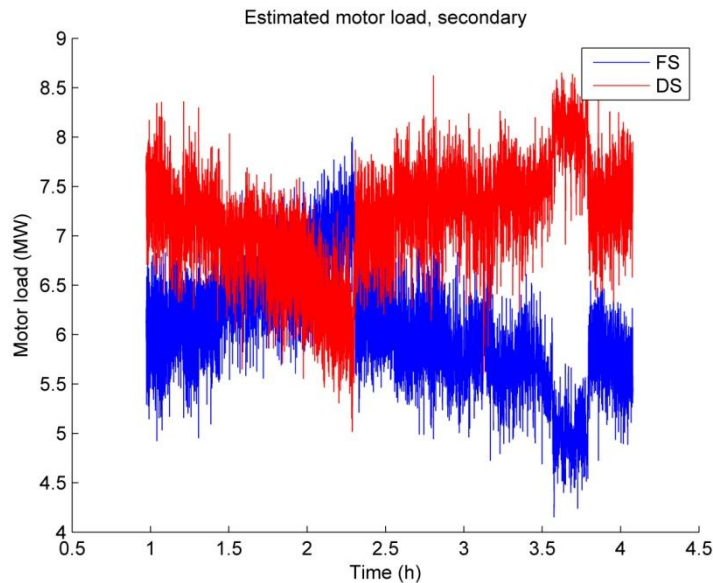
Figure 12: Motor load for the secondary refiner on L2 during step changes in dilution water as seen in Figure 8.

While a large value for ΔD on the secondary refiners might lead to decreased energy consumption, no estimation of this potential reduction will be made. This is partly due to the erratic behaviour of the motor load which makes it difficult to make an accurate estimation, and partly because large values of ΔD affect the balance and stability of the refiner negatively, see sections Acceleration and Temperature. Because of this it is probably better to set a value of ΔD that minimizes the acceleration on the secondary refiner.

It seems like the consistency is of little importance to the motor load. On the primary refiners the motor load increases with increased consistency, while on the secondary refiner it decreases with increased consistency, see Figure 15 and Figure 16.

Acceleration

Primary: The accelerations on the primary refiners decrease somewhat on both zones when there is a positive difference in dilution water, see Figure 13. The effect was more prominent on L1. During one of the tests on L2 the acceleration was increased on both sides for small changes in dilution water and decreasing for larger changes. On the primary refiners the solution to lower acceleration and better balance is to increase ΔD. There is obviously a limit to how much this can be done, but with the changes made in the experiments the acceleration was continually decreasing on both FS and DS.
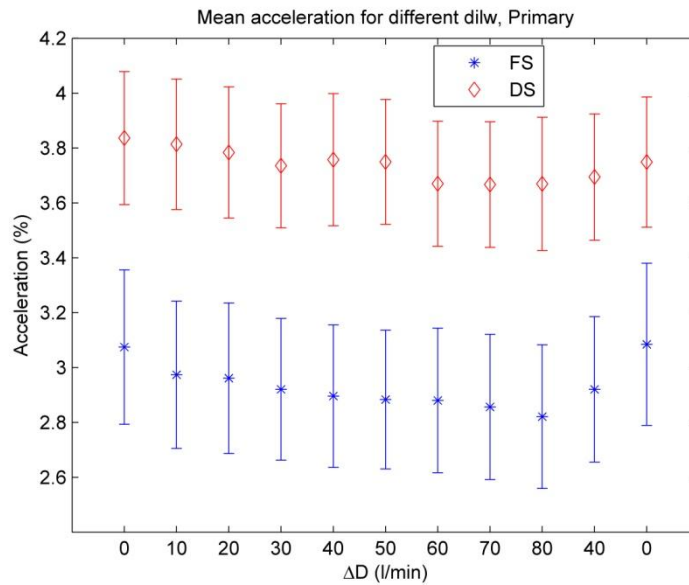
Figure 13: Mean acceleration for the primary refiner on L2 during step changes in dilution water. The different values represent the different levels of dilution water seen in Figure 7.

Secondary: On the secondary refiners the acceleration seems to be inversely proportional to the plate gap, i.e. increased dilution water leads to increased acceleration and vice versa, see Figure 14. This relationship is nonlinear, as the increase in acceleration on one side for large values of ΔD is much larger than the decrease in acceleration on the other side. Lowest total acceleration was achieved for small (positive) differences in dilution water (between 10 and 20 litres per minute difference between FS and DS). The consistency was more uneven between FS and DS for these levels of dilution water than it was for equal levels. It would therefore seem that the original hypothesis (that a more even consistency distribution between the refining zones leads to lower acceleration and better balance) can be discarded. The accelerations for FS and DS on the secondary refiner seem to be largely dependent on their individual process variables (such as plate gaps and motor loads), unlike the accelerations on the primary refiners which follow each other. For the secondary refiner the lowest total acceleration was achieved when the ratio Q (see Equation (3)) between the relative difference in plate gap and the relative difference in dilution water approached 1. It is important to note that this relation between Q and acceleration is only assumed to be valid for the refiner on L2 under certain conditions, and not for other refiners or other process conditions.

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$$Q = \frac{g_{FS}/g_{DS}}{D_{FS}/D_{DS}} \tag{3}$$
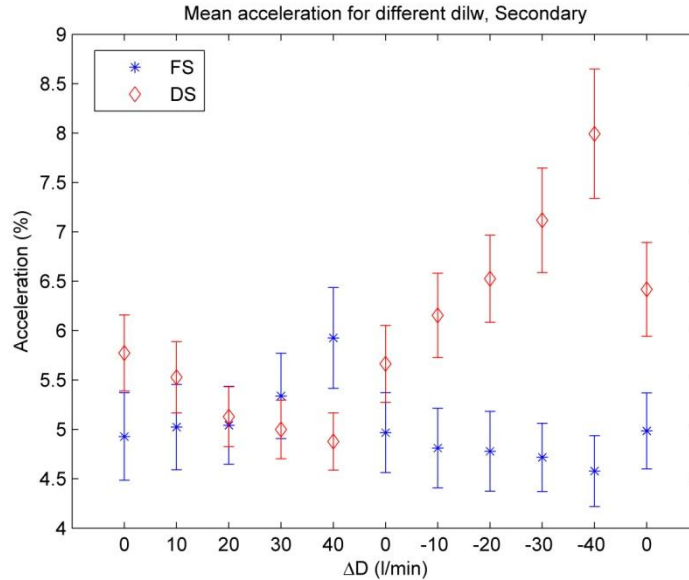
*Figure 14: Mean acceleration for the secondary refiner on L2
during step changes in dilution water. The different values
represent the different levels of dilution water seen in Figure 8.*

The acceleration on the primary refiners seem to be of little concern when changing the levels of dilution water, as it did not change much during the experiments. On the secondary refiner however, the increase in acceleration (and the standard deviation of that acceleration) on FS for large values of ΔD was too large to ignore. It might therefore be wise to only use small values of ΔD in the operation of the secondary refiner, using the ratio Q as a guideline.

The reason for the changes in acceleration is unknown. It is possible that it is tied to the plate gap (much like the motor load is hypothetically assumed to depend on the plate gap, and for similar reasons), but this would only explain the results for the secondary refiner. A lower motor load could likely lead to lower acceleration as well. On the primary refiner the results are quite surprising in that the acceleration on both sides are affected pretty much the same, while the other variables tend to change in opposite direction on the different sides. The lower accelerations cannot be attributed to a more even consistency distribution between the refining zones, as the consistencies diverge for increasing ΔD, see Figure 15.

Pulp Quality
The quality of the pulp was measured in three different variables: mean fibre length (MFL), shives (percentage of pulp) and freeness. Overall there were no clear trends for the mean fibre length during the experiments, though two tests on the primary refiner on L2 indicated a slight increase for increasing ΔD. On L2 the shive measurement showed no clear trends, while on L1 it seemed to be slightly higher for larger ΔD. Freeness seemed to increase slightly for larger differences in dilution water, but the trends were not clear. The quality measurements were taken with a sampling interval of about five minutes, making them quite unreliable due

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to the small amount of data gathered. The shive measurement in particular is known to be defective, making the values obtained nearly useless. While it seems that the quality did not suffer significantly during the experiments it is not possible to safely draw any conclusions from the obtained data. Given that the consistency (and other variables) changed considerably for the different refining zones during the experiments, it seems plausible that the pulp quality would have been affected in some way. The lower motor load on one side could indicate poorer quality in the pulp from that side, as reductions in motor load are often associated with negative impacts on quality (Hill (1993), Berg et al (2003), Eriksson (2005)). The change in r_{peak} on the secondary refiner could also have an impact on pulp quality (Sikter et al (2007)). Since the observed variables are measured on the mixed pulp from both refining zones, it would be possible for the different zones to produce pulp of very different quality without it showing in the measurements, providing that the changes in quality on each side cancel each other. For example, if the pulp from one side has a very short mean fibre length and the pulp from the other side has a very long mean fibre length, the pulp would likely have different qualities than if both sides produced similar pulp even though the resulting mean fibre length may be similar. Further testing is needed to establish how pulp quality is affected by changes in ΔD.

Consistency

As is to be expected, consistency decreases with increasing dilution water and vice versa. The original assumption however, that the consistency would be higher in the zone with the larger plate gap if the dilution water was the same to both zones, proved to be false. On the primary refiners the initial consistencies were the opposite, with higher consistency in the zone with the smaller plate gap, see Figure 15. On the secondary refiners the initial consistencies varied from being in line with the original hypothesis to being rather similar to each other, see Figure 16. These results do not indicate that Hypothesis A (see Equation (1)) is false, as it only deals with the pulp distribution between the refining zones and not the actual consistencies.

The total consistency was kept fairly constant during the tests (decreasing only slightly) on the primary refiners, despite the larger amount of pulp on the side with more water. This is due to the nonlinear relationship between the consistency and the amount of dilution water seen in Figure 15. On the secondary refiners the estimated consistency displayed a more chaotic behaviour, but the total consistency was still kept at roughly the same level.
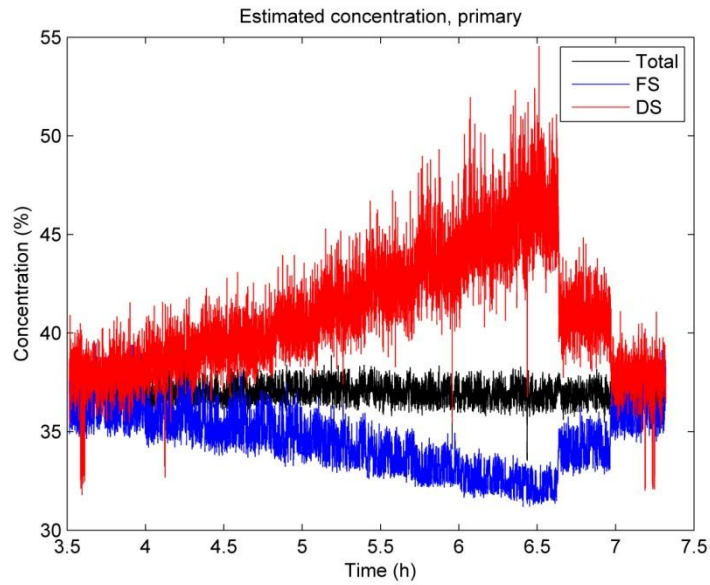
*Figure 15: Outgoing consistency for the primary refiner on L2
during step changes in dilution water as seen in Figure 7.*
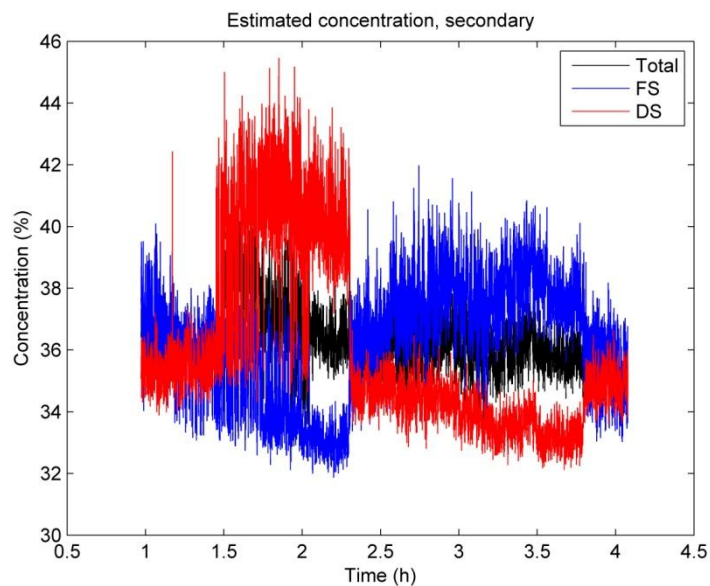
*Figure 16: Outgoing consistency for the secondary refiner on L2
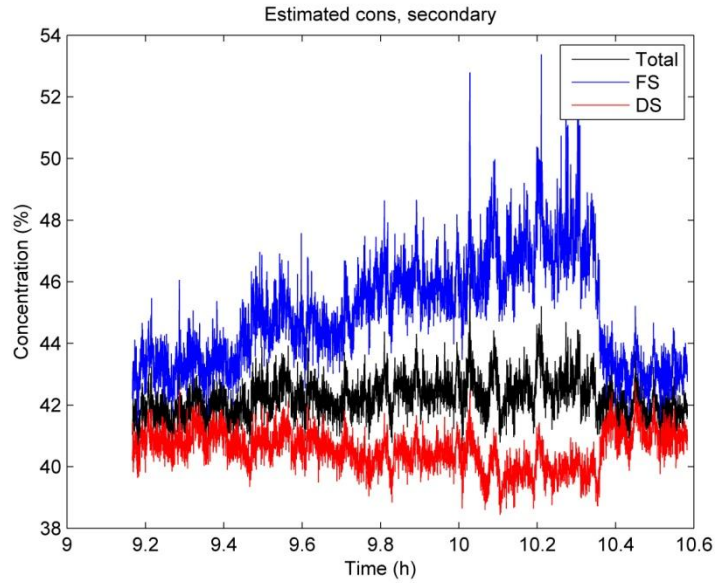during step changes in dilution water as seen in Figure 8.*

It is clear from the obtained results that the positive effects (regarding motor loads and stability) from increasing ΔD cannot be contributed to a more even consistency distribution in the two refining zones, as the difference in consistency was larger for the values of ΔD that exhibited these positive effects than for $\Delta D=0$. The consistency seems to have little impact on the motor load and acceleration of the refiners, though it may still affect the quality of the pulp.

It seems that the temperature is of great importance for the consistency. The most obvious sign of this is the previously mentioned initial consistencies on the primary refiners, where the consistencies were higher on the sides with the smallest plate gaps for $\Delta D=0$, contrary to what was previously believed. This means that it is very difficult to estimate the consistency using only the dilution water and plate gap measurements.

The consistency estimations obtained using the extended entropy model has previously been shown to be very close to the measured consistency in a twin refiner (Karlström and Eriksson (2014a, 2014b, 2014c, 2014d)). Unfortunately manual testing has shown that the consistency measurements at Stora Enso are unreliable, so there are no reliable measured values to compare the estimations with for the tests described in this paper.

From the results obtained it is deemed that it would be beneficial to implement the extended entropy model to continuously estimate the consistency in the refiners. This would provide the possibility to not only control the consistency of the mixed pulp from both refining zones but also control the consistency out from each refiner. As has been shown the consistency in a zone can easily be increased or decreased by decreasing or increasing the dilution water to that zone, which makes a control platform easy to implement. Such a platform would offer much better control over the consistency than the current implementation.

While no certain conclusions can be drawn from the results of these experiments regarding the quality of the pulp, it is reasonable to assume that the consistency can have an impact as the residence time, i.e. the amount of time spent inside the refiner by the pulp, is intertwined with the consistency, see Figure 17 and Figure 18, especially for the primary refiners. It has been shown by Karlström and Hill (2014a) that the residence time is of great importance for the quality of the pulp. This means that the previously mentioned control platform most likely can provide improved control of pulp quality.
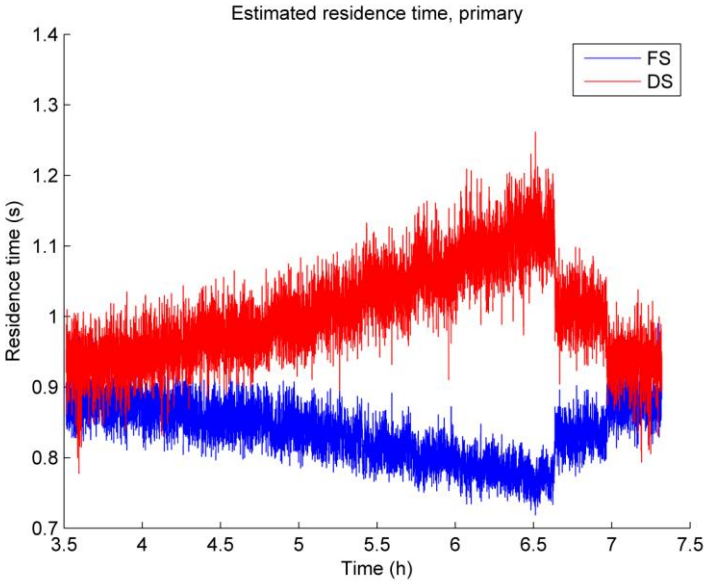
Figure 17: Estimated residence time of the pulp in the primary refiner on L2 during step changes in dilution water as seen in Figure 7.
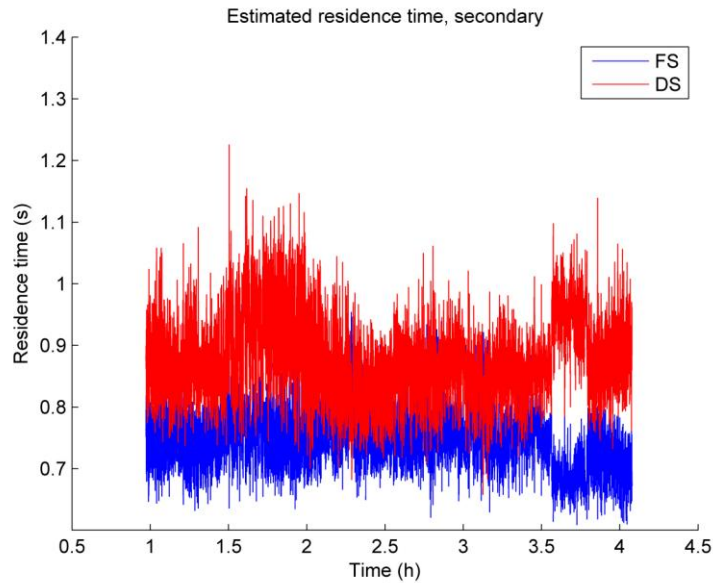
Figure 18: Estimated residence time of the pulp in the secondary refiner on L2 during step changes in dilution water as seen in Figure 8.

Temperature

The temperature behaves mostly as expected when changing the amount of dilution water, see Karlström and Hill (2014a). For increased dilution water the temperature is lowered in the beginning of the refining zone and increased in the end, and for decreased dilution water the temperature is increased in the beginning and lowered in the end, see Figure 19 and Figure 20. The position of the maximum temperature changes accordingly on the secondary refiners (T_{max} is moved toward larger radius with increasing dilution water and moved toward smaller radius for decreased dilution water), while remaining fairly constant on the primary refiners. The reason why the position does not change on the primary refiners is likely that there is a build-up of fibres, chips and shives, as described in the Twin refiner section. For very large amounts of dilution water on the primary refiners the entire temperature profile is lowered. This is likely due to the cooling effect of the water as well as the lower motor load.
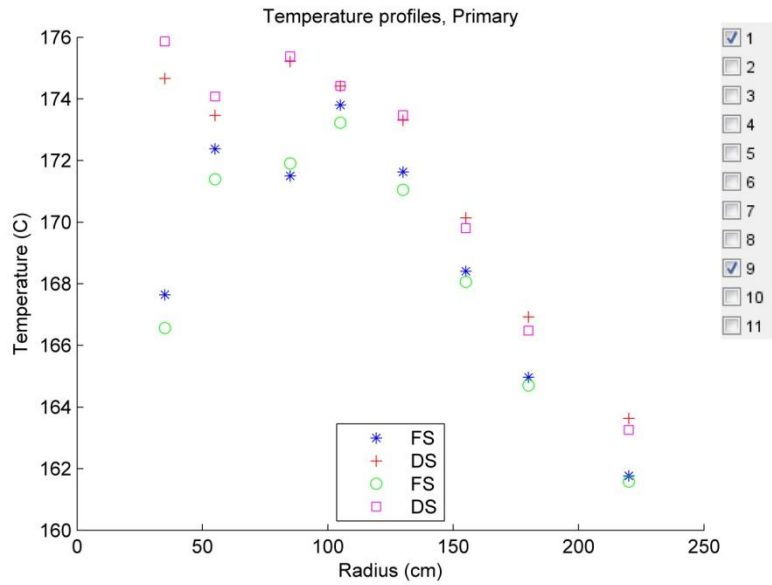
Figure 19: Temperature profile for the primary refiner on L2 during step changes in dilution water as seen in Figure 7. The blue stars and red crosses represent the mean temperatures measured on each temperature sensor for ΔD=0. The other values are for ΔD=80, i.e. the largest value of ΔD for the experiment. Note that the third sensor on FS and the first sensor on DS are likely somewhat malfunctioning.
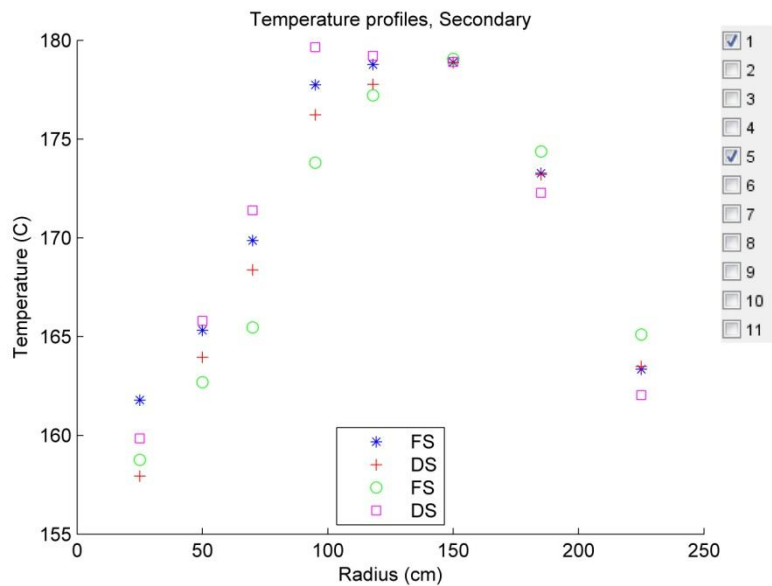
Figure 20: Temperature profile for the secondary refiner on L2 during step changes in dilution water as seen in Figure 8. The blue stars and red crosses represent the mean temperatures measured on each temperature sensor for ΔD=0. The other values are for ΔD=40, i.e. the largest value of ΔD for the experiment.

On the secondary refiner the standard deviations of the temperatures before the maximum temperature were lowered for the cases with increased dilution water (see Figure 21),

indicating a more homogenous mass and better stability. For decreased dilution water there was instead an increase in standard deviation. This indicates opposite effects on stability than what is indicated by the accelerations. On the primary refiner there were no recurrent trends regarding the standard deviation of the temperature before the maximum temperature. This is likely due to the superior stability of the primary refiners (compared to the secondary refiners), which makes the effect of the changes in dilution water negligible.
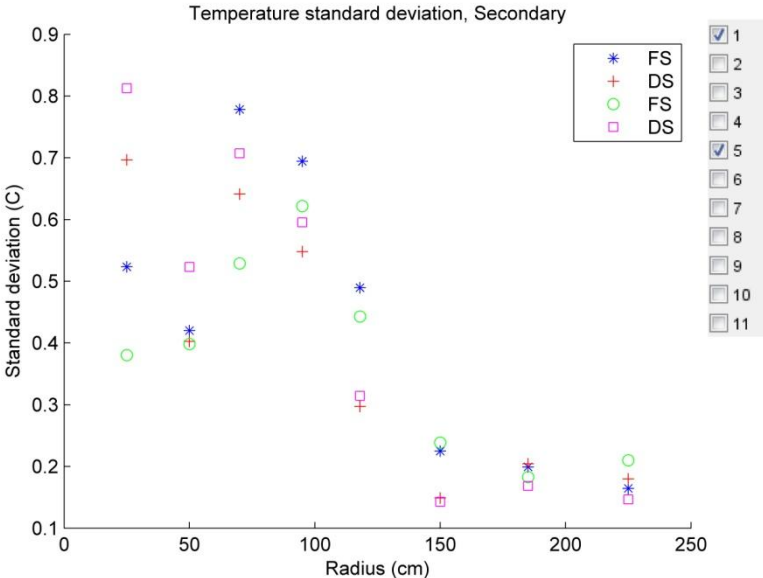
Figure 21: Standard deviation for the temperatures seen in Figure 20.

Mass flows (pulp and water)

The pulp mass flows through the refiners are as to be expected, i.e. a larger plate gap means more pulp/wood, see Figure 22 and Figure 23. The water mass flows are equally predictable on the primary refiners; more dilution water means more water, see Figure 24. On the secondary refiners the relationship is similar (see Figure 25) though the water flows behave much more erratically, at times showing no clear trends. The water flows after changes in dilution water tend to converge to the original toward the end of the refiner. One test was an exception to this, as the water flow for the increased dilution water was lower than the original (for unknown reasons). The trend was still the same, however, as the water flows for increased ΔD were relatively lower toward the end of the refiner.
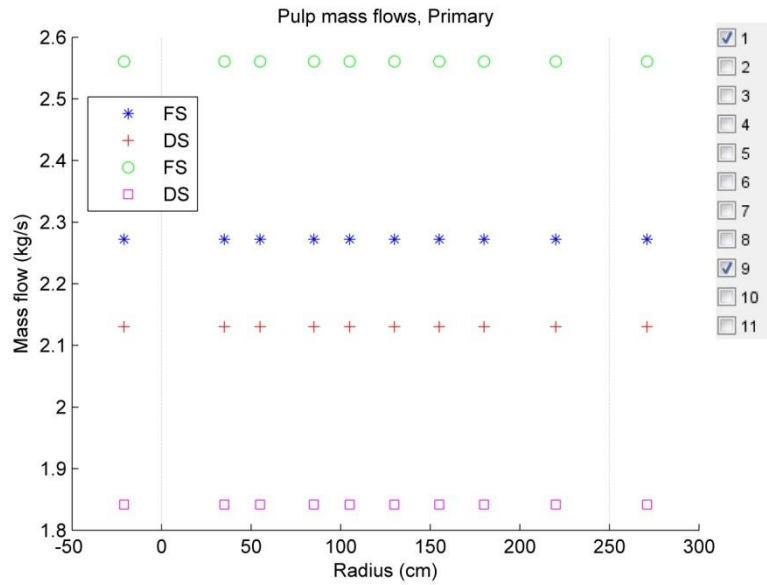
Figure 22: Pulp mass flows for the primary refiner on L2 during step changes in dilution water as seen in Figure 7. The blue stars and red crosses represent the mean mass flows estimated on each temperature sensor for ΔD=0. The other values are for ΔD=80, i.e. the largest value of ΔD for the experiment. The first and last values are for the inlet and outlet respectively.
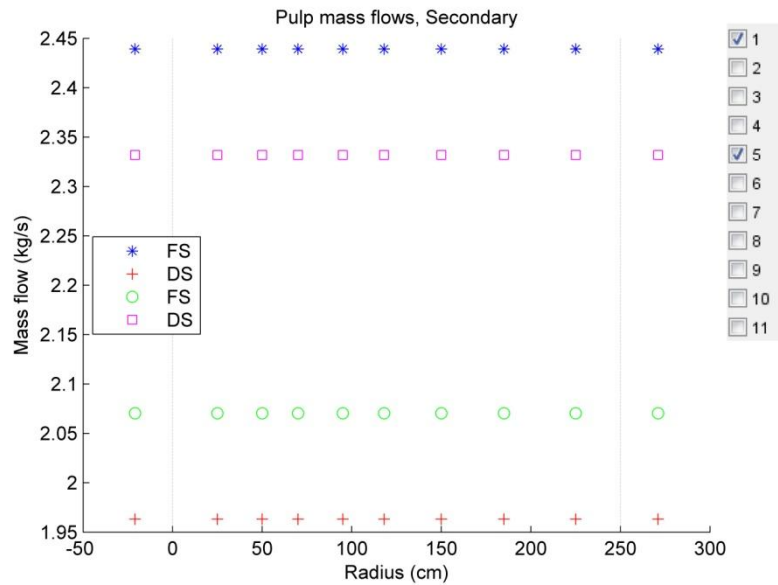
Figure 23: Pulp mass flows for the secondary refiner on L2 during step changes in dilution water as seen in Figure 8. The blue stars and red crosses represent the mean mass flows estimated on each temperature sensor for ΔD=0. The other values are for ΔD=40, i.e. the largest value of ΔD for the experiment. The first and last values are for the inlet and outlet respectively.
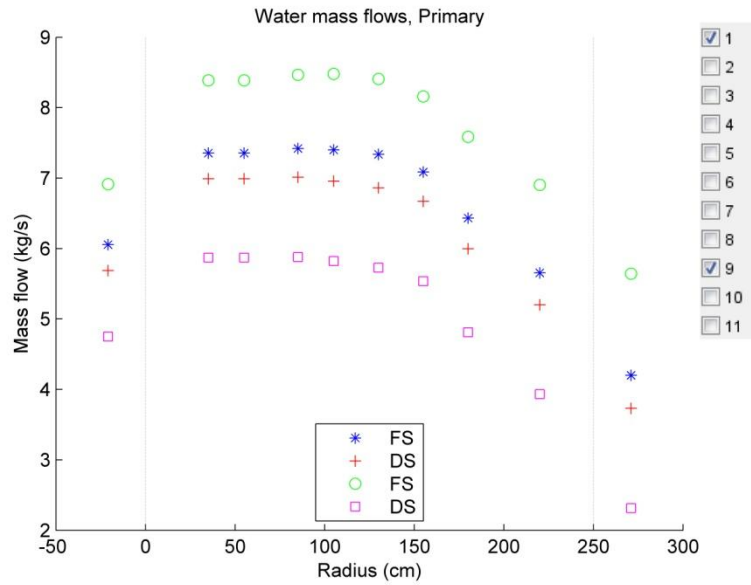
Figure 24: Water mass flows for the primary refiner on L2 during step changes in dilution water as seen in Figure 7. The blue stars and red crosses represent the mean mass flows estimated on each temperature sensor for ΔD=0. The other values are for ΔD=80, i.e. the largest value of ΔD for the experiment. The first and last values are for the inlet and outlet respectively.
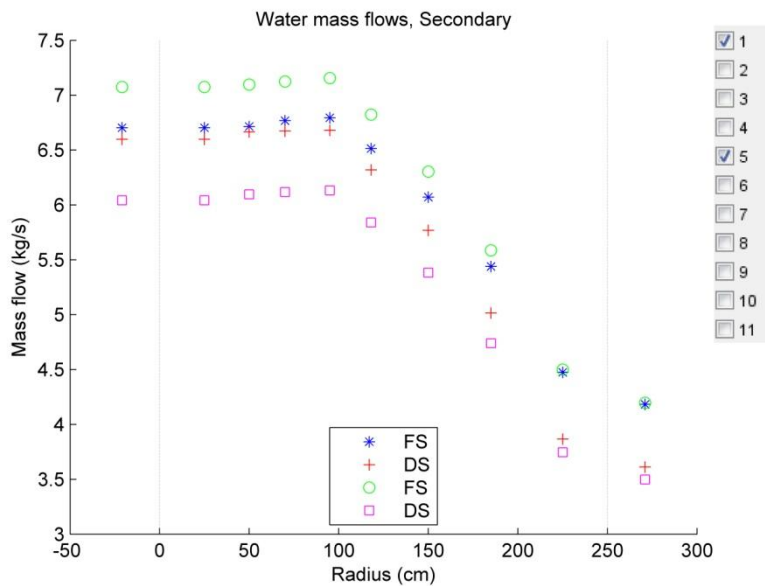
Figure 25: Water mass flows for the secondary refiner on L2 during step changes in dilution water as seen in Figure 8. The blue stars and red crosses represent the mean mass flows estimated on each temperature sensor for ΔD=0. The other values are for ΔD=40, i.e. the largest value of ΔD for the experiment. The first and last values are for the inlet and outlet respectively.

Mass flows (steam)

The results for the steam flows are not conclusive, though some possible trends can be seen. *Primary*: The negative (backward) steam flows on the primary refiners tend to decrease for both positive and negative changes in dilution water, except for in one case where it increased for small to medium positive changes, see Figure 26. For the case with increased dilution water, this is likely due to the cooling effect of the water, which can also be seen in the temperature profile. The increased steam may be due to the larger amount of water allowing more steam to form. For the case with decreased dilution water the changes are much smaller, often non-existent. A smaller amount of water means less steam generation, but the higher temperature counteracts this somewhat. The positive (forward) steam flows on the primary refiners seem to decrease for positive changes in dilution water, though it sometimes increases for small changes. This is a result similar to that obtained for the negative steam flow, and the same reasons probably apply. While the decrease is larger for the forward flowing than the backward flowing steam, the amount of forward flowing steam is much larger, leading to a smaller relative decrease. This is to be expected as the decrease in temperature is smaller towards the end of the refining zone. For negative changes in dilution water the forward flowing steam is unchanged or increased.
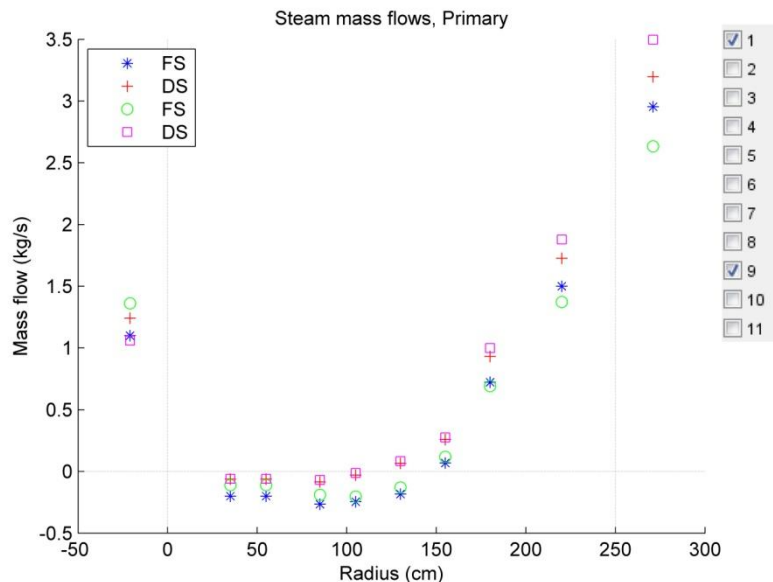
Figure 26: Steam mass flows for the primary refiner on L2 during step changes in dilution water as seen in Figure 7. The blue stars and red crosses represent the mean mass flows estimated on each temperature sensor for ΔD=0. The other values are for ΔD=80, i.e. the largest value of ΔD for the experiment. The first and last values are for the inlet and outlet respectively.

The steam flows often change very little when the amount dilution water is changed, and the changes are not always consistent for different experiments. This can be attributed to several factors. A larger amount of dilution water naturally means that there is more water to evaporate, which could suggest a higher steam production. However, more water also means that more energy is used to heat the water, leaving less energy for the evaporation. This might explain why there often is more steam formed when decreasing the dilution water; less water means less energy used for heating liquid water and thus more energy for evaporation. For

large positive changes in dilution water this cooling effect can actually be seen in the temperature profile, as the temperature is lowered across the entire refiner.

Secondary: For the secondary refiner on L2 the negative steam flow increases for a larger amount of dilution water, while the positive steam flow increases, see Figure 27. The results are the opposite for negative changes in dilution water, i.e. less water means more forward flowing and less backward flowing steam. The temperature profiles seen in Figure 20 show that the steam mass flows does not behave as one might expect with regard to the temperature; lower temperature in the beginning and higher temperature in the end coincide with more backwards flowing and less forward flowing steam, and vice versa. This can be contributed to the changes in r_{peak} (position of the maximum temperature). Since the direction of the steam flow depends on the pressure gradient and the pressure depends on the temperature, a large value for r_{peak} means that most of the generated steam will flow backward while a small value means that most of the generated steam will flow forward. The position of T_{max} varies considerably for different amounts of dilution water on the secondary refiner, and the amount of backward flowing steam is higher for a larger radius (as in the case with increased dilution water) and lower for a smaller radius (as in the case with decreased dilution water). The amount of forward flowing steam toward the end of the refiner seem to follow the water flows in the same area, i.e. there is a larger increase or decrease relative to the original values (for unchanged dilution water). This is to be expected, as less water naturally means more steam being generated.
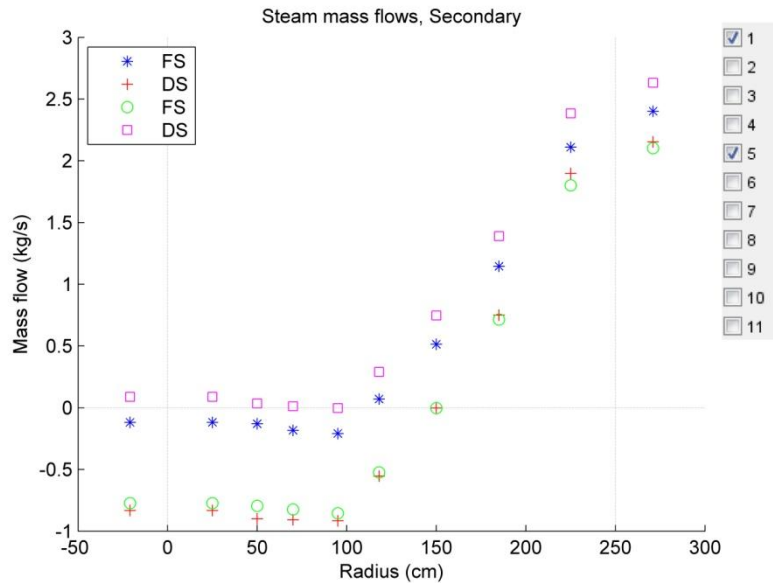
Figure 27: Steam mass flows for the secondary refiner on L2 during step changes in dilution water as seen in Figure 8. The blue stars and red crosses represent the mean mass flows estimated on each temperature sensor for ΔD=0. The other values are for ΔD=40, i.e. the largest value of ΔD for the experiment. The first and last values are for the inlet and outlet respectively.

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Secondary refiner on L1
The secondary refiner on L1 did not exhibit the same characteristics as the one on L2. Since only one rather incomprehensive test was done the results have not been reproduced, which gives them little scientific value. The most striking difference compared to the refiner on L2 was that the plate gaps were almost unaffected by changes in dilution water, see Figure 28 and Figure 29. This is likely tied to the increased motor loads seen in Figure 30. Unlike the other refiners, the motor load increased on both sides for changes in ΔD. Looking at the accelerations and standard deviations in temperature it seems as if the stability suffered as well. The consistency did however behave as expected (see Figure 31).

The reason for the unchanged plate gaps is not known. It is possible that an explanation can be found in the large plate gaps (relative the secondary refiner on L2, see Figure 10). The larger volume between the plates leads to lower pressure pushing the plates apart. At the same time the hydraulic pressure (pushing the plates together) was slightly higher for the secondary refiner on L1 (about 91 bar) than the one on L2 (about 85 bar). This indicates that the pressure from the steam inside the refiner is of less importance to the plate gap on the secondary refiner on L1 than it is on the secondary refiner on L2, which would explain why the plate gaps are practically unaffected by changes in dilution water.
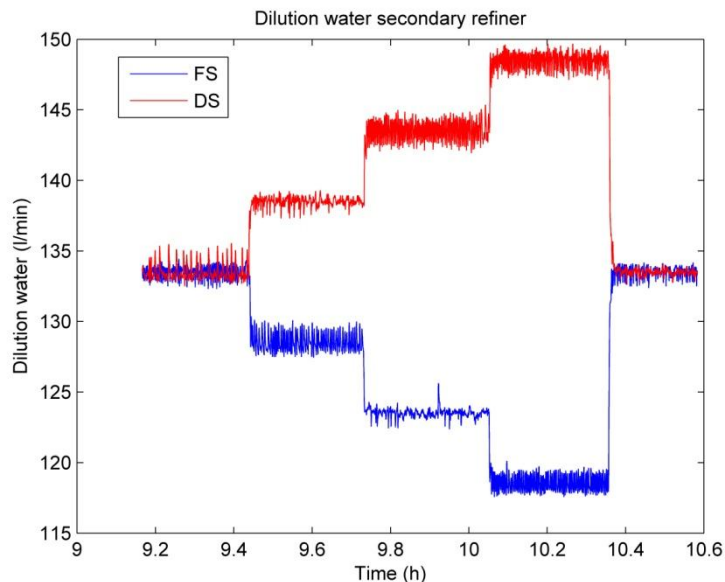
Figure 28: Dilution water for the secondary refiner on L2
during the test performed 2014-12-12.

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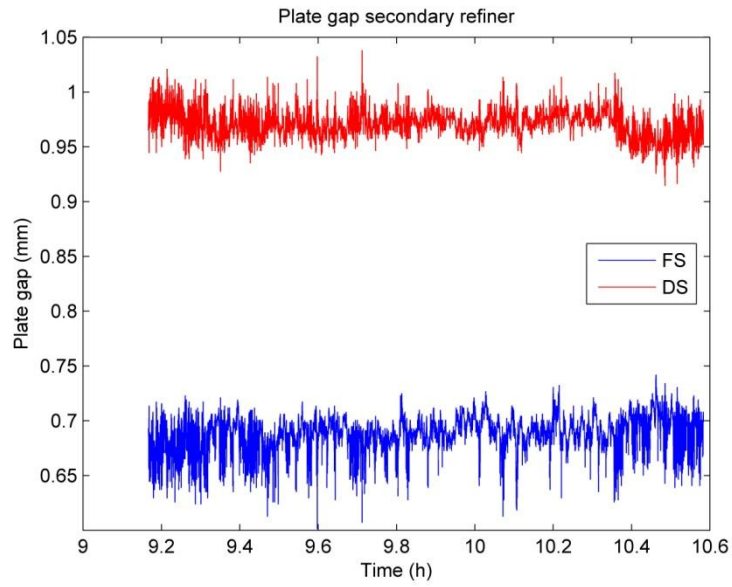
Figure 29: Plate gap for the secondary refiner on L2 during step changes in dilution water as seen in Figure 28.
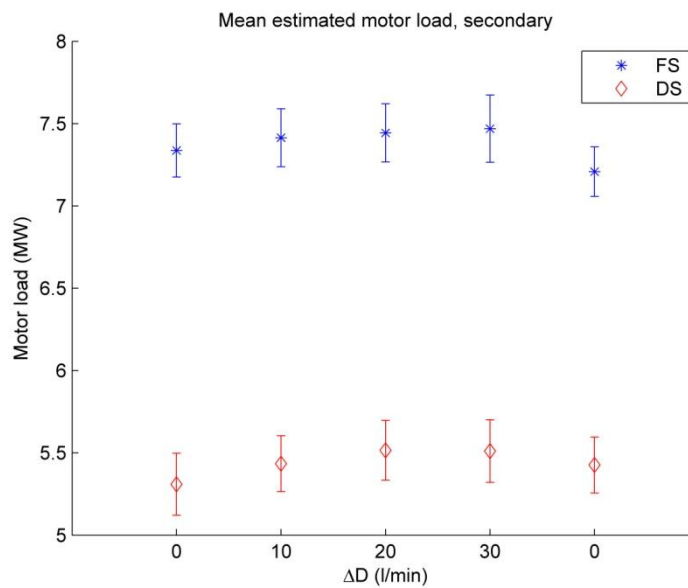
Figure 30: Motor load for the secondary refiner on L2 during step changes in dilution water as seen in Figure 28.

Figure 31: Consistency for the secondary refiner on L2 during step changes in dilution water as seen in Figure 28.

Stability

Primary: In the following, figures depicting the standard deviation in temperature on FS (Figure 32), the standard deviation in temperature on the DS (Figure 33), the standard deviation in acceleration (Figure 34) and mean acceleration (Figure 35) on the primary refiner on L2 during one of the tests[4] are shown. The standard deviations in temperature from the sensors before the maximum temperature can be used as a measure of the stability of the refiners, as can the acceleration and the standard deviation of the acceleration. While the acceleration is higher on DS than it is on FS (Figure 35), the standard deviation in acceleration is lower (Figure 34), as are the standard deviations in temperature before T_{max} (Figure 32 and Figure 33). On the primary refiner on L1 the relationship is the same for the standard deviation in acceleration and the standard deviations in temperature, but the acceleration is higher on FS than on DS, see Appendix I. As mentioned in the Acceleration section the acceleration likely depends on the plate gap, which would explain the differences in acceleration between the primary refiners on L1 and L2 ($g_{DS} > g_{FS}$ on L1 while $g_{FS} > g_{DS}$ on L2). The other variables do not seem to have the same plate gap dependency however, but instead indicate that DS is more stable than FS on both of the primary refiners. Both the standard deviations in acceleration and the standard deviations in temperature before T_{max} are lowered for increased ΔD, which further indicates that the stability of the primary refiners is somewhat improved for larger values of ΔD. The temperature changes very little on the primary refiners when changing the levels of dilution water, see Figure 36 and Figure 37.

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[4] Standard deviations and mean values in these figures are based on a time horizon of 100 samples (100 seconds).
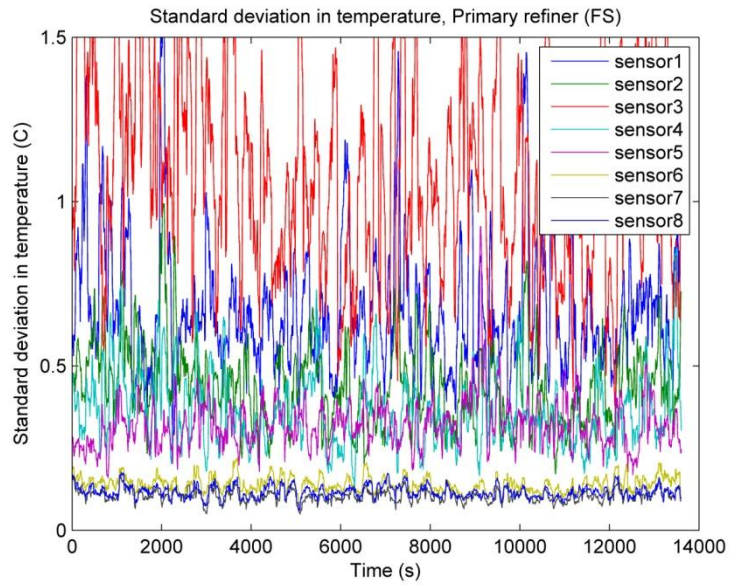
Figure 32: Standard deviation in temperature for the different temperature sensors in the primary refiner (FS) on L2 during step changes in dilution water as seen in Figure 7.
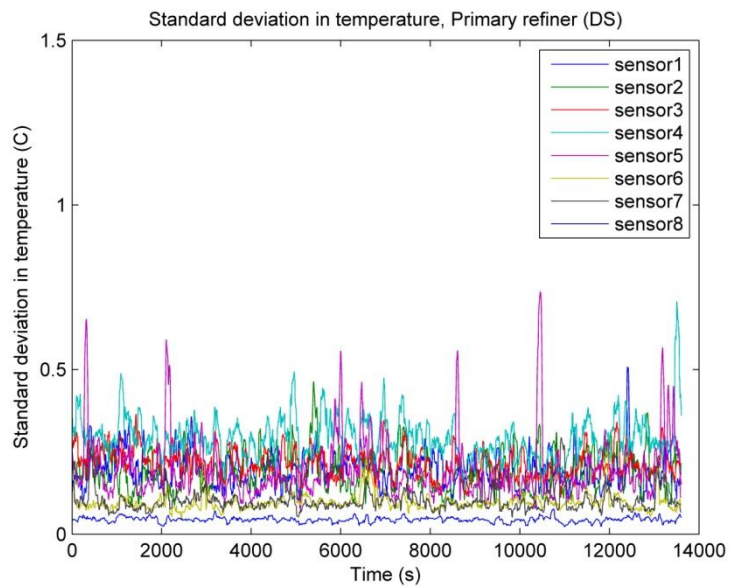
Figure 33: Standard deviation in temperature for the different temperature sensors in the primary refiner (DS) on L2 during step changes in dilution water as seen in Figure 7.
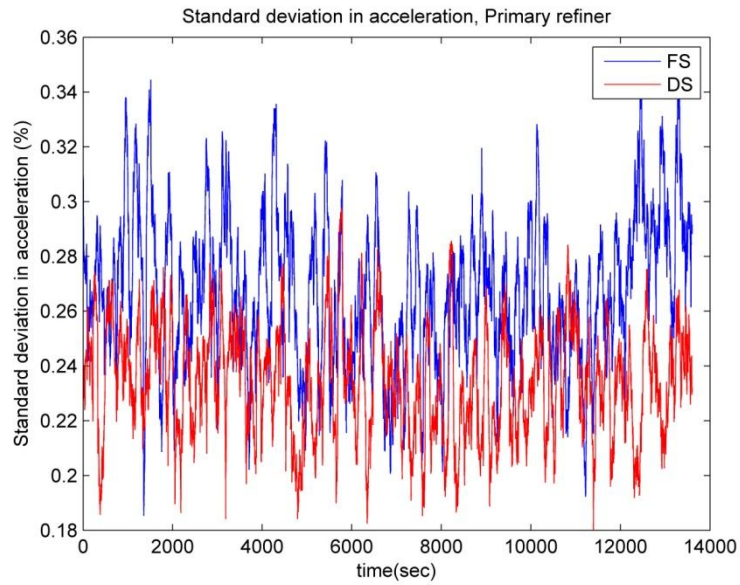
Figure 34: Standard deviation in acceleration for the primary refiner on L2 during step changes in dilution water as seen in Figure 7.
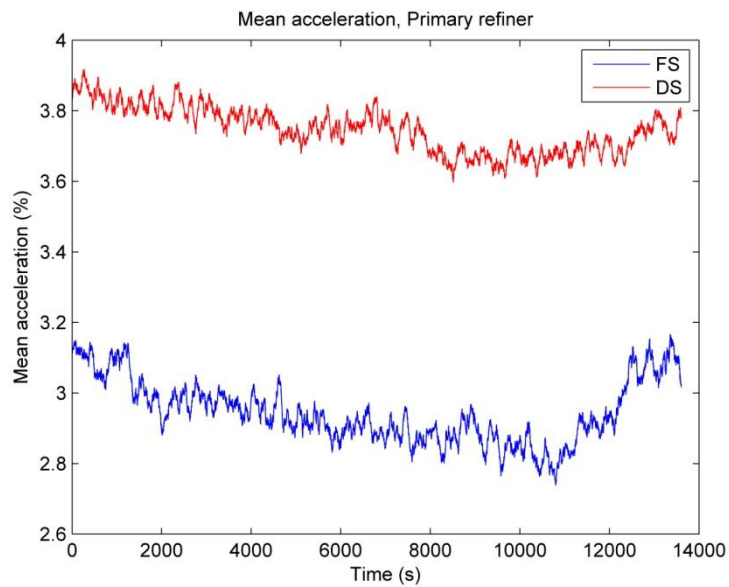
Figure 35: Mean acceleration on the primary refiner on L2 during step changes in dilution water as seen in Figure 7.
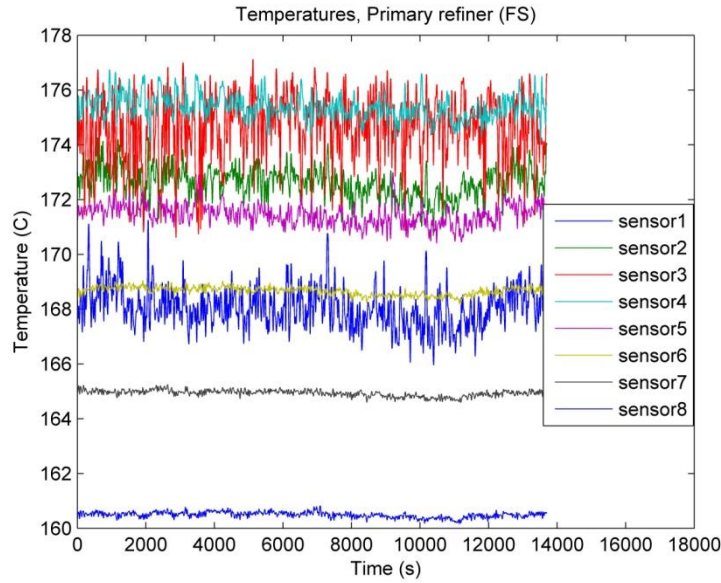
Figure 36: Temperature for the different temperature sensors in the primary refiner (FS) on L2 during step changes in dilution water as seen in Figure 7.
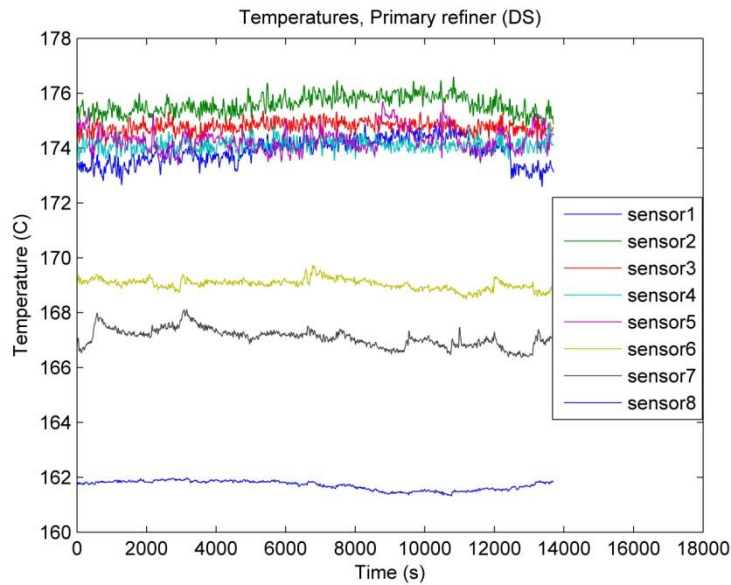
Figure 37: Temperature for the different temperature sensors in the primary refiner (DS) on L2 during step changes in dilution water as seen in Figure 7.

Secondary: The standard deviation in temperature on FS (Figure 38), the standard deviation in temperature on the DS (Figure 39), the standard deviation in acceleration (Figure 40) and mean acceleration (Figure 41) on the secondary refiner on L2 during one of the tests are shown below. The standard deviations in temperature for the different tests indicate that DS is slightly more stable than FS on both of the secondary refiners, but it is not nearly as apparent as on the primary refiners. Unlike for the primary refiners, where all of the variables changed in the same direction during changes in dilution water, the standard deviations in temperature indicate an opposite relation between dilution water levels and stability compared with the acceleration and standard deviation in acceleration. On the side with increased dilution water the standard deviation in temperature before T_{max} indicate improved stability, while the

stability on side with decreased dilution water is reduced. Changes in acceleration and standard deviation in acceleration contradicts those results, and indicate improved stability for decreased dilution water and vice versa. The temperature is much more sensitive to changes in dilution water than on the primary refiners, see Figure 42 and Figure 43.
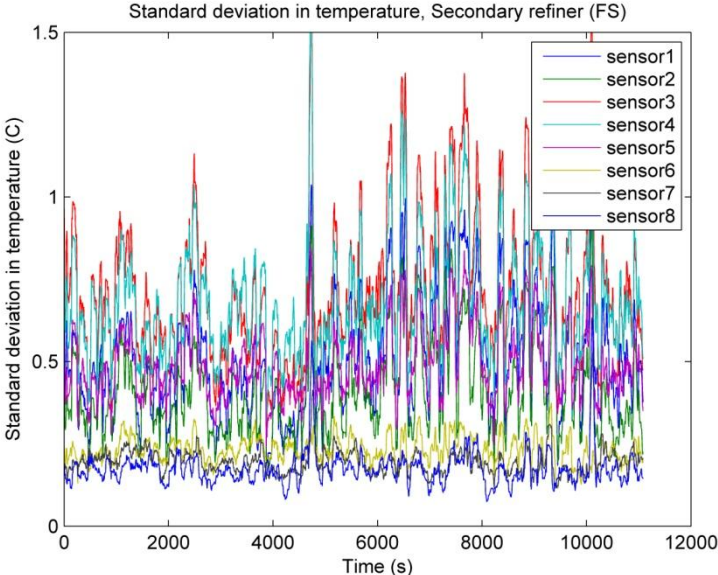
Figure 38: Standard deviation in temperature for the different temperature sensors in the secondary refiner (FS) on L2 during step changes in dilution water as seen in Figure 8.
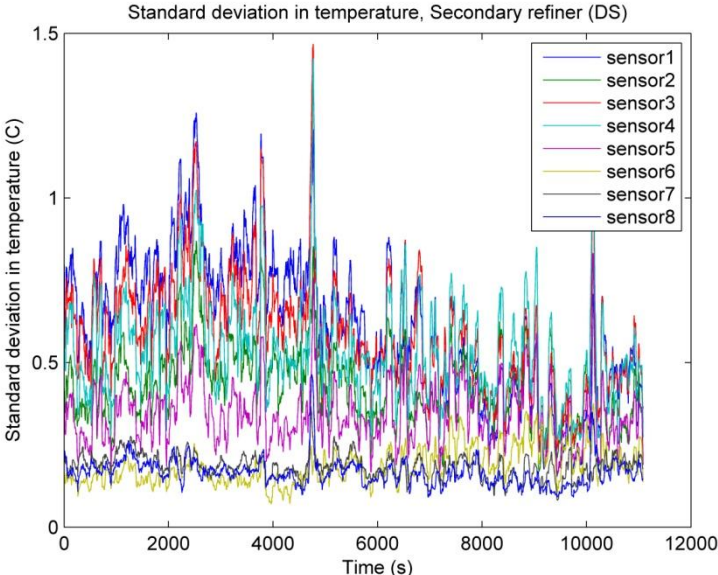
Figure 39: Standard deviation in temperature for the different temperature sensors in the secondary refiner (FS) on L2 during step changes in dilution water as seen in Figure 8.
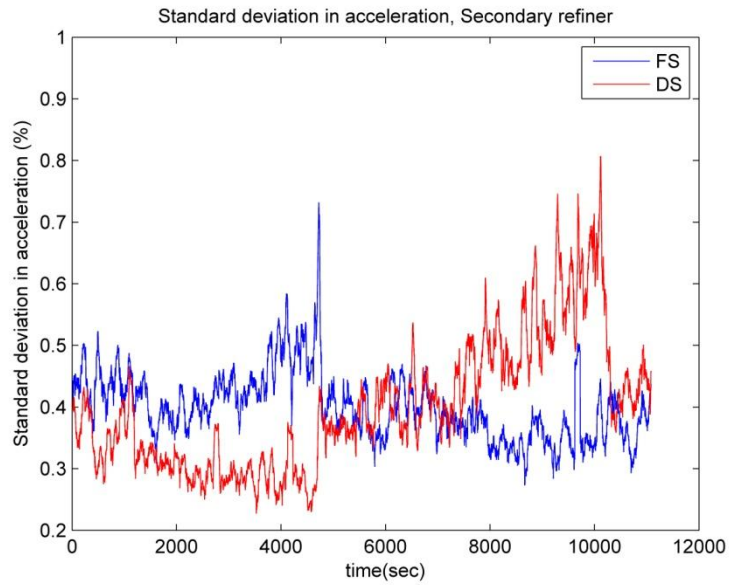
Figure 40: Standard deviation in acceleration for the secondary refiner on L2 during step changes in dilution water as seen in Figure 8.
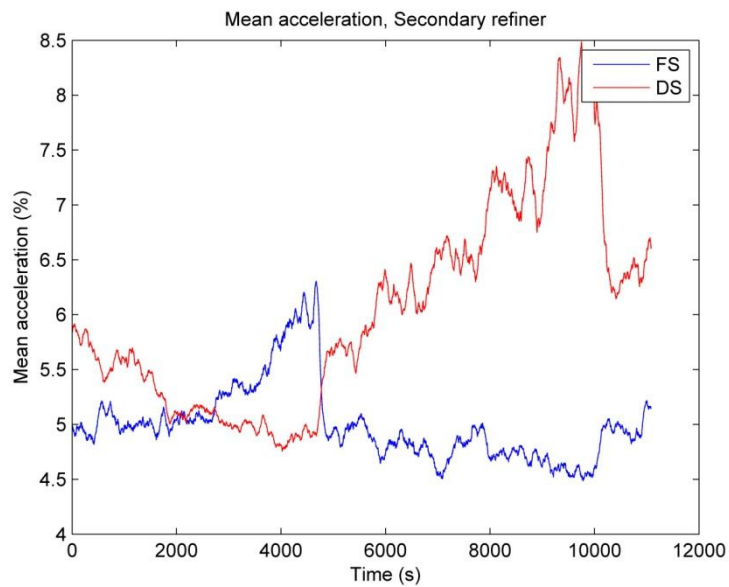
Figure 41: Mean acceleration on the secondary refiner on L2 during step changes in dilution water as seen in Figure 8.
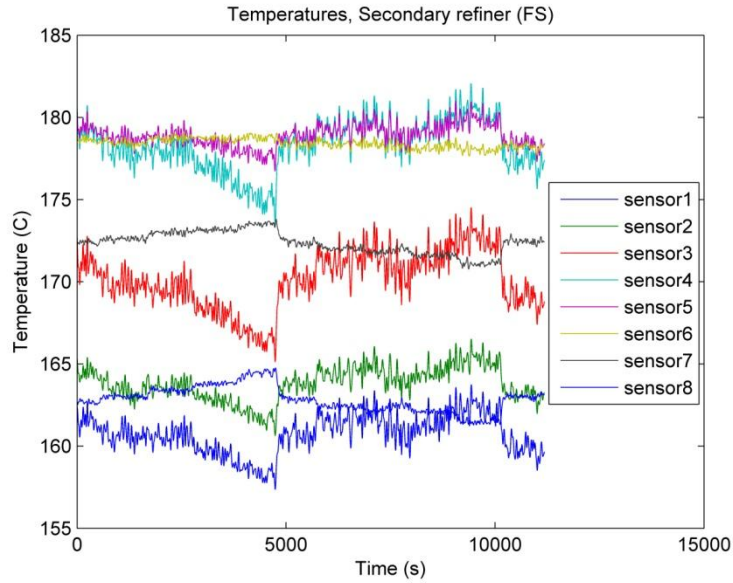
Figure 42: Temperature for the different temperature sensors in the secondary refiner (FS) on L2 during step changes in dilution water as seen in Figure 8.
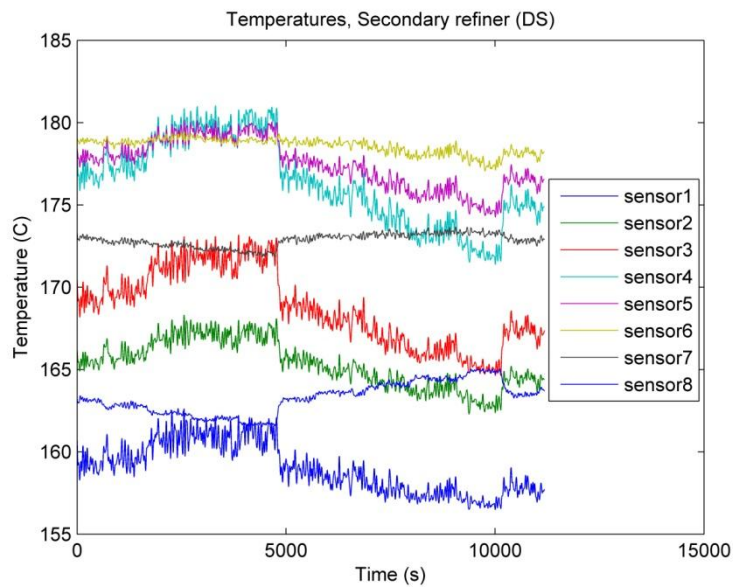
Figure 43: Temperature for the different temperature sensors in the secondary refiner (DS) on L2 during step changes in dilution water as seen in Figure 8.

According to Anders Karlström (2015, private conversation) the acceleration is not necessarily a reliable indicator of stability. Since the accelerations and standard deviations in temperature before T_{max} give conflicting results regarding the difference in stability between FS and DS (on all the refiners) and the effect of changes in dilution water (secondary refiner on L2), it is assumed that the standard deviation in temperature before T_{max} might be a better indicator of stability than the acceleration. However, this statement has to be analyzed further.

Optimization

One of the aims referred to optimization of FS and DS by controlling the dilution water feed rates individually to reach the same consistency at each side of the refiners. It was hoped that a more homogenous consistency would lead to increased stability and lower power consumption, but that was not the case[5]. According to the obtained results similar consistency inside the refiners seems to be of little importance when it comes to the minimization of the motor loads, accelerations and standard deviations in temperature before T_{max}, i.e. the variables that we want to decrease in order to reduce power consumption and increase stability. Because of these findings, two general optimization techniques will be proposed: one to optimize for power consumption and stability, and one to control the consistency inside the refiners.

Power consumption and stability: On the primary refiners there seems to be only positive effects to be gained from increasing ΔD. Setting at least ΔD=60 *l*/min would have a large positive impact on the energy consumption and a minor improvement on the stability of the refiners. It is important to note that this optimization is likely to have negative effects on pulp quality since the changes in consistency from each refining zone become very large. Further study of the pulp quality is needed before considering such an implementation.

Due to the differences between the secondary refiners on L1 and L2 and the uncertainty regarding both power consumption and stability, no general optimization techniques are proposed for the secondary refiners.

Consistency: While it may be presumed that the consistency from each refining zone could be approximated by just looking at the plate gaps and levels of dilution water, the results from the tests suggest otherwise. The environment inside the refiner plays an important role in the outgoing consistency, making it hard (if not impossible) to accurately control the consistency from each zone using the currently available equipment. If the consistencies from each zone are known however, it would be fairly simple to individually control them by changing the levels of dilution water. As can be seen in Figure 15 and Figure 16 the consistencies respond well to such changes. If the extended entropy model is implemented in a control platform it can provide continuous estimations of the consistency from each refining zone, allowing better control than what is currently possible. Such a control platform can be used on all four refiners on L1 and L2 and most likely on any other similar twin refiner as well.

Conclusion

The results obtained show that it is possible to accurately control the consistency on each side in a twin refiner (using the extended entropy model) by manipulating the dilution water to each side. While the consistencies respond mostly as expected to changes in dilution water, the consistencies for equal amounts of dilution water on each side are not positively correlated to the plate gaps as previously believed. This can be a consequence of the dynamics in the temperature profiles inside the refiners, which seems to have a more important impact on the outgoing concentration than expected. Better stability and power consumption were achieved by increasing the difference in dilution water between the zones on the primary refiners. These positive results were only achieved for positive changes in ΔD (increased dilution water on the side with the largest initial plate gap and decreased dilution water on the side

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[5] This is based on measurements of motor loads and accelerations, as well as standard deviations in acceleration and temperature.

with the smallest initial plate gap). Standard deviation in temperature before T_{max} is probably a better indicator of stability than acceleration.

The primary and secondary refiners react differently to changes in dilution water. Most importantly the plate gap changes in different directions on the primary refiners compared to the secondary refiner on L2. While the position of T_{max} seem to be fairly constant on the primary refiners, it changes considerably on the secondary refiner on L2 when changing the level of dilution water. This is likely a reason for the different behaviours of the primary and secondary refiners, as the position of T_{max} determines the steam flow. The steam flow in turn has an impact on the plate gaps. On the primary refiners the temperatures change very little when altering the levels of dilution water, in contrast to the secondary refiners where the temperatures vary several degrees for different levels. The secondary refiner on L1 reacts very differently than the one on L2; most notably the plate gap barely responds to changes in dilution water. Further study is needed to determine the cause of the differences between the refiners.

The concentration seems to be of little importance when it comes to the stability and motor loads of the machines. No significant effects on pulp quality can be seen when changing the levels of dilution water, but the small amount of data and poor measurements of the amount of shives make it impossible to draw any certain conclusions. Further testing is needed to find how changing the levels of dilution water affect the quality. Since the residence time was shown to be well correlated to the consistency, improved quality control could probably be achieved with the aid of the extended entropy model, provided that the relation between residence time (as well as other variables) and pulp quality for the refiners is studied in more detail.

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Karlström, A. and Eriksson, K. (2014b): Fiber energy efficiency Part II: Forces acting on the refiner bars. Nord. Pulp Paper Res. J., Vol 29(2), Pages 332-343.

Karlström, A. and Eriksson, K. (2014c): Fiber energy efficiency Part III: Modeling of fiber-to-bar interaction. Accepted for publication in Nord. Pulp Paper Res. J.

Karlström, A. and Eriksson, K. (2014d): Fiber energy efficiency Part IV: Multi-scale modeling of refining processes. Accepted for publication in Nord. Pulp Paper Res. J.

Karlström, A. and Hill J. (2014): Refiner Optimization and Control Part I: Fiber residence time and major dynamic fluctuations in TMP refining processes. Submitted for publication in Nord. Pulp Paper Res. J.

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Appendix I

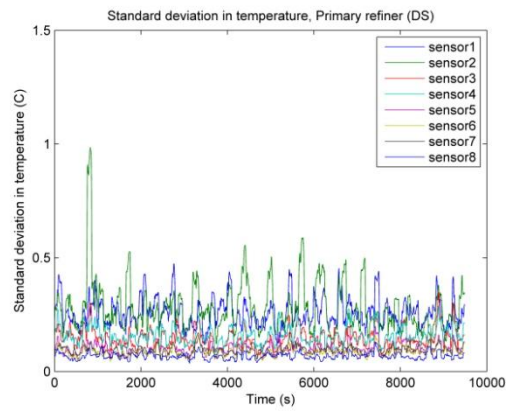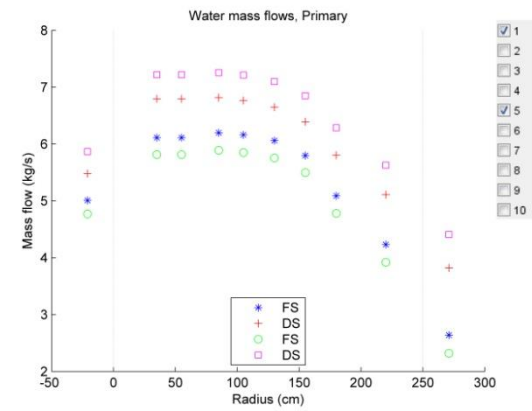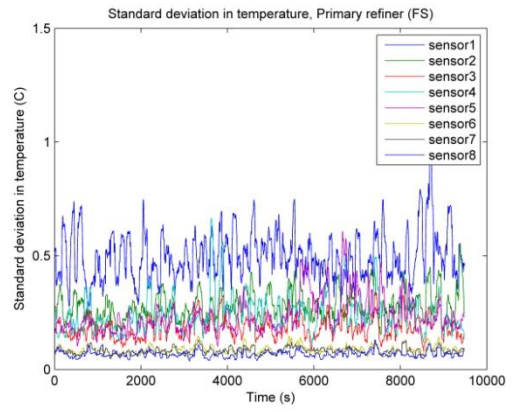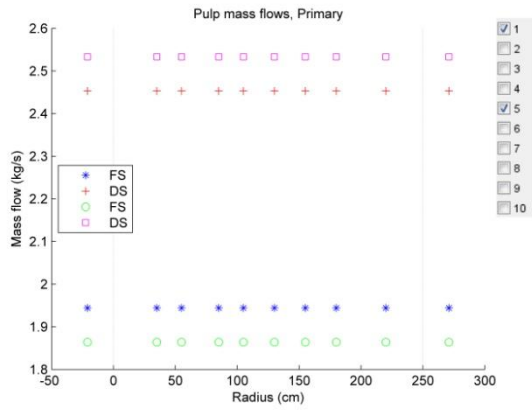In this appendix graphs of several process variables for the different tests are presented. The figures are seen as self-explanatory.

2014-11-05, Primary refiner L2

Standard deviation in temperature, Primary refiner (FS)

Temperatures, Primary refiner (FS)

Standard deviation in temperature, Primary refiner (DS)

Temperatures, Primary refiner (DS)
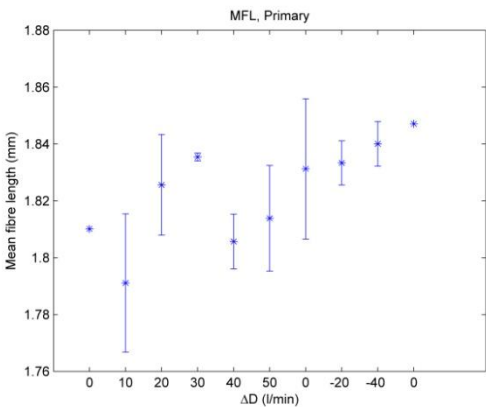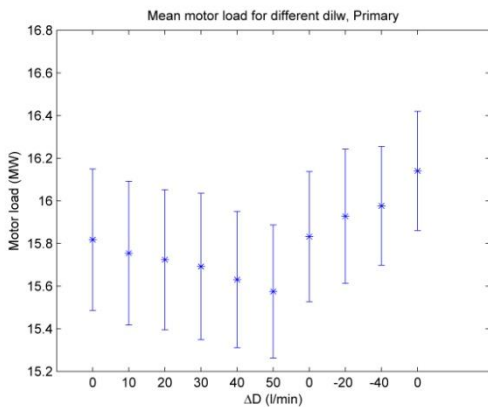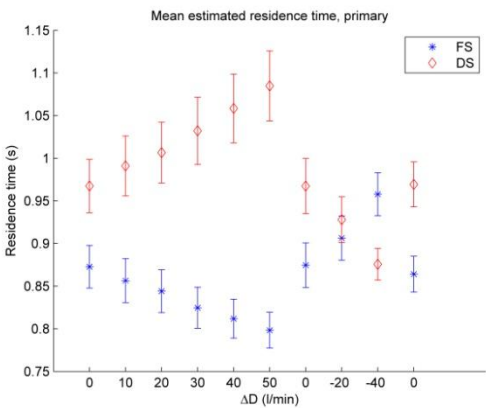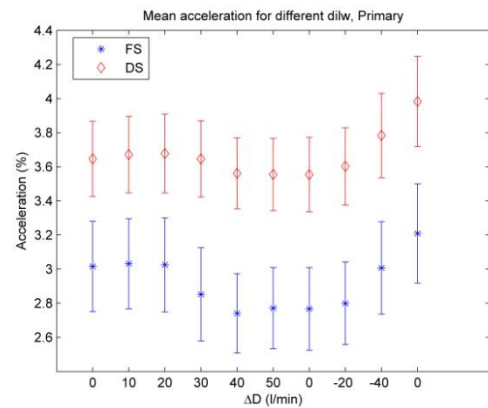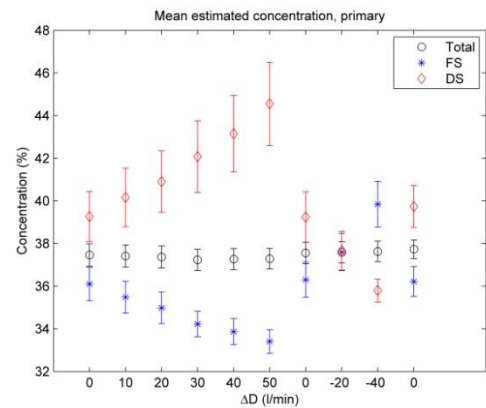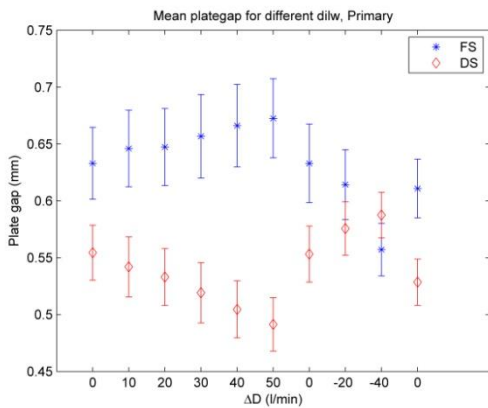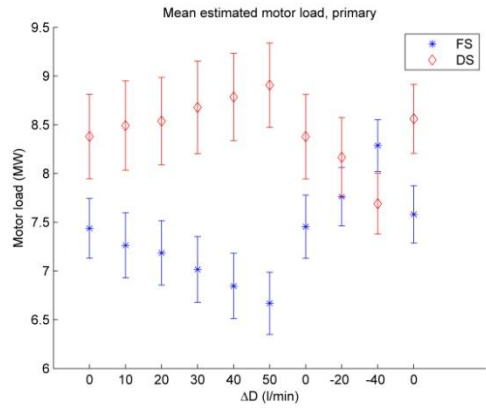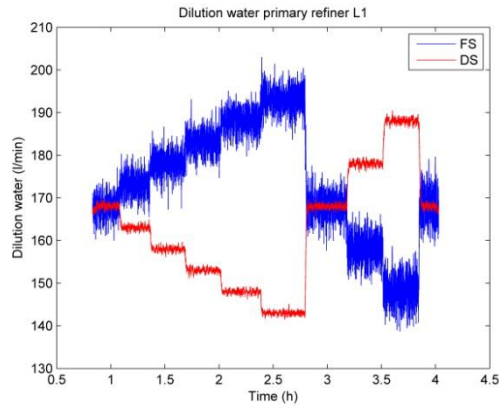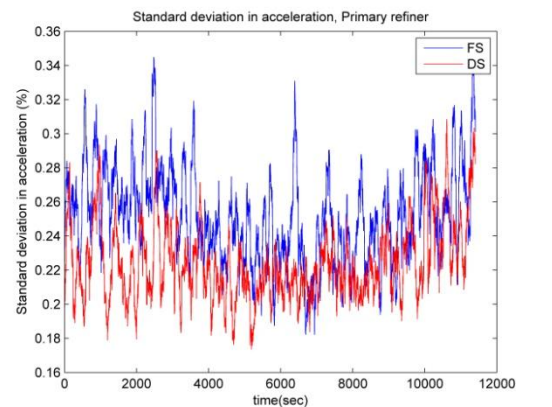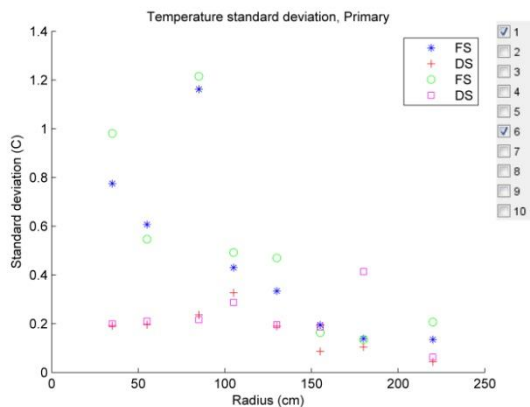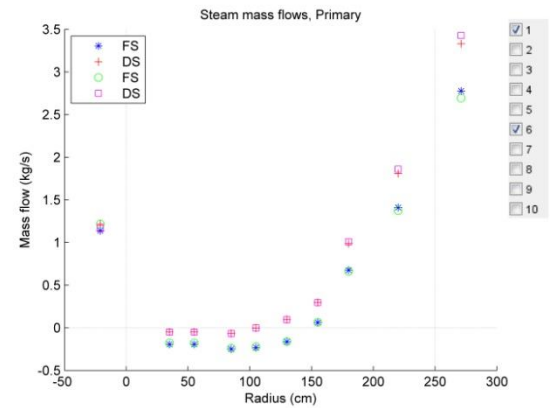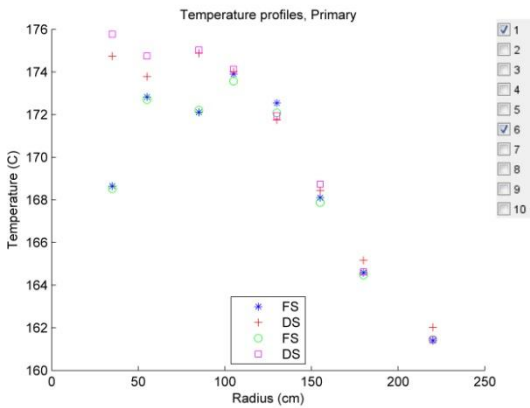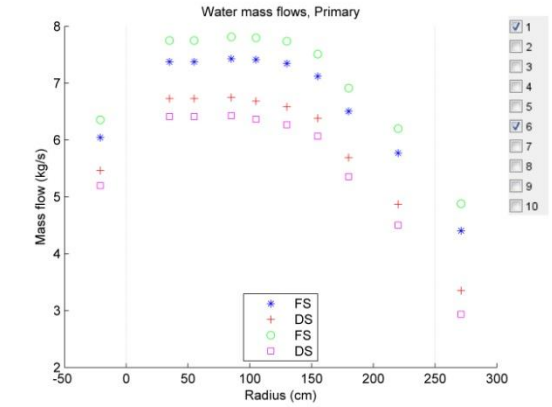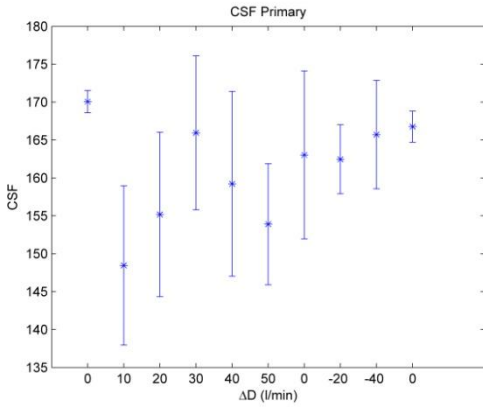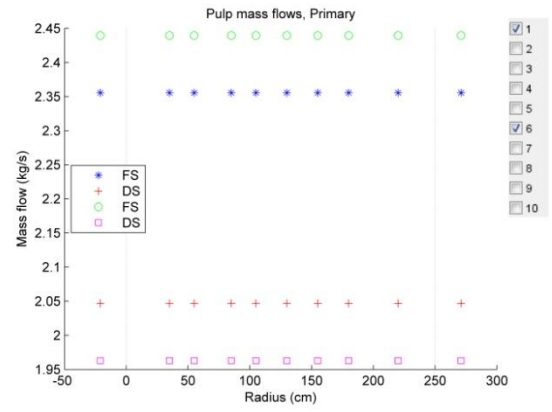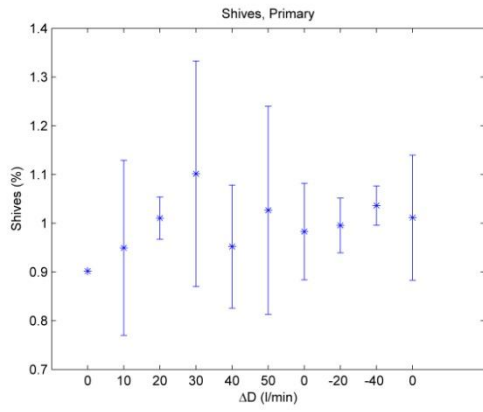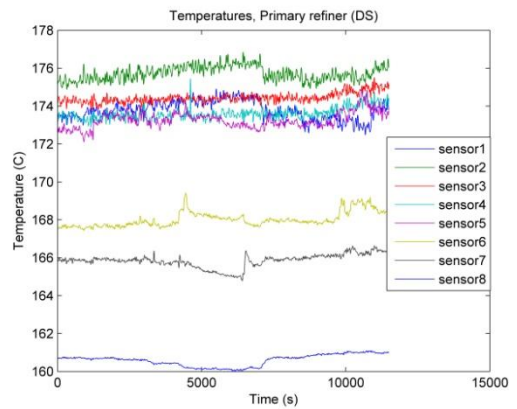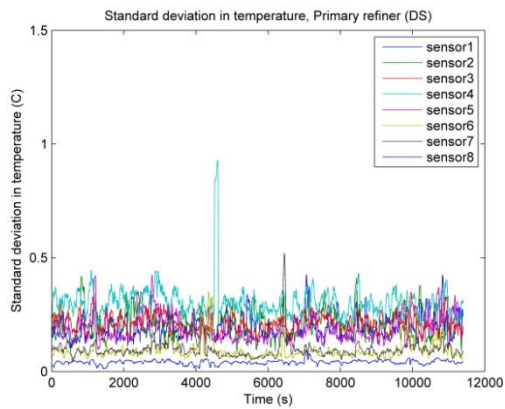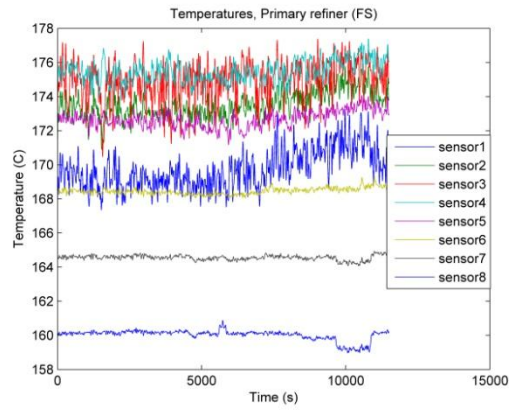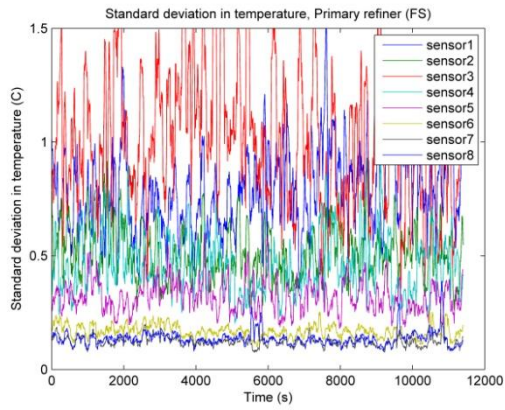
2014-11-11, Primary refiner L2

Dilution water primary refiner

Mean acceleration for different dilw, Primary

Mean plategap for different dilw, Primary

Mean motor load for different dilw, Primary

2014-11-11, Secondary refiner L2

Standard deviation in temperature, Secondary refiner (FS)

Temperatures, Secondary refiner (FS)

Standard deviation in temperature, Secondary refiner (DS)

Temperatures, Secondary refiner (DS)
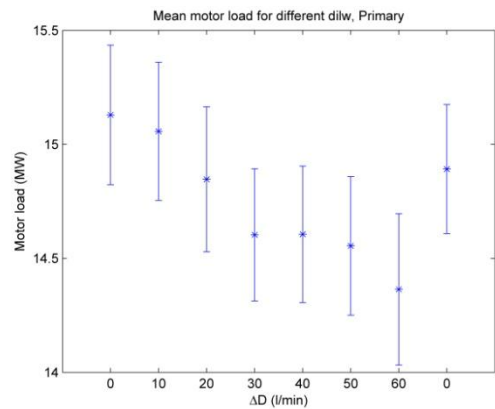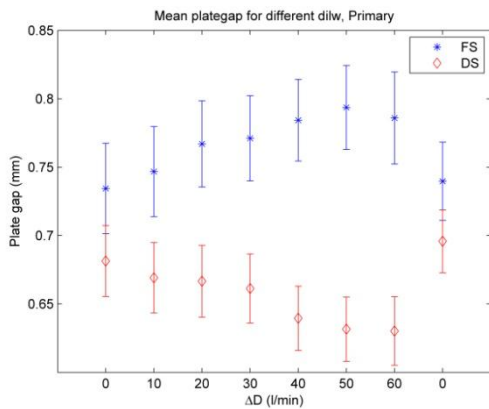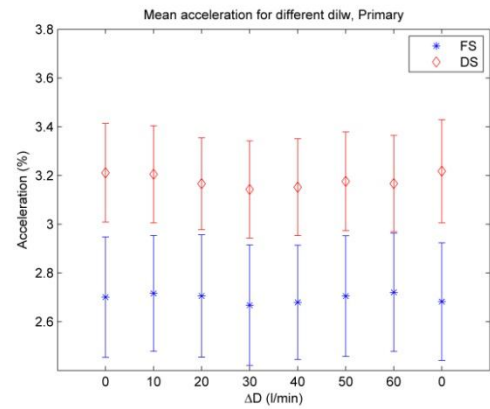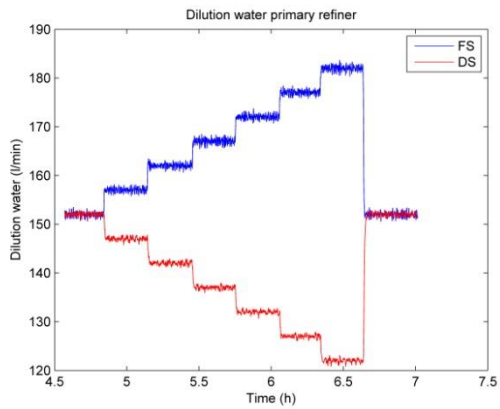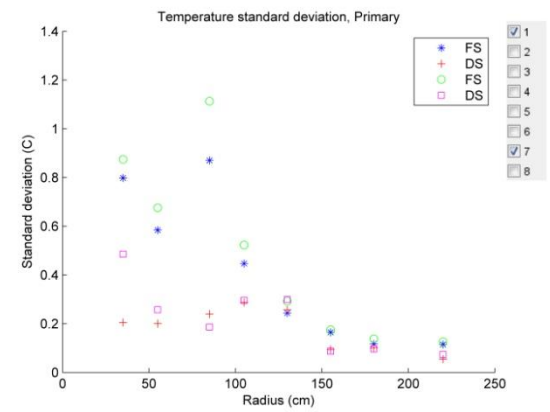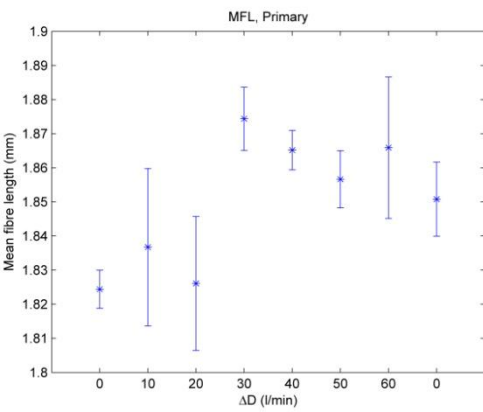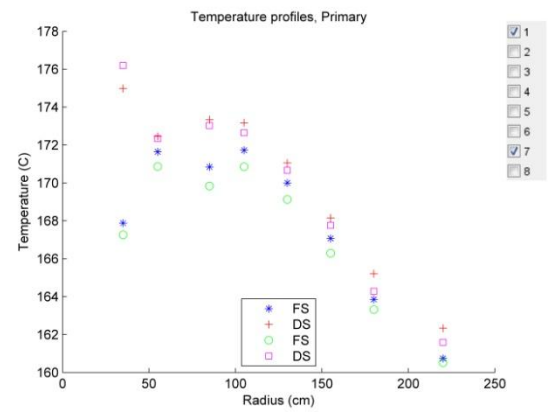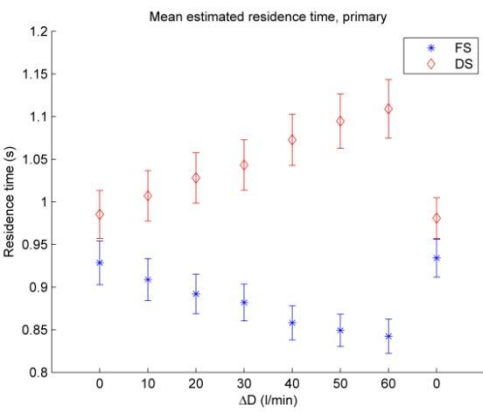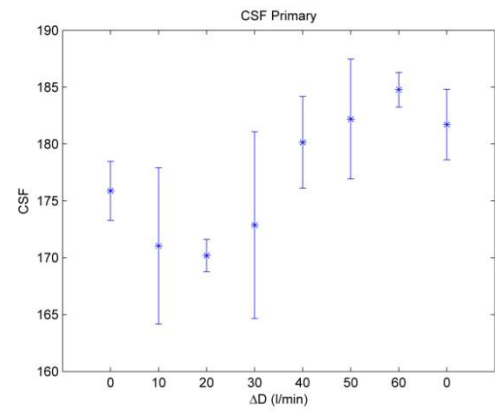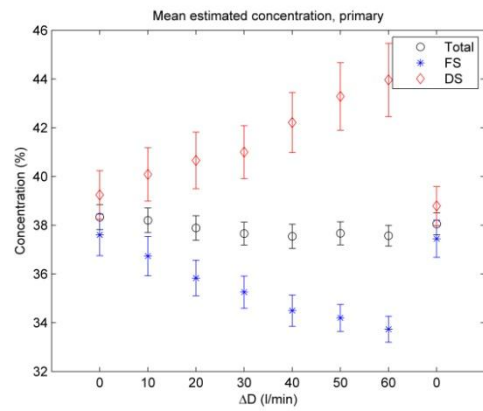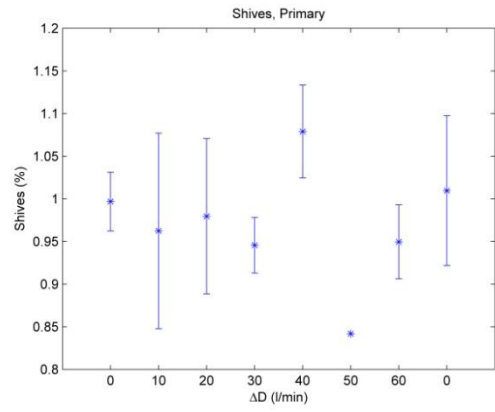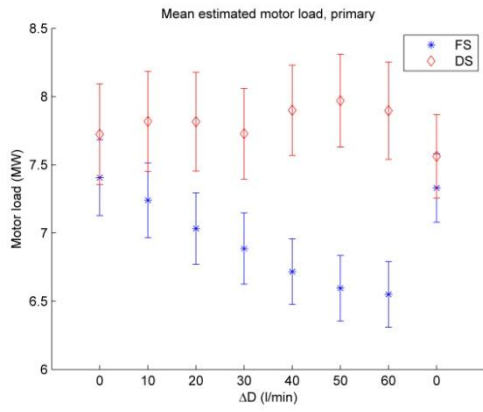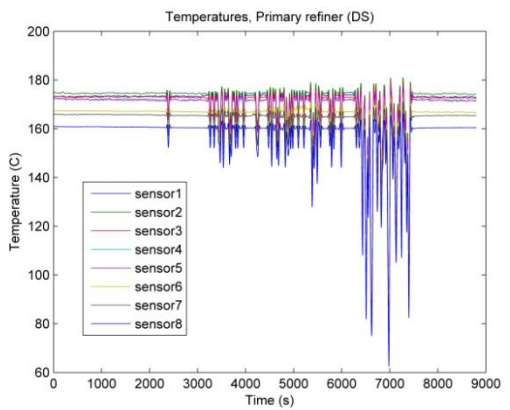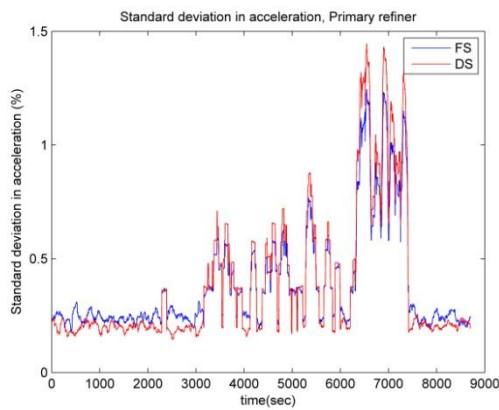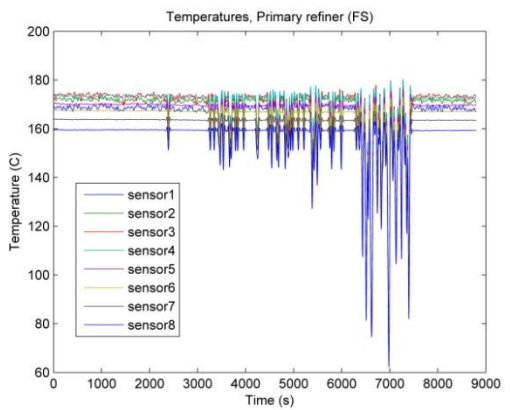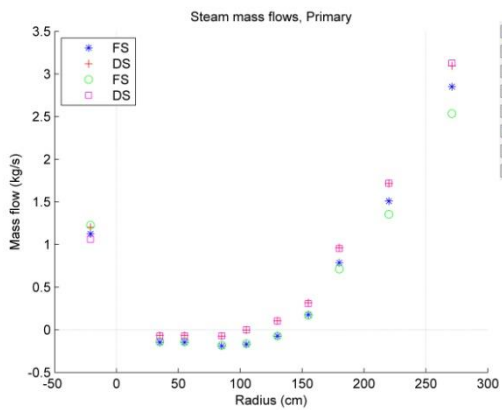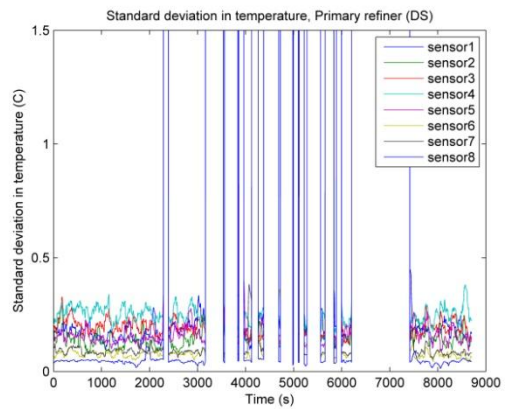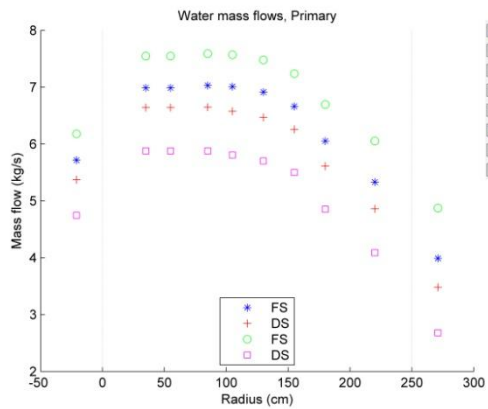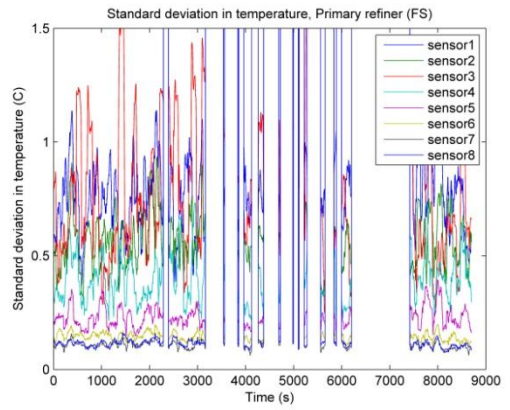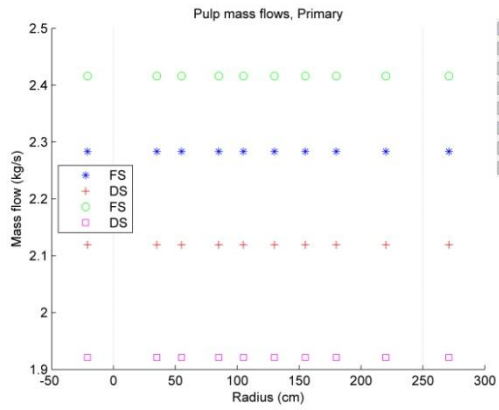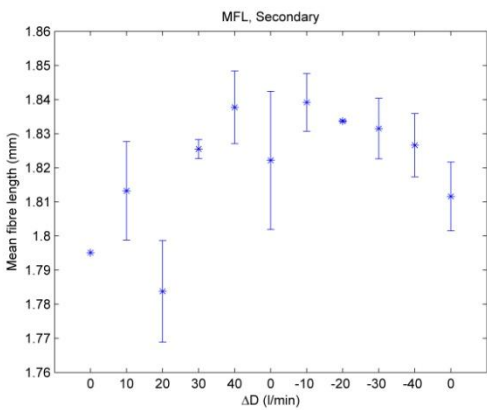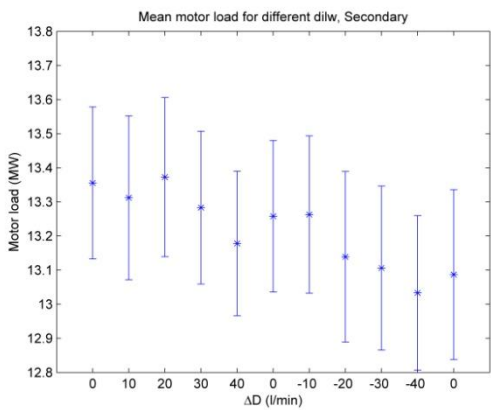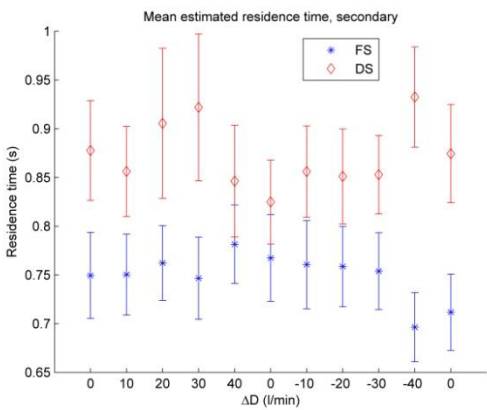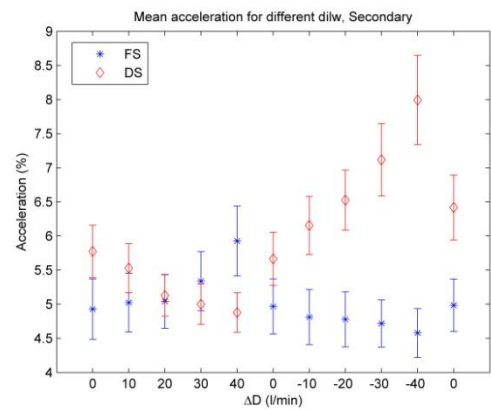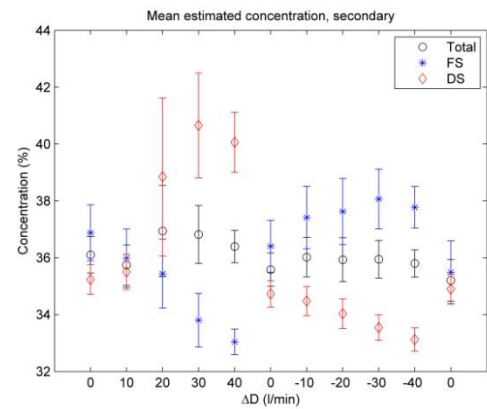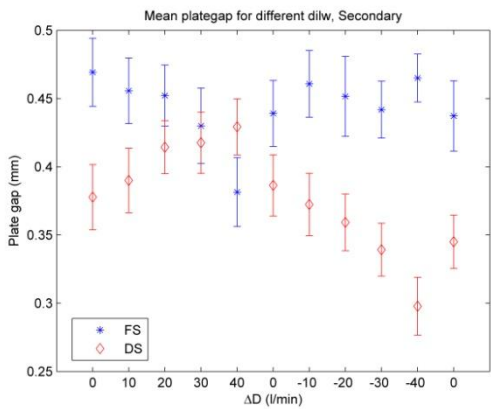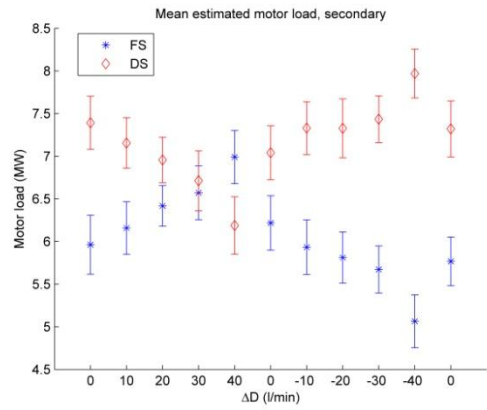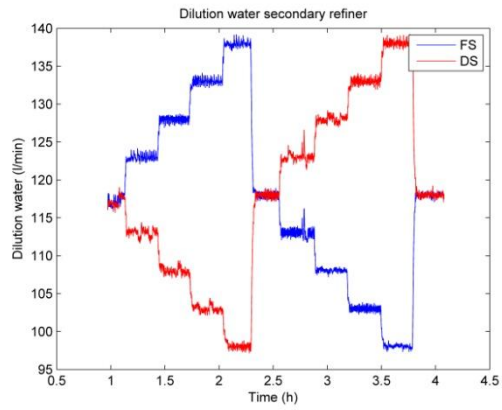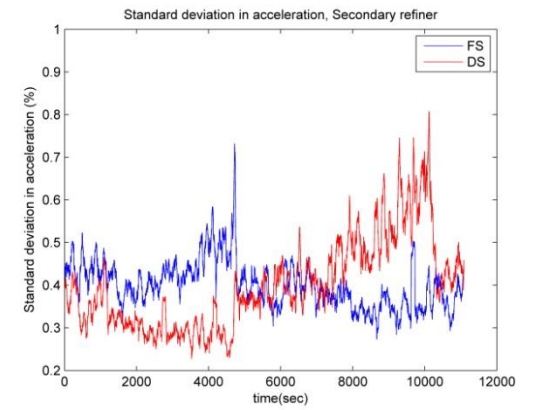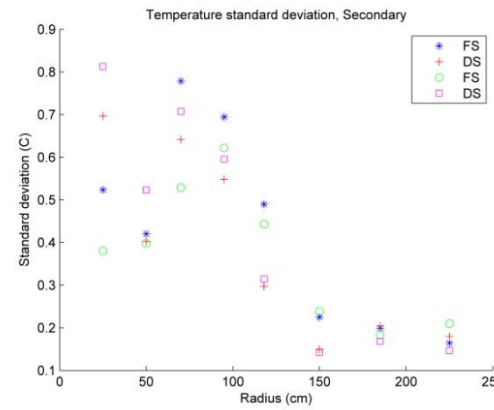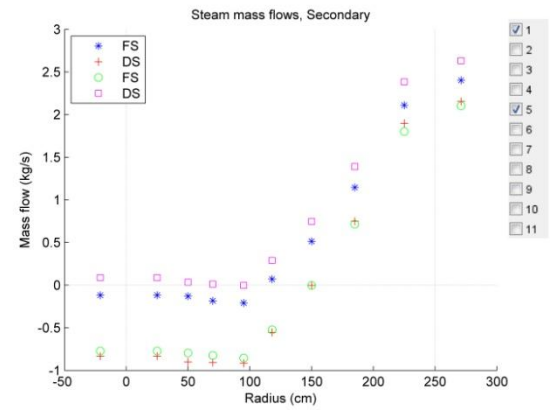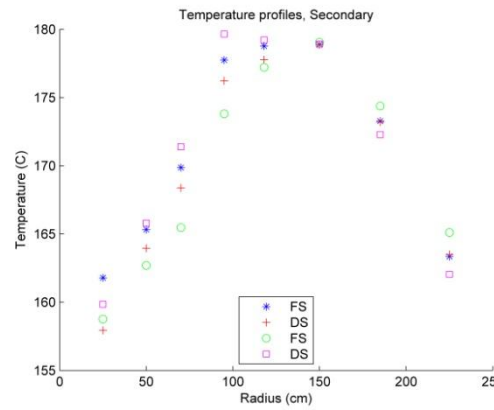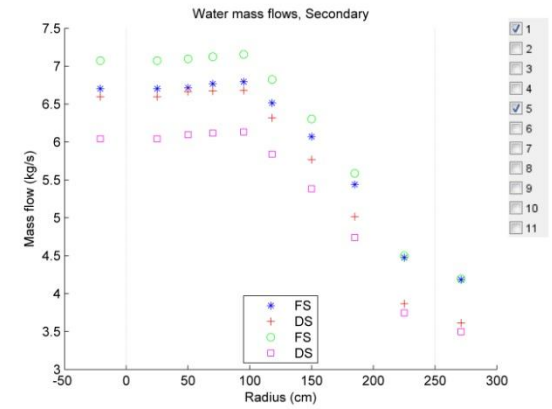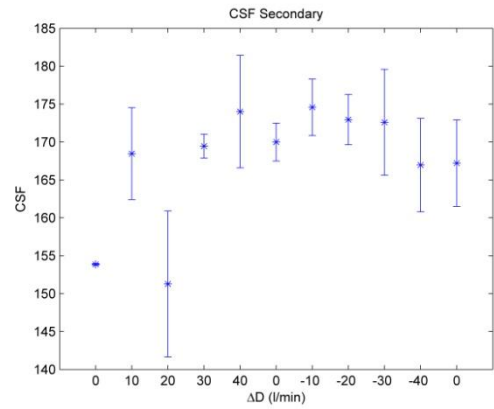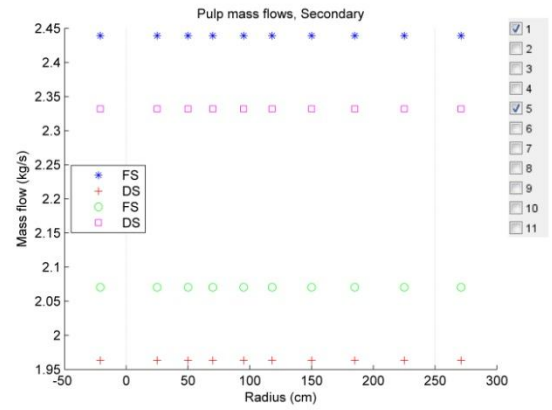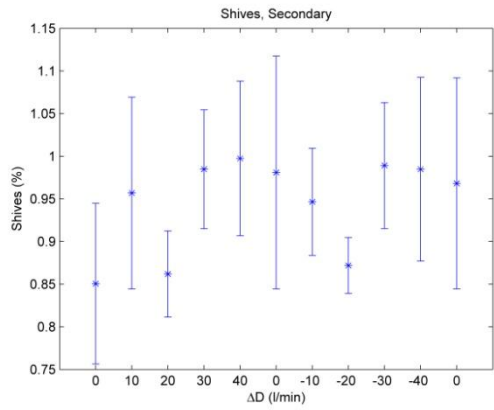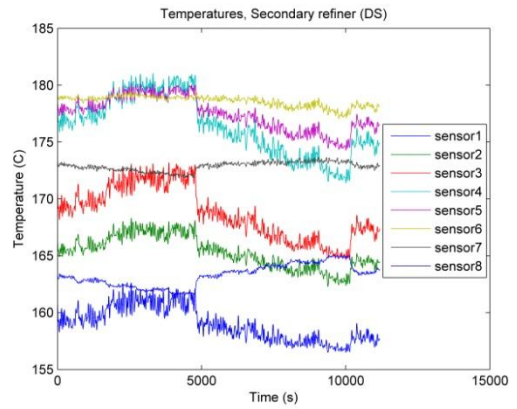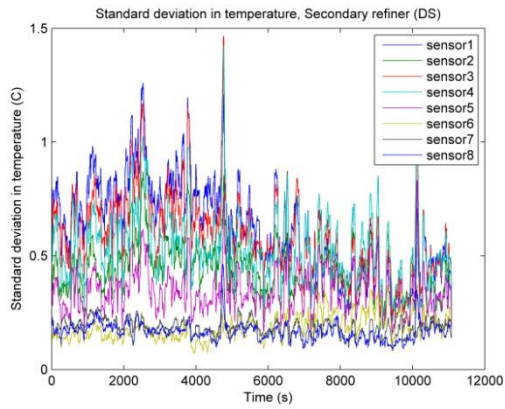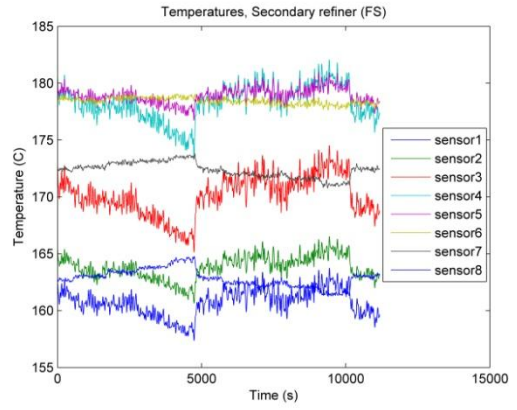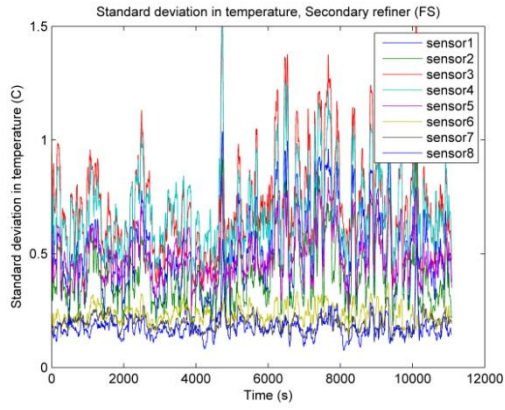
2014-11-12, Primary refiner L2

Dilution water primary refiner

Mean acceleration for different dilw, Primary

Mean plategap for different dilw, Primary

Mean motor load for different dilw, Primary

2014-11-12, Secondary refiner L2

Standard deviation in temperature, Secondary refiner (FS)

Temperatures, Secondary refiner (FS)

Standard deviation in temperature, Secondary refiner (DS)

Temperatures, Secondary refiner (DS)

2014-11-24, Primary refiner L2 (Low energy segments)

Dilution water primary refiner

Mean acceleration for different dilw, Primary

Mean plategap for different dilw, Primary

Mean motor load for different dilw, Primary

2014-11-24, Secondary refiner L2 (Low energy segments)

Standard deviation in temperature, Secondary refiner (FS)

Temperatures, Secondary refiner (FS)

Standard deviation in temperature, Secondary refiner (DS)

Temperatures, Secondary refiner (DS)

2014-11-24, Primary refiner L1

Dilution water primary refiner L1

Mean acceleration for different dilw, Primary

Mean plategap for different dilw, Primary
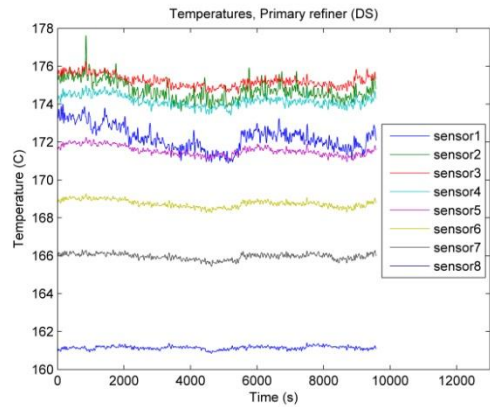

Mean motor load for different dilw, Primary
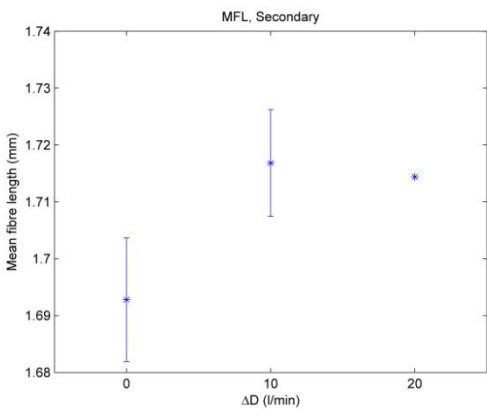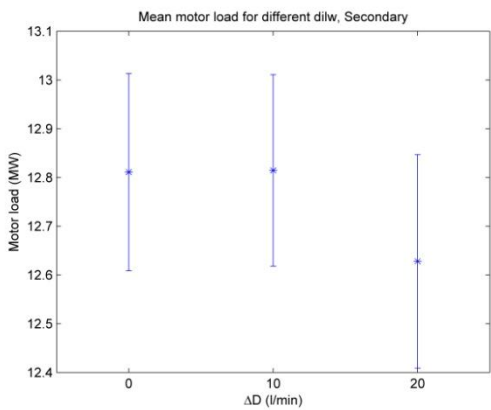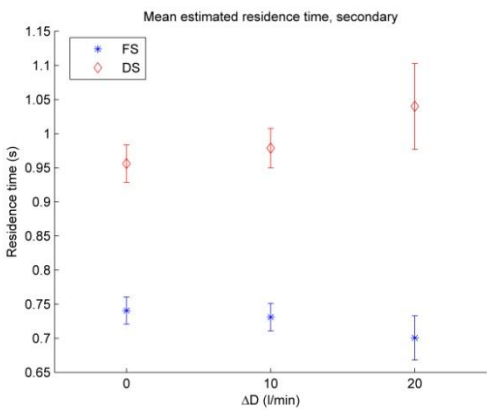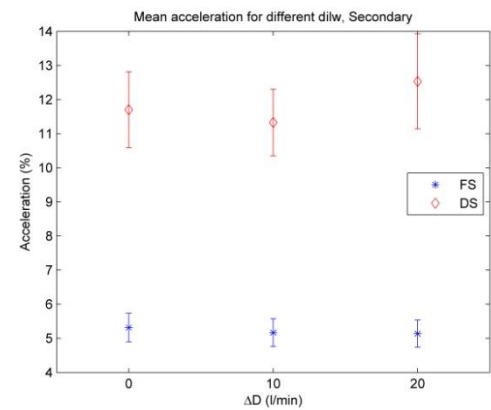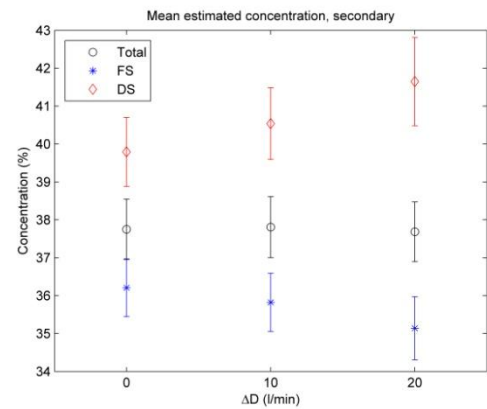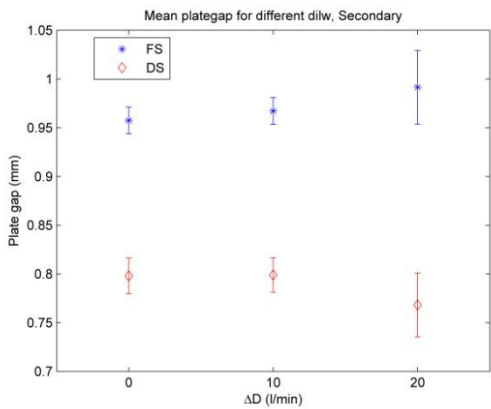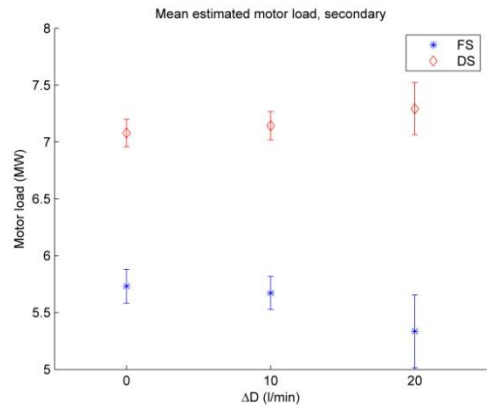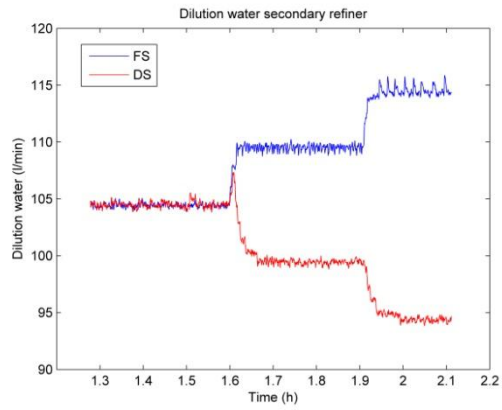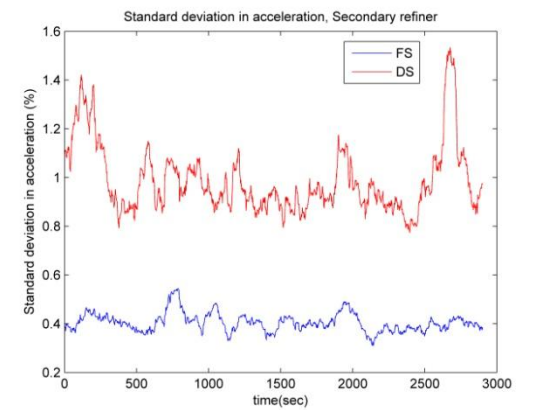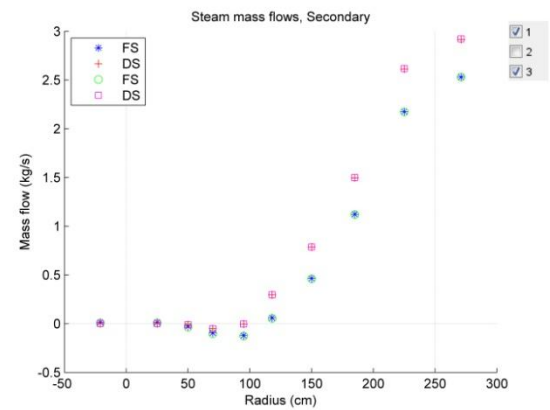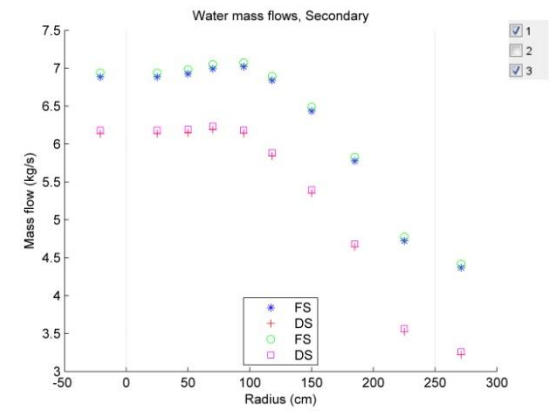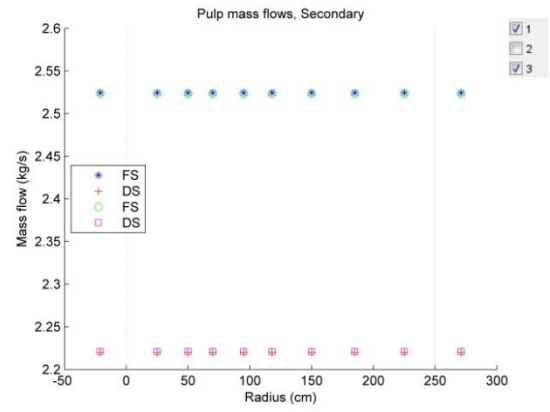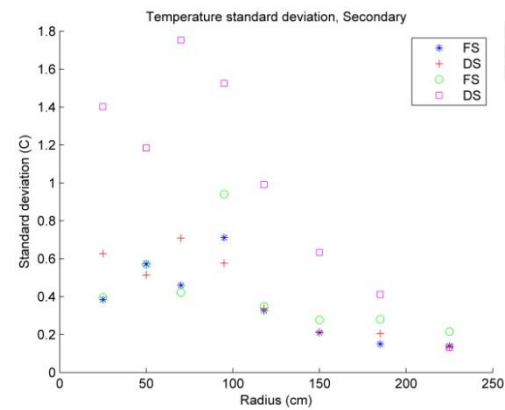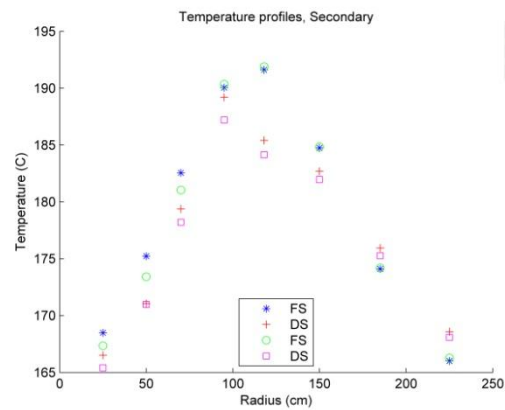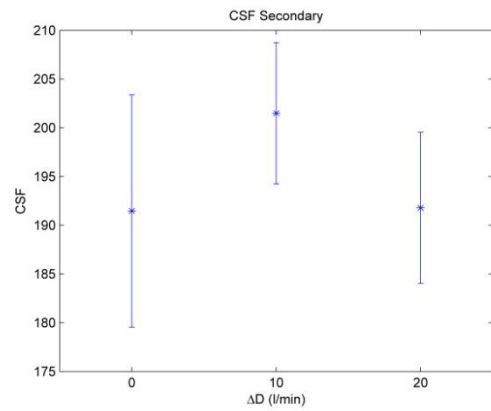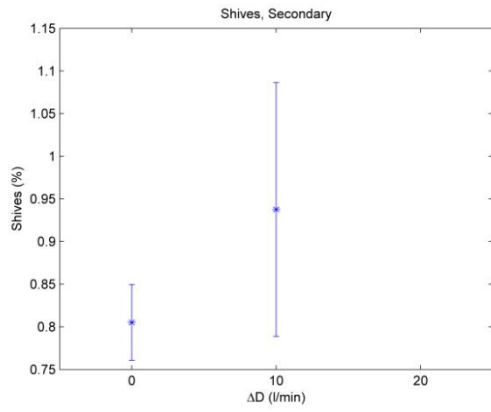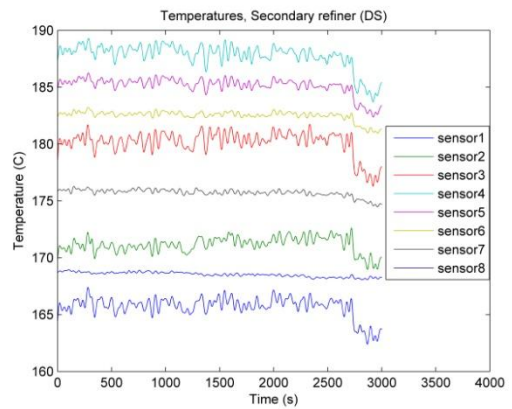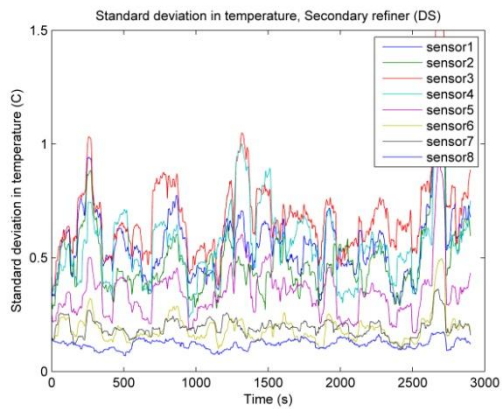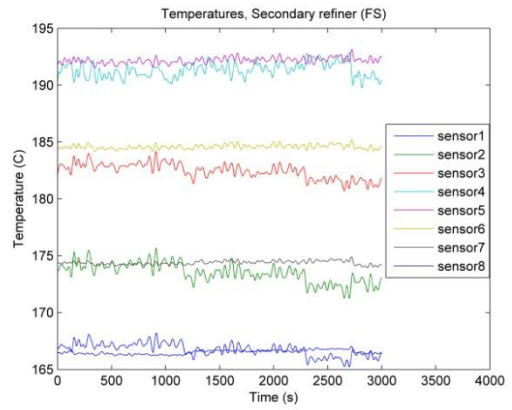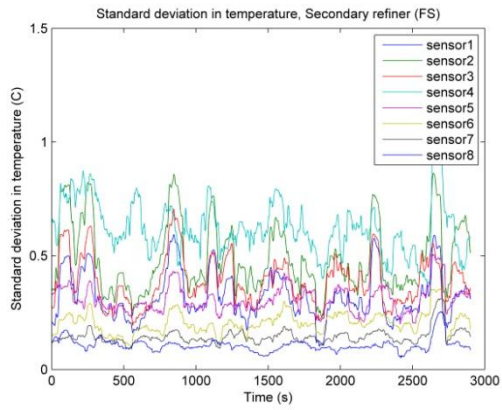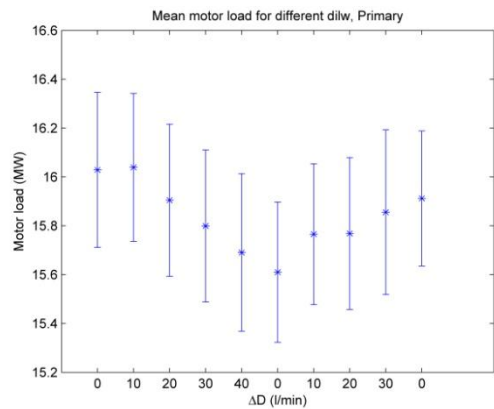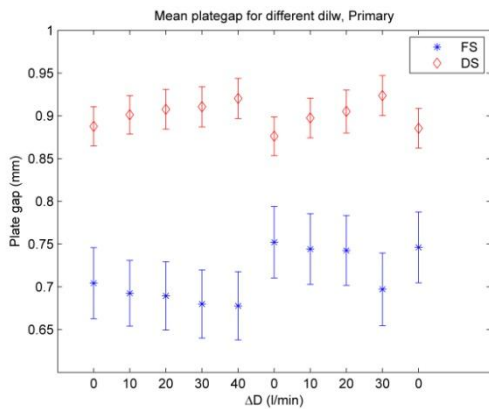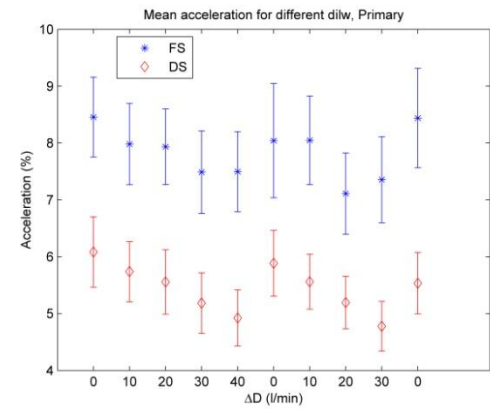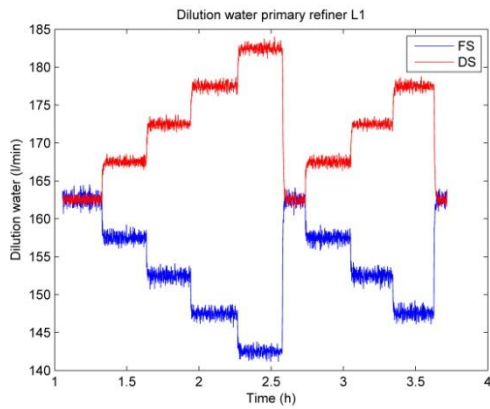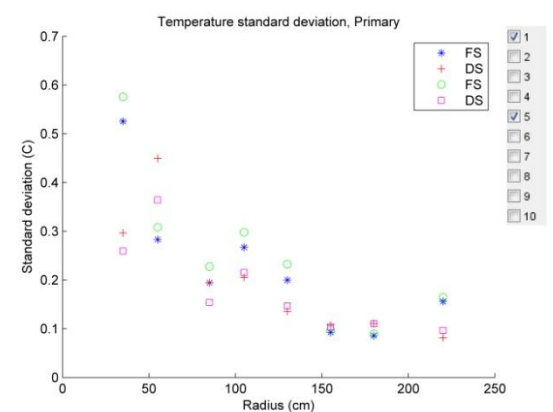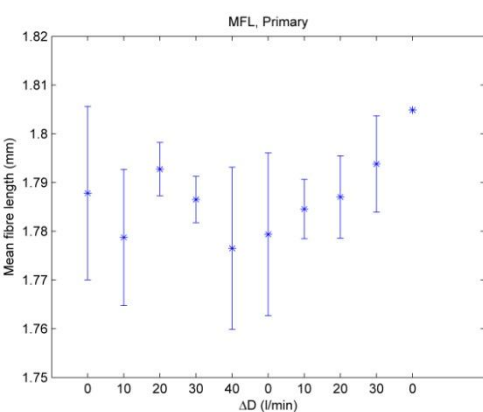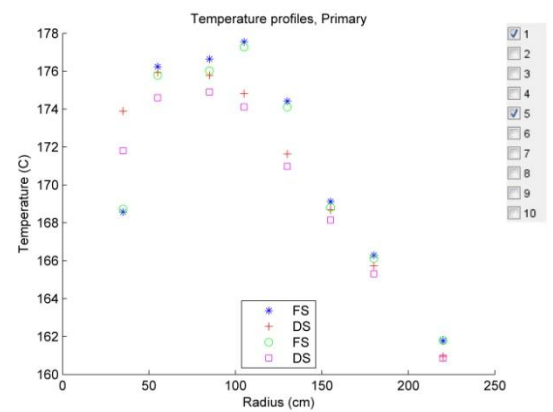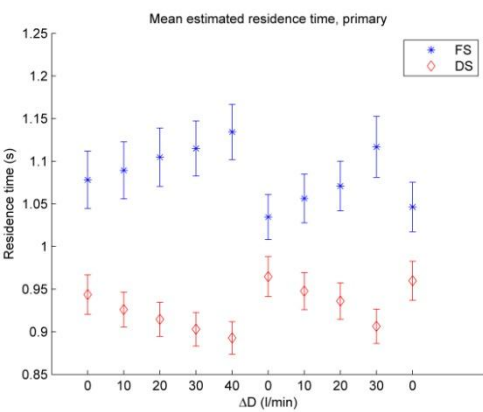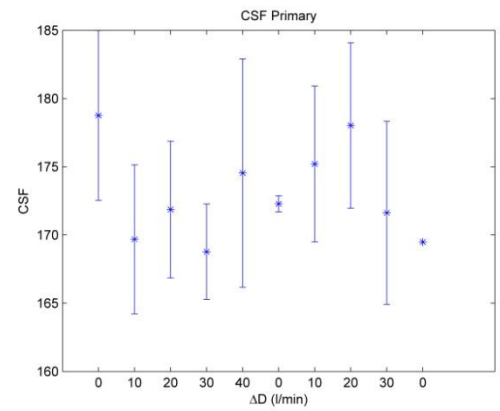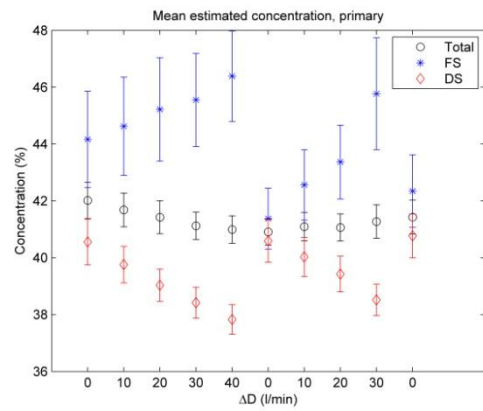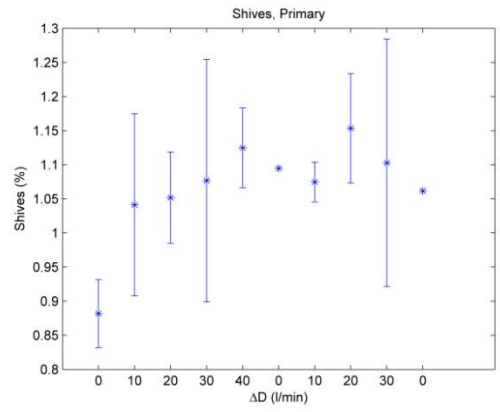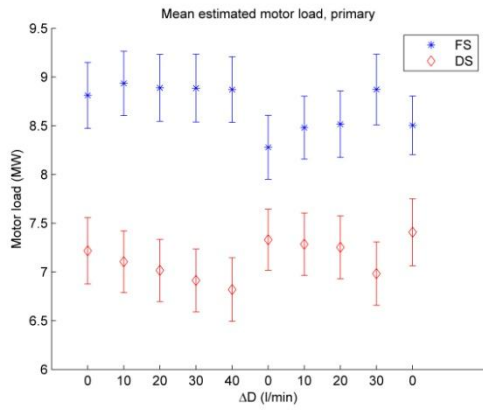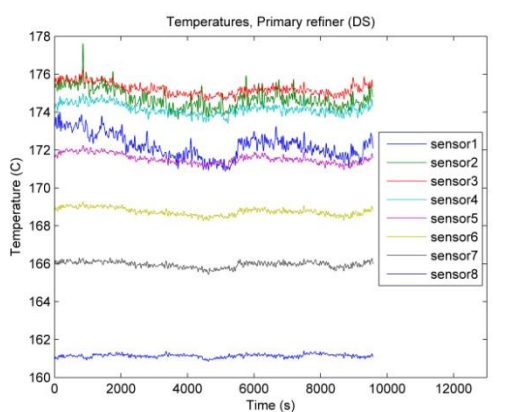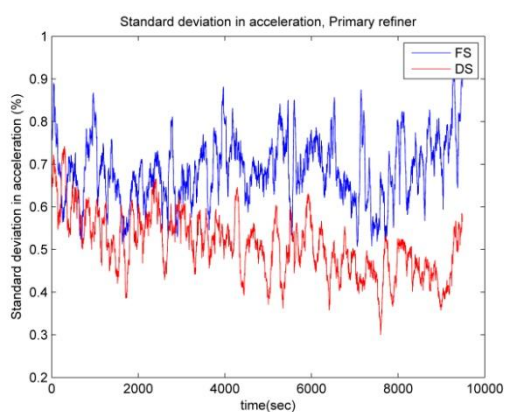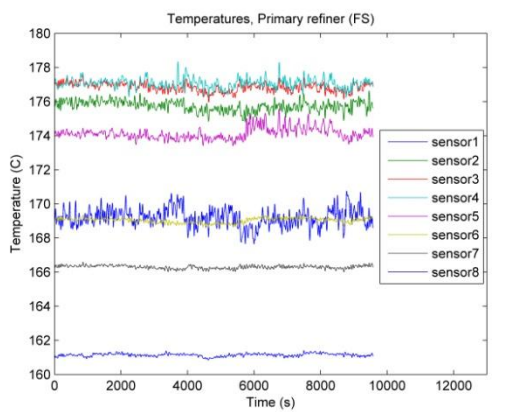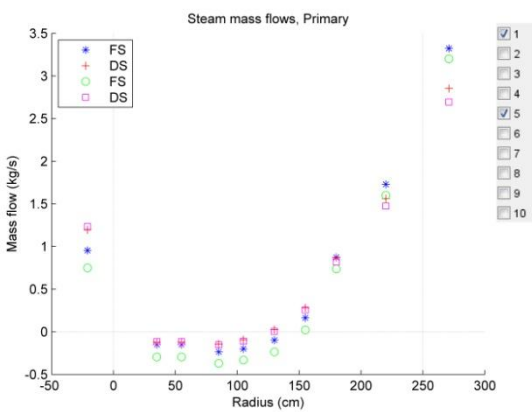
2014-11-25, Secondary refiner L2 (Low energy segments)

Standard deviation in temperature, Secondary refiner (FS)

Temperatures, Primary refiner (FS)

Standard deviation in temperature, Secondary refiner (DS)

Temperatures, Primary refiner (DS)
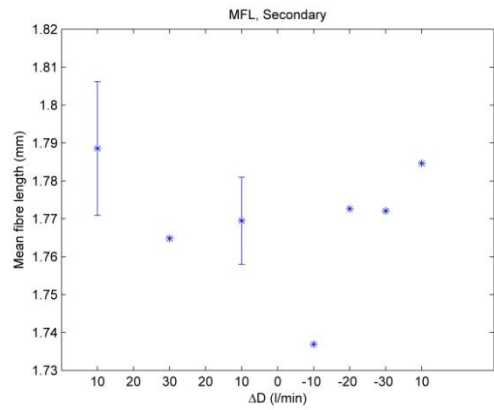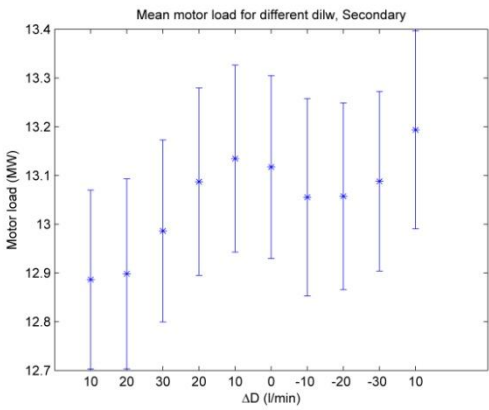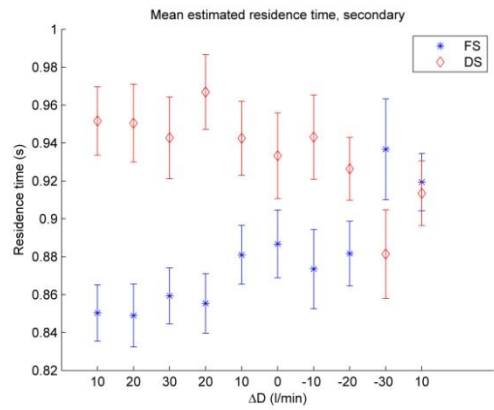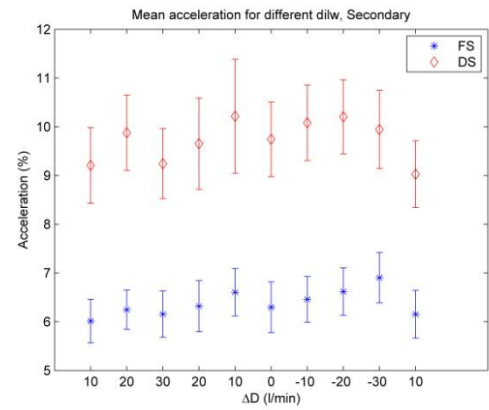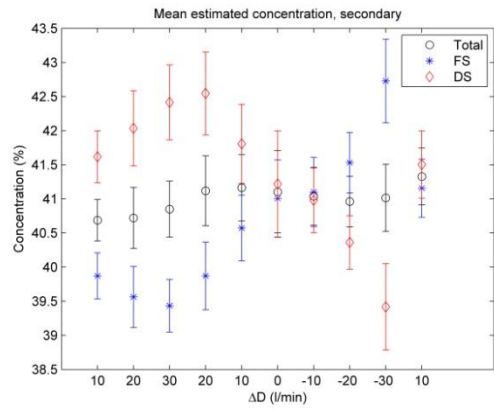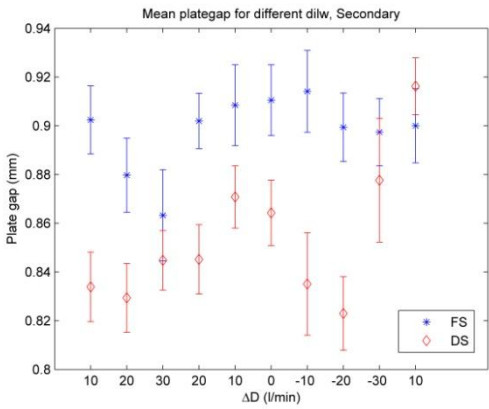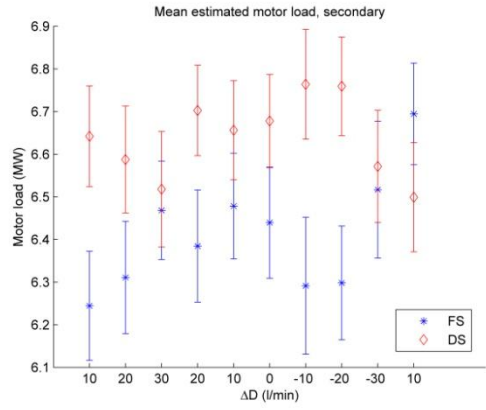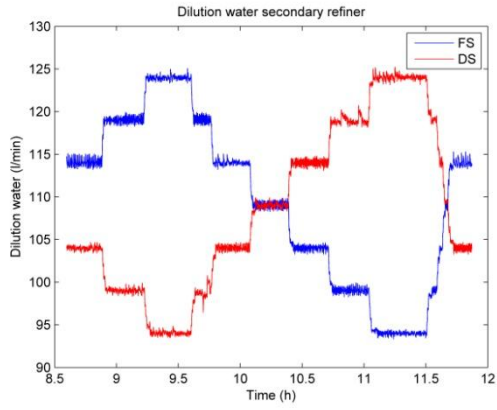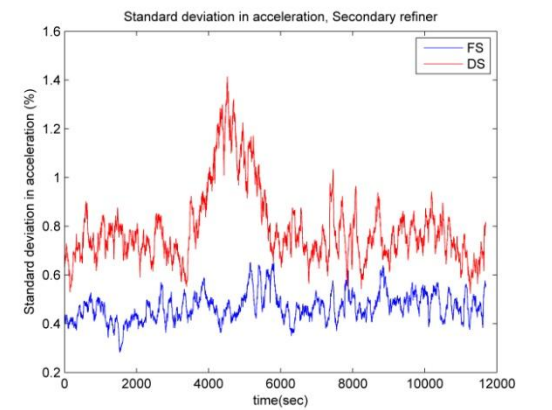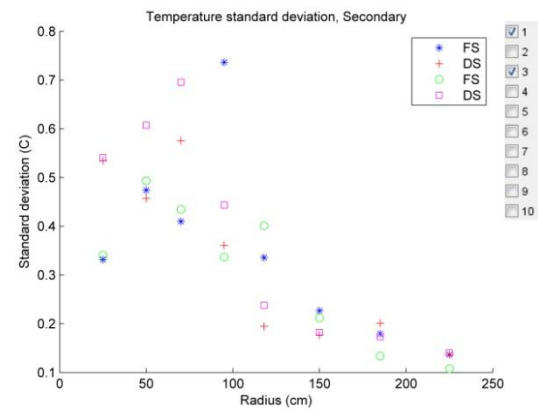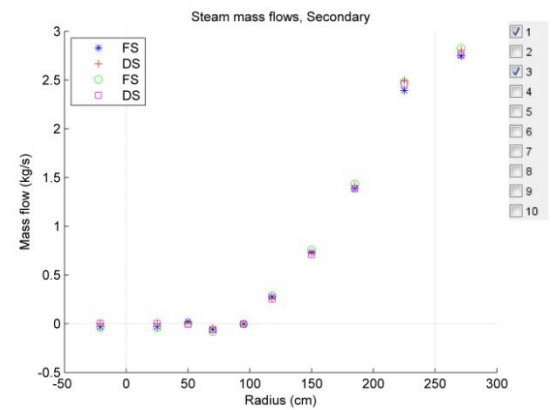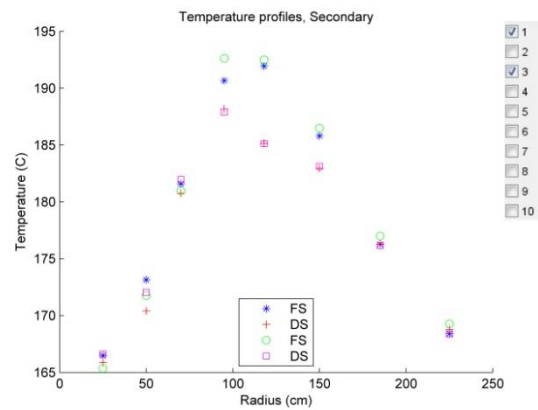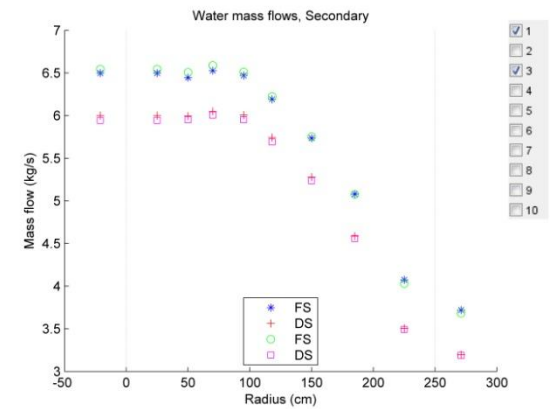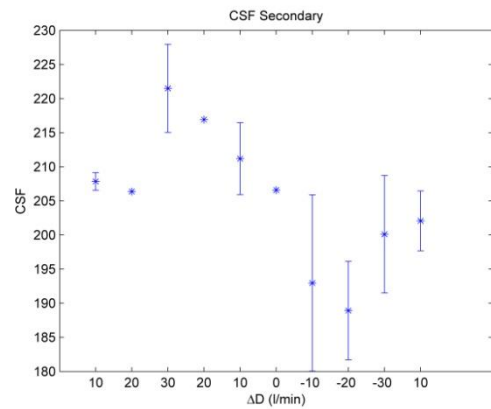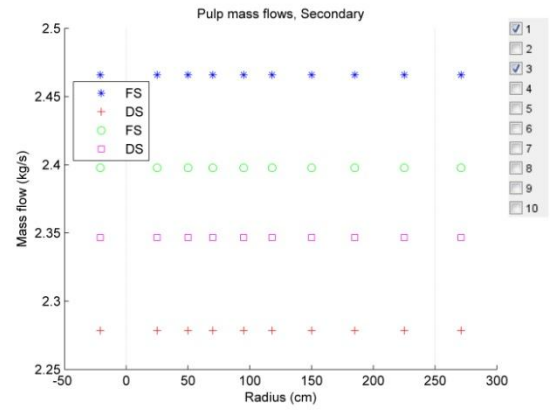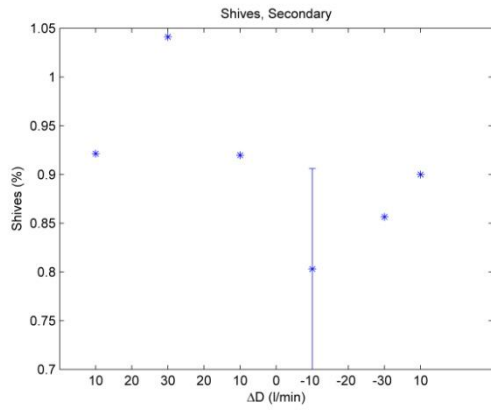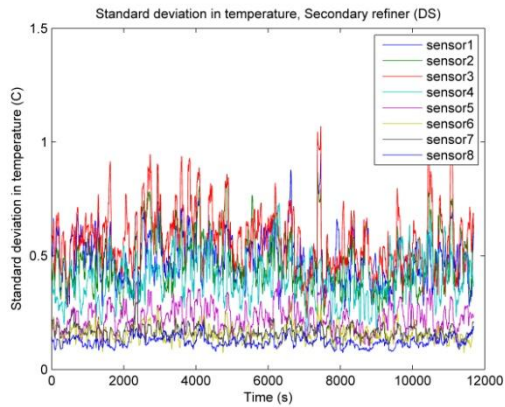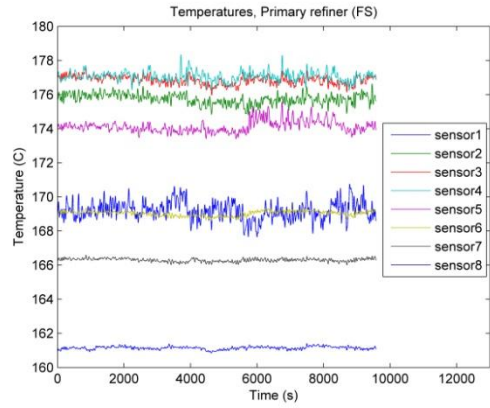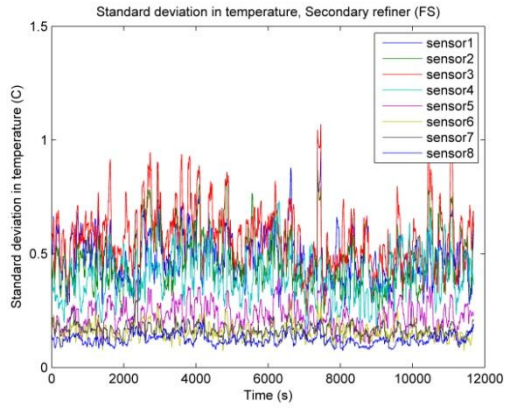
2014-12-22, Secondary refiner L1

Dilution water secondary refiner

Mean acceleration for different dilw, Secondary

Mean plategap for different dilw, Secondary

Mean motor load for different dilw, Secondary