Department for Energy Security & Net Zero

Lab testing - boiler cycling

Validation of the Home Energy Model methodology for boilers

December 2023

Acknowledgements

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Introduction

A boiler model was developed in Home Energy Model (HEM) to determine the efficiency of gas boilers (mains gas and LPG). For more information on the boiler model please see HEM-TP-14 Boiler Methodology.

This report uses data from lab tests, HEM modelling and real-world field trials to explore the effectiveness of the HEM's boiler model in predicting boiler performance.

Boiler modulation refers to the ability of a boiler to reduce its output to match the energy demand. It is crucial for improving the efficiency of the heating system as it reduces the energy waste associated with boiler cycling while maintaining the desired temperature. Boilers that can modulate have a minimum output that the boiler can modulate down to. The minimum modulation is the minimum output as a percentage of the maximum output of the boiler. When the demand on the boiler falls below the minimum output, the boiler begins cycle. Cycling is when the boiler switches on and off to maintain temperature, this leads to a decrease in efficiency and increased energy losses.

The HEM's boiler model calculates an adjustment when the boiler cycles. A particular focus in this study is to validate the cycling behaviour at different minimum modulation in the HEM boiler model.

Lab testing was carried out by KIWA using their Dynamic Heat Load Test Rig (DHLTR) and involved a series of constant load tests on a 24kW boiler set at 10% and 30% minimum modulation at 35°C and 55°C return temperatures. The results were compared to the HEM boiler model and analysed to determine the accuracy of the model in capturing the impact of boiler cycling. Further validation of the HEM boiler model was carried out by using EST field trail data.

Methods and materials

The Dynamic Heat Load Test Rig (DHLTR) has been designed to allow domestic wet central heating appliances to be evaluated in conditions that reflect 'real-life' usage. The rig is constructed in such a way that both the appliance and its associated controls are tested in combination, this allows for the fact that the control system and system commissioning may play a significant role in the overall efficiency of any installed system.

The rig is designed to run over a 24-hour cycle, reproducing the behaviour of the system under test within a simulated property of known thermal characteristics, but in a controlled manner.

It is possible to test an appliance with a range of environmental conditions and loads. These could be for instance a winter day, a spring/autumn day or a summer day, representing the extremes of normal operation, with the thermal characteristics of the ‘house load’ being determined as required.

The tests carried out on this rig are entirely different to those done to the existing boiler testing standards. The dynamic nature of the tests with this rig ensures the boiler is operated in a way that would be encountered in normal use.

The DHLTR can also be used to provide a constant heat load demand, and it is in this mode that the work described in this report has been done.

The rig is based around a wet central heating system of the Y-plan design. The bulk of the rig is a large steel cylinder. This is used to retain the equivalent volume of water as the system being simulated. The cooling load, to represent the heat loss from the household radiators and pipework, is simulated in hardware using a pair of plate heat exchangers. The pipework includes a range of different control systems encountered in household heating systems, such as pumps, manual bypass loops, automatic bypass loops and thermostatically controlled valves (TRV). Provision is made for control system hardware such as timers/programmers, room thermostats, outside temperature sensors and remote TRV modules. These items can be installed into two separate temperature-controlled enclosures. For units such as Air source heat pumps, an additional environmental chamber is available, which can be operated at a steady temperature or can track a pre-defined outside temperature profile. DHW systems with either combination boiler types or those that require a DHW cylinder can be accommodated. Alternatively, a constant or pre-programmed load can be applied to the system to test heating system performance under a predetermined load. The Figure 1 below shows the test rig itself with a condensing boiler installed.

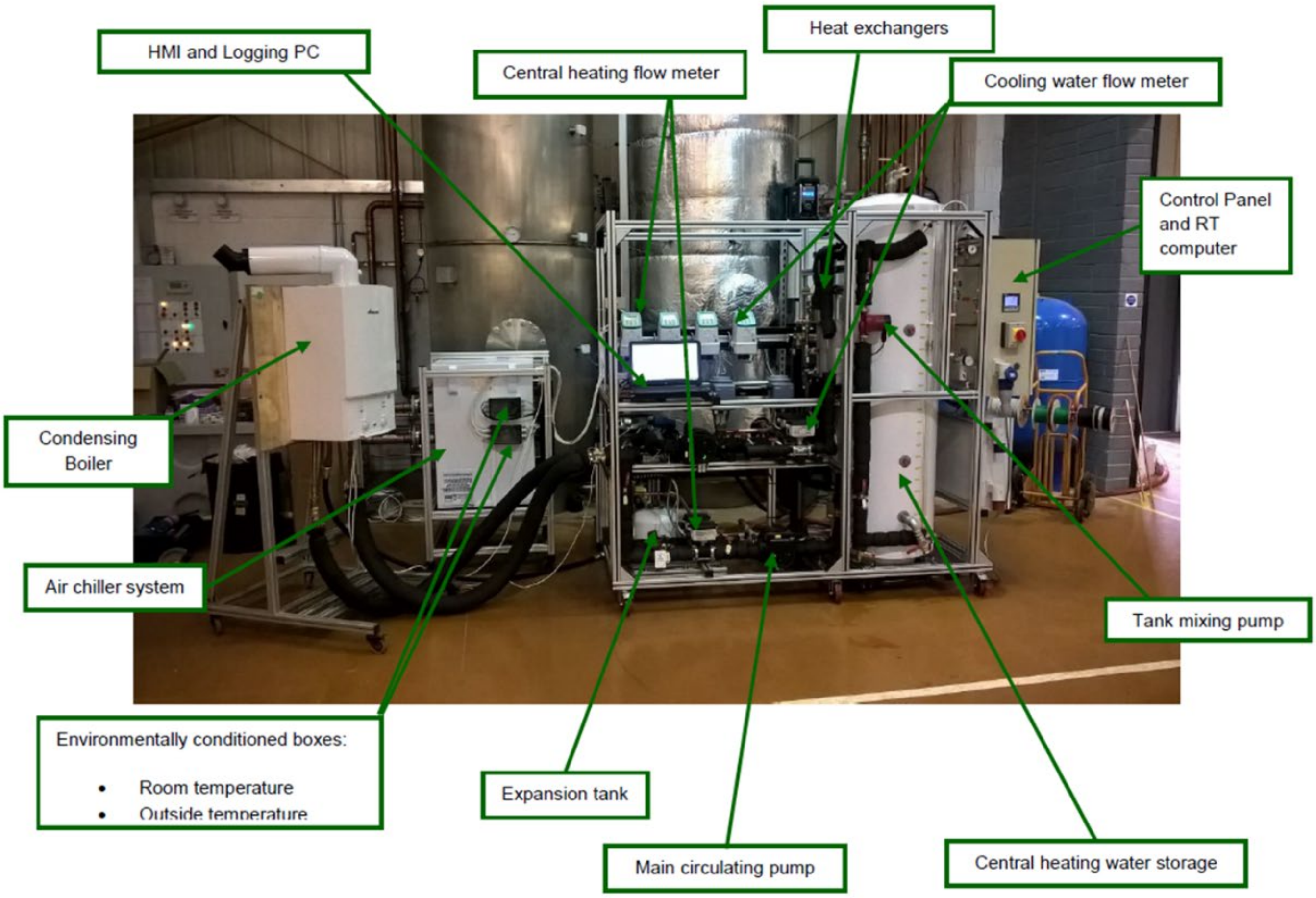
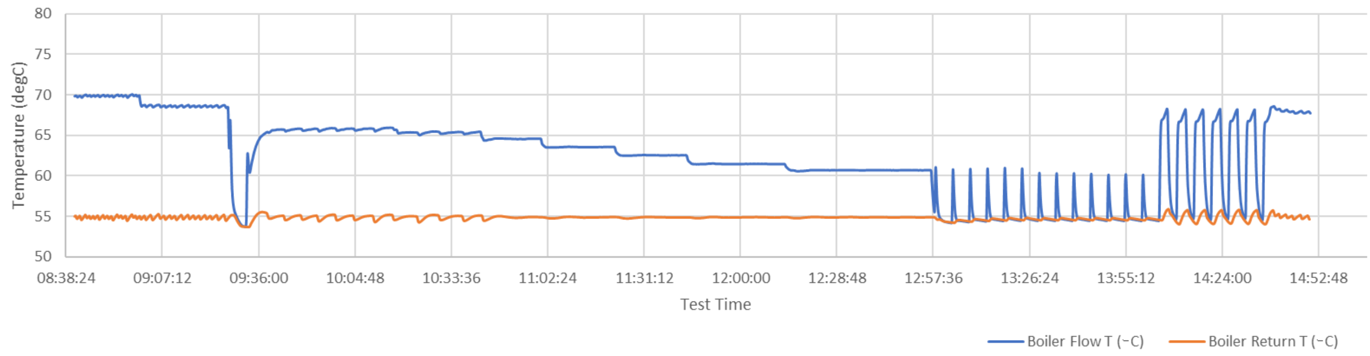


Figure 1 – A photograph of the Dynamic Heat Load Test Rig (DHLTR)

A new condensing boiler with the ability to set the minimum modulation rate was used in these tests. The boiler minimum output was set at either 10% or 30% of the maximum heating output of 24kW. Also, there was a setting which allowed the boiler to exceed the flow set point temperature by a certain amount (default 6K) this was set at 2K, this was avoid too much variation in water temperature whilst testing. The fuel supply was G20 test gas, to avoid issues with variation of the quality of the Natural gas supply.

The return temperature was set on the boiler at either 35°C or 55° C and the cooling load set such that the boiler operated in a steady (modulated) mode by adjusting the flow temperature. The data was recorded for a period then the heat load was slightly reduced, by dropping the flow temperature, and data recorded again. This was repeated for loads down as low as was possible.

The graph below shows an example of this type of test, where modulation is maintained then switches to cycling behaviour.



There is an issue with these tests in that the rig heat loss becomes a larger proportion of the heat load as the heat load decreases. For this reason, the boiler efficiencies were calculated based on heat output at the boiler rather than cooling load. Doing so removes the influence of rig heat losses.

Results and discussion

In this section, we present the outcomes of both the lab tests conducted using the Dynamic Heat Load Test Rig (DHLTR) and the analysis of field trial data from the Energy Savings Trust (EST).

Comparison of HEM boiler model to lab results

The lab tests were carried out by KIWA on a 24kW boiler with varying minimum modulation settings (10% and 30%) and different return temperatures (35°C and 55°C). The same boiler setup, return temperatures, and minimum output was modelled in HEM. During the modelling, the HEM's calculation of the standing loss was adjusted to use the current boiler power instead of a default nominal power to align with lab results. The results of both the lab tests and HEM modelling can be seen in Figure 2.

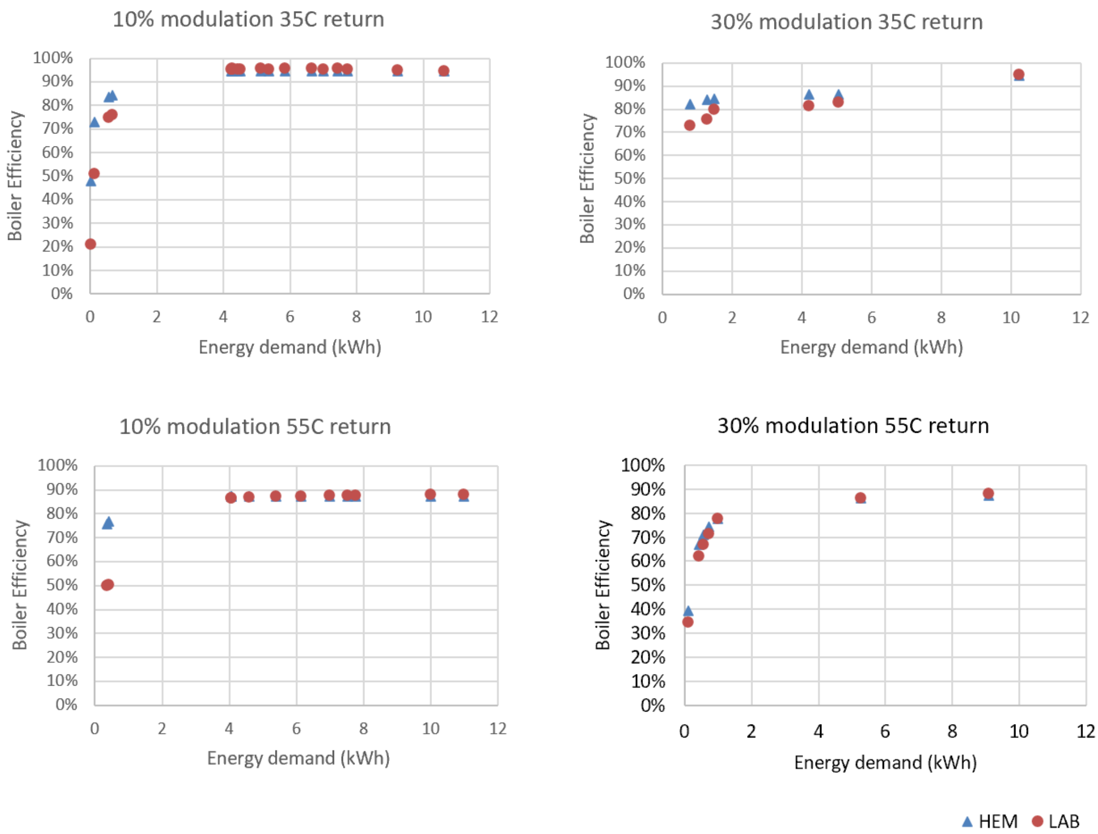


Figure 2 - Boiler efficiencies for a range of load tests in labs also modelled in HEM.

Figure 2 shows HEM has good alignment with the lab results. However, at 10% modulation when the boiler's demand falls below the minimum output, HEM is significantly overestimating the boiler efficiency compared to the lab tests.

As the HEM efficiencies do not align with the lab results at 10%, HEM will not allow the use of lower minimum modulation rates in the initial version. Further tests may be needed to validate boiler efficiencies at lower modulation rates.

As part of the HEM project, the product characteristics database (PCDB) will be rebuilt (see Section 3.3 of the Home Energy Model consultation for further detail). The existing PCDB does not record boiler's minimum modulation ratios. Therefore, all boilers will be assumed to provide 30% modulation in the initial instance. This is in line with standard boiler part load tests which are conducted at 30%.

Comparison of HEM boiler model to field trial data

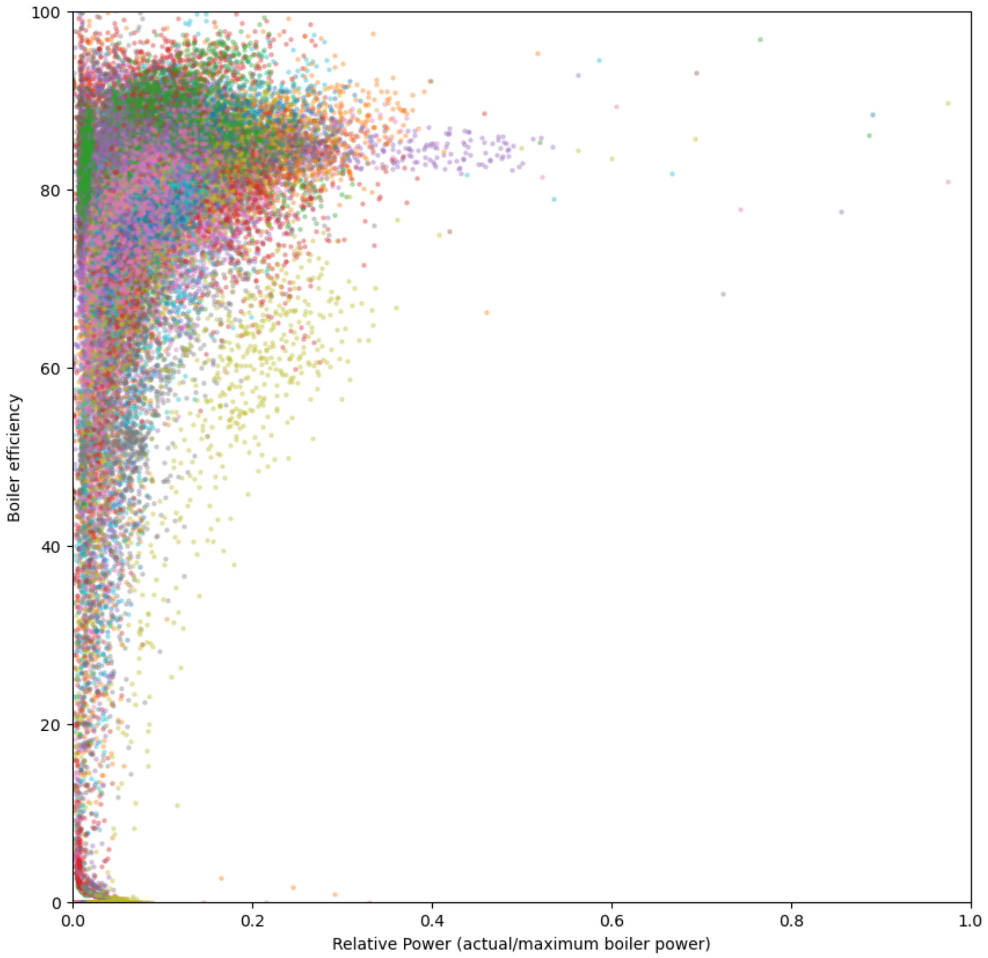
To supplement the lab test results, raw data from the In-situ monitoring of efficiencies of condensing boilers and use of secondary heating trial - final report (2009) was also collected and analysed against HEM.

The impact of load factor (amount of gas burnt, expressed as a percentage of the possible gas burnt) on boiler efficiency was covered on a monthly basis. The analysis showed that with load factors of 5% or below, the monthly average efficiency was greatly reduced, although this mostly occurred during the summer trial months. The principles of increasing losses due to standby and purge losses are characterised in the report and have influenced the boiler modelling in the HEM.

Since the HEM is a half hourly model and the heat loss of new buildings will be less than in the 2009 data, a fresh analysis of the trial data was undertaken to compare with the HEM boiler model on the basis of load factor on a daily basis. The resulting plot for all boiler types in the trial is shown in the left-hand plot of Figure 3.

Relative Power is analogous to the monthly load factor from the original analysis, calculated on the mean power of the boiler over that day compared to its rated max central heating power (both in kW). The efficiency is the simple ratio of measured gas input to measured heat output (both in kWh). The resulting plot has significant noise compared to the monthly analysis; however the trend is similar with the majority of days operating below a relative power ratio of 0.2, equivalent to 20% load factor. Note that the hourly analysis was not viable due to increased noise in the data at that time resolution, due to this being the same or close to the original measurement resolution, therefore minor errors/delays in sampling were had increased visibility, reducing the usefulness of analysis at hourly resolution.

Daily boiler efficiencies were plotted against the relative power as shown in Figure 3. Two dwellings were modelling in HEM over a year to capture a range of energy demands with the same boiler used in labs. The daily efficiencies were then included in Figure 3 for comparison. The same boiler used in the lab work was used, set at 30% minimum modulation.



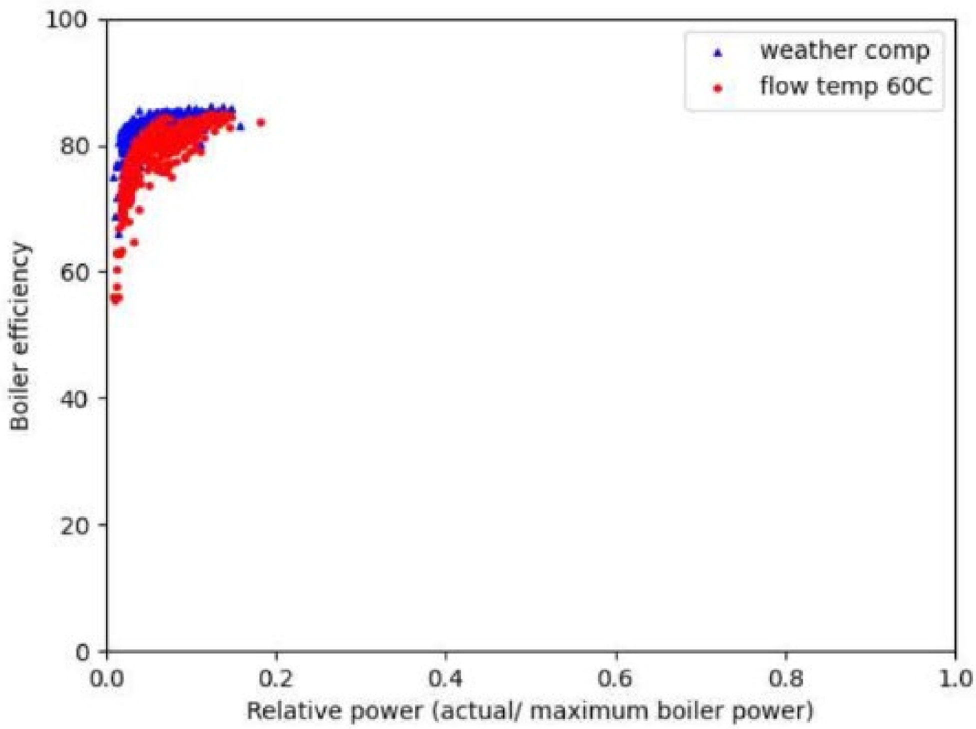


Figure 3 - Boiler efficiency against relative power measured in Field trial (top). HEM boiler efficiencies in a Victorian flat archetype (bottom). Both efficiencies were calculated on a daily basis.

It is noted that the daily efficiencies from HEM did not fall to lower efficiencies as they did in the EST field trial data. The expected reasons for the lower efficiencies in the EST field trial, but not limited to are:

1. Boiler degradation: The boilers in the field trial having degraded over time.
2. Higher flow temperature: The boilers may also have a higher flow temperature than the boiler used in the HEM modelling. This means the EST boilers are less likely to go into condensing mode and thus have lower efficiencies.
3. Sample size: The EST field trial involved 60 homes, while the HEM modelling was undertaken on one boiler.

Further modelling may be needed using more dwellings and boilers similar to that used in the field trial to observe lower boiler efficiencies.

The impact of controls can also be seen in the HEM modelling, where the boiler efficiencies are lower for the case where flow temperature was fixed at 60C compared to weather compensated controls.

Conclusion

The study shows that the HEM boiler model is a reliable tool for capturing the impact of boiler modulation on efficiency.

The new boiler methodology requires the minimum modulation as an input. Therefore, the assumption is that all modulating boilers can modulate down to 30%. This is sensible as the standard part load test is conducted at 30% modulation. If manufacturers can supply evidence for a smaller minimum modulation, this could be stored in the PCDB record for potential use in the future.

Future testing

Further tests may be needed to validate the results, especially at lower modulation levels. Further work could be carried out comparing EST return temperatures and HEM return temperatures and the impact of different boiler sizes. However, this was determined to be unnecessary at this stage.

Where range rating is claimed, and a boiler rate is set at the lowest output there is no modulation available and so operation is driven towards on/off. The risk is with systems that are likely to operate with demands below the minimum modulation rate leading to high frequency of cycling. An assessor would not be aware of the boiler power if range rated down – they only know the max rated power listed in the application.

Annex A – Lab raw test data

Minimum Modulation (%)	Return temperature (deg C)	Energy Demand (kWh)	Time Period (hh:mm:ss)	Boiler Efficiency (%)
10%	54.91	10.98	00:16:10	87.95
10%	54.91	9.98	00:12:20	87.99
10%	54.9	7.76	00:21:20	87.67
10%	54.92	7.52	00:06:30	87.57
10%	54.87	7.00	00:05:00	87.47
10%	54.9	6.14	00:10:40	87.23
10%	54.91	5.40	00:10:40	87.10
10%	54.91	4.59	00:12:40	86.79
10%	54.91	4.06	00:09:40	86.48
10%	54.9	4.06	00:09:40	86.49
10%	54.63	0.42	00:15:30	50.40
10%	54.69	0.36	00:25:50	50.06
10%	54.91	9.07	00:51:00	87.93
30%	54.89	5.26	00:40:20	86.30
30%	54.64	1.00	00:20:30	77.54
30%	54.72	0.74	00:20:30	71.43
30%	54.71	0.57	00:41:10	66.72
30%	54.69	0.44	00:20:30	62.15
30%	54.30	0.11	00:20:00	34.59
30%	35.03	7.01	00:19:50	95.25
10%	35.02	7.72	00:20:00	95.25

10%	35.03	9.23	00:19:50	95.13
10%	35.03	10.64	00:19:50	94.71
10%	35.03	7.44	00:19:50	95.52
10%	35.03	6.66	00:19:50	95.57
10%	35.04	5.86	00:19:50	95.60
10%	35.02	5.13	00:19:50	95.58
10%	35.03	4.42	00:19:50	95.44
10%	35.01	4.28	00:19:50	95.60
10%	35.02	4.25	00:19:50	95.38
10%	35.02	4.26	00:19:50	95.35
10%	35.04	4.27	00:15:00	95.51
10%	35.06	4.24	00:28:00	95.32
10%	33.01	0.03	00:52:10	21.16
10%	34.86	0.13	00:52:50	51.15
10%	35.02	0.67	00:05:10	76.08
10%	35.06	5.38	00:10:00	95.16
10%	35.05	4.51	00:09:50	95.31
10%	35.03	0.55	01:38:20	74.86
10%	35.02	10.24	01:51:50	94.70
30%	35.03	5.05	01:02:00	82.79
30%	35.03	4.20	01:12:10	81.49
30%	35.03	1.48	00:30:50	79.74
30%	35.02	0.79	00:20:30	75.72
30%	35.03	1.27	00:41:10	72.97