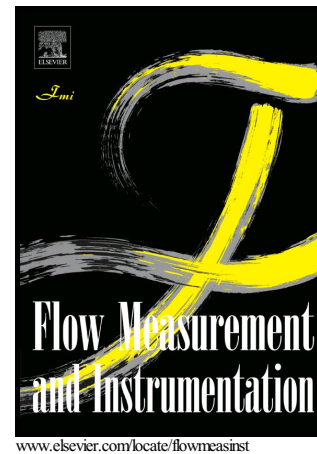


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Field Experience of Well Testing using Multiphase Coriolis Metering

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Abstract

A previously described Net Oil & Gas Skid [1] combines a multiphase Coriolis mass flow meter with a water cut meter to generate on-line estimates of oil, water and gas flow rates, with an update rate of one second. This system has received approval from GOST, the Russian standards agency, for use in upstream oil and gas applications. The NOG system has been applied to well testing, where the output of an individual well is measured, typically over several hours. The conventional equipment used for this task is a test separator; however, a separator only provides the totalised flows of oil, water and gas over the test period. By contrast, the NOG system is able to provide time series of each flow rate, thus allowing more detailed characterisations of well behaviour. This paper draws on the results of several hundred well tests carried out in Russia to illustrate the different types of well behaviour observable using the Net Oil & Gas Skid.

Keywords: Coriolis; Mass Flow; Neural Net; Multi Phase Flow; Two Phase Flow; Oil and Gas.

INTRODUCTION

It is a surprising fact, to those unfamiliar with the upstream oil and gas industry, that it remains impractical to monitor the output of every well on a continuous basis. Most wells produce mixtures of oil, water and gas, and in some cases additional components such as sand. Simultaneous three-phase (oil/water/gas) metering is technically difficult and current solutions remain expensive. Falcone *et al.* [2] provide a book-length treatment of three-phase flow metering technologies, while Thorn *et al.* [3] give an article-length summary of the main commercial technologies, their development, and their applications in the petroleum industry. A further barrier to more widespread adoption of several of the current multiphase technologies is their use of radioactive materials, which, in the current climate of heightened security concerns, significantly raises the cost of ownership. Accordingly, a widely used means of assessing the production of each well is by well testing [4].

In well testing, the production streams from several wells (typically 6 – 20) are piped to a test station (Figure 1, right), where a single three-phase flow metering system is provided. While this can be any type of three-phase metering technology, commonly a separator system is used. Here, a storage vessel of sufficient capacity is used to hold the incoming production stream to enable at least the gas to separate from the liquid; in more elaborate designs separation of the oil and water also takes place. The gas and liquid streams are metered independently as they emerge from the separator. A key aspect of any separator operation is that it acts as an integrator: instantaneous flow behaviour of the production stream is lost, while the flow profiles of the gas and liquid outputs are a function of the control scheme. Typically, level and/or pressure controls are used to trigger short batches of gas and liquid expulsion. Accordingly, measurements recorded from a separator-based well test consist only of totalised flows for gas, oil and water over the test period (typically several hours) as effectively all well flow profile information is lost through the operation of the separator.

With only a single three-phase measurement system at each test station, it is only possible to measure the output of each well (or a combination of wells) on an occasional basis. A common arrangement is for each well to be tested for a twenty four hour period once per month. The production of a well for the entire month

is then estimated from the results of its one day test period. Furthermore, as discussed above, when a separator is used for well testing, only the totalised flows are provided, and so it is not in general possible to identify which wells have stable flows and which have irregular flow profiles.

If it were possible to provide detailed flow time series this could be valuable in determining a more optimal schedule of well testing: for example wells with stable flows could be monitored less frequently.

Additionally, flow time series may enable the identification of well behaviour features that can be valuable in reservoir management. For example, the effect of changes in extraction arrangements (e.g. pumping strategy) may be observed in the real-time production of the affected well or wells. Finally, flow time profiles may assist in identifying poorly executed well tests, for example where a substantial and unexpected step change in well behaviour is observed during the course of the test, so that the results of a poor test could be discounted and a new test rescheduled.

The authors have developed, together with their industrial partners, a new commercial three-phase flow metering system, called the Net Oil & Gas skid (NOG). This system is based on combining a multiphase Coriolis mass flow meter with a water cut meter, along with pressure and temperature measurements, and has been described in detail in [1]. Having received GOST certification for use in upstream oil and gas applications in Russia, a number of systems have been applied to well testing in field trials. At the time of writing, several hundred well tests have been carried out. The results of many of these have been made available to the authors, and permission has been obtained to present anonymised data in this paper to illustrate the wide range of flow profiles that have been observed, in order to demonstrate the benefits of providing relatively high frequency (1 second update) time series of oil well production. Similar benefits may be provided by other multiphase technologies with comparable update rates.

The paper is arranged as follows. Section 2 provides an overview of the NOG technology and describes its application in field trials. Section 3 gives examples of stable flow profiles, and explains how the limited flow profile graphs provided in this paper are derived from the complete reports generated by the

commercial system. Section 4 illustrates the disruption caused to flow profile time series when a separator is used. Sections 5 – 7 describe classes of well test profile identified among the hundreds of examples collected thus far. These include cycling, slugging and erratic profiles, with further examples where it is possible that the well test has not been executed properly.

2 NET OIL & GAS SKID

A detailed description of the Net Oil & Gas skid (NOG), including its construction, functionality and performance in formal laboratory trials, is given in [1]. A brief summary is provided here. Figure 2 shows the design. The instrumentation consists of a Coriolis mass flow meter, a water cut meter, and pressure and temperature sensors. A central computing and communication unit regularly polls each of the instruments and calculates a set of measurements, including the instantaneous mass flows of oil, water and gas passing through the skid, with measurements updated once per second. Meter sizes for the NOG range from 15mm to 80mm. One feature of the NOG skid introduced since the publication of [1] is the ability to estimate the dissolved gas in the production stream. This capability is based upon an empirical, widely used, ‘black oil model’ [5, 6] and will be described in a forthcoming paper.

For single phase liquid flow, Coriolis meters have a large turn-down: the ratio between the highest and lowest flow rates with acceptable uncertainties is typically 100:1. By contrast, with multiphase flow, the turndown ratio of the NOG is around 6:1. For example, a 50mm flowtube has a maximum liquid flow rate of 11kg/s, with a corresponding uncertainty of approximately 0.1%, while at 0.011 kg/s the mass flow measurement uncertainty for a single phase liquid is approximately 1%. For three phase (oil/water/gas) flow, the Russian Standard GOST 8.165 [5] requires, among other criteria, the total liquid flow rate to have an error of 2.5% of reading or less, and 5% for the gas flow rate. For a 50mm flowtube, this performance requirement has been achieved in formal laboratory trials down to 2 kg/s [1], a turndown ratio of 5.5:1. Similarly, formal laboratory testing has been carried out on a limited range of the Gas Volume Fraction (GVF), i.e. the proportion of gas by volume in the three-phase mixture, to no more than 50%, reflecting the current limitations of the NOG technology [1].

For applications where it is not possible to ensure that all well flow conditions will fall within the range of the selected size of NOG, a technical solution has been developed which combines the NOG with a small separator system. For example, Figure 3 shows the inside of a mobile testing unit (the external view is shown in Figure 1) where the separator is on the left, and the NOG system is in the centre and back of the figure. When a test occurs within the range of the NOG, all of the well production flow is directed through the NOG. If the well parameters are expected to fall outside the range of the NOG, the flow is directed to the separator. In this case the gas flow exiting the separator is measured by another Coriolis meter (seen on the left in Figure 3), while the liquid output of the separator is passed through the NOG. This design has the advantage that the NOG does not require the liquid to be entirely free from gas in order to meter it accurately, so that only a small separator is required. On the other hand, as will be shown later in the paper, good flow profile information is only obtained when the separator is not used.

All the well tests reported in this paper have been obtained from mobile units similar to the ones shown in Figures 1 and 3. The mobile test units have been deployed by a service provider to the Russian oil industry to test hundreds of wells over the past year. Limited information is available to the authors beyond the test data itself. For example, it is not known whether all the wells in a particular reservoir have been tested systematically using the NOG system, or whether only potentially ‘difficult’ wells have been examined. It is also not known whether, during some tests, external operating conditions have been deliberately manipulated in order to observe the resulting change in well behaviour via the NOG measurements. Accordingly, with this set of test records, it is not possible to offer a statistical analysis on the relative frequency of ‘stable’, ‘unstable’, or other possible categories of well behaviour. Furthermore, in some cases the recorded flow rates are below the lower limit for the GOST certification. In these cases, although the accuracy of the measurements cannot be guaranteed to fall within the GOST specification, the pattern of flow is still likely to provide useful information. Note that the focus of the remainder of this paper is on monitoring well flow behaviour, rather than flow measurement accuracy, which is addressed in [1], and will be the subject of further publications.

With stationary well testing units, it is practical to have fixed, and often long, well test durations. With mobile units providing a commercial service, and potentially travelling hundreds of miles between wells, test durations may be more variable. In the examples shown here, test duration range from 2 and 24 hours. There are also recorded examples of fast tests, typically used as checks prior to starting a longer test. One 15 minute test is described later in the paper.

3. EXAMPLES OF STEADY WELL BEHAVIOUR

Figure 4 shows an example of steady flow behaviour in a well test lasting just over three hours. The same format of six graphs is used to report all well tests in this paper, as follows. The top two graphs show the total liquid volumetric flow rate, combining oil and water together, and the total gas flow rate, the latter in standard meters cubed per day i.e. normalised to atmospheric pressure. The NOG system can support the various national norms for reporting standard gas volume: for Russia the standard pressure is 101.325 kPa and the standard temperature is 20 C. In this example, both flow rates are relatively steady, the 1 second updates exhibiting high frequency noisy with a variation of approximately $\pm 5\%$ of their mean values. The middle two graphs show the inlet pressure and fluid temperature. These are automatically scaled to show whatever variation occurs during the test, but the trending of both variables is insignificant in this example.

The lower two graphs are more complex, and show the pattern of flow for the different well production stream components. In the left graph, the absolute flow rates of oil, water, dissolved gas and free gas are shown, where both of the gas flow rates are given at line conditions i.e. in this case around 2.66 MPa. Note that the dissolved gas volume is calculated based on a black oil model of gas solubility [5, 6]; it is displayed here as if it were also ‘free’ at the line temperature and pressure conditions. The right hand graph shows the actual volume of oil, water and free gas as a percentage of the whole, so that the total is always 100%. Again, the gas volume is shown at line conditions. Note that in this graph, the dissolved gas is not shown, as in practice it will be incorporated within the oil fraction. In this example the water cut is low.

This standard set of six plots will be used for all the other examples given in this paper, being a minimum set to show the range of behaviours observed. In the complete report generated by the well testing system, additional plots are provided for the oil and water mass flow rates, the dissolved gas, free gas and (where applicable) separator gas mass flow rates, the gas volume rates at standard (as opposed to line) temperature and pressure, the water cut and GVF, along with tables summarising the average (and where appropriate totalised) parameter values for each test.

Figure 5 shows a second example of a steady well test profile, here with a high water cut. Other than a very slight decline in the liquid and gas flow rates, the parameter values are essentially steady.

This steady behaviour, irrespective of water cut (which in the recorded well tests has varied over the full range of 0% to 100%), is observed in around 70% of the test records available; however, as stated above, it is unknown how representative the wells selected for testing are for the reservoirs concerned. In all the other examples in this paper, significant variation will be seen from this steady behaviour.

4. EFFECTS OF SEPARATOR ACTION ON WELL FLOW PROFILE INFORMATION

Figure 6 shows the measurements obtained over a short test of 15 minutes duration in which the separator system is used in series with the NOG system. In this configuration, an additional gas flow measurement is taken from the gas leg outlet of the separator, as discussed above, and this separator gas is shown as an additional colour in the lower left graph. As is clear from the lower right graph, the liquid is almost entirely oil, with only trace amounts of water present. Note also that there is effectively no free gas seen by the NOG system: the separator is successfully removing all of the gas from the production stream. There are two narrow bands of white in the lower right plot, corresponding to periods when the flow through the NOG is zero, and so no data is plotted.

While the fluid temperature plot shows essentially steady behaviour, the flow rates and inlet pressure plots all show cycling behaviour, with a frequency of around 30 seconds. This behaviour is induced by the action

of the separator. The actual volume flow plot (lower left) illustrates this most clearly. It can be seen that the cycles consist of a surge in liquid with little or no separator gas flow, followed by a surge in separator gas, with little or no liquid flow. While the exact control strategy used by separators may vary, the pattern shown here is fairly typical, where valves are operated to use the production stream supply pressure to expel either gas or liquid out of the separator via their respective legs. The liquid and gas flow rates (top graphs) both exhibit rapid fluctuations on the 30s cycle, which the NOG inlet pressure peaks during a separator liquid purge and drops during a separator gas purge.

With the separator in use, the actual well production flow characteristic is only one of many factors affecting the observed measurement output. Others include the pressure and/or level thresholds used by the separator control system (which may themselves be adjusted in real time by higher level control loops), and the capacity of the separator. There can be confidence that, over a sufficiently long test period, the quantities of liquid and gas entering the separator are approximately matched by the quantities recorded leaving via the gas and liquid legs, but any short-term correlation between input and output is unlikely to be strong.

Figure 7 shows the results from a ten hour test on a different well where the separator has also been used. Little can be discerned about trends in the flow data, other than that the water cut appears to be constant at around 50%, the pressure is approximately constant, and the temperature shows a steady decline throughout the test. Thus Figures 6 and 7 illustrate the general principle that the default well test technology, separation, unavoidably destroys well flow profile information.

5. EXAMPLES OF CYCLING WELL BEHAVIOUR

Figure 8 shows data from a four hour test, on a low water cut well. Here, the well exhibits a gentle cycling of flow rate with a period of just over one hour. There appears to be no particular correlation between the flow cycling and the inlet pressure; rather the pressure time series exhibits a separate, low amplitude cycling with a period of around 10 minutes, possibly attributable to the well pumping arrangement. However, there appears to be some correlation between the flow oscillation and temperature.

Figure 9 shows another four hour test where a strong cycling pattern develops, but only after a long settling period at the start of the test. For the first two hours of the test, the liquid and gas flows have fairly random behaviour, but after two hours strong cycling is manifest, with a cycle time of around 10 minutes. The liquid flow varies by about 10% over the established cycle, while the gas flow rate varies by around 50%. There is also a significant rise in the average gas flow rate in the second half of the test.

This example illustrates another potential benefit of having well test flow parameter time series. The process of setting up a well test involves at the very least rerouting, and possibly even temporarily shutting off, the established flow path of the production fluid for the well concerned. This change may lead to a disruption of the flow, so that a settling period may be required before the well returns to its ‘natural’ pattern of flow. Real time flow profile data enables the identification of such settling periods – in this case, discarding the data for an initial two-hour settling period might be appropriate in order to ensure the test is actually representative of the well production.

6. EXAMPLES OF SURGING FLOW IN WELL BEHAVIOUR

Here ‘surge’ is used to describe a large step change in the well flow rate. In the well test data set obtained, such surges are often separated by periods of little or no flow, and typically occur on the timescale of minutes or hours. They may be attributable to the operational procedures (e.g. variations in pump duty), or to reservoir properties.

Figure 10 shows an example of surging flow caused by step changes in the supply pressure. During the 19 hour test, the inlet pressure exhibits step changes, switching between approximately 1.5 MPa and 0.5 MPa with a cycle time of around 8 hours. These pressure step changes result in corresponding surges in flow. When the supply pressure increases from low to high (around $t = 5$ hours and 13 hours) there are short pauses in the flow prior to the onset of the next surge. When the pressure decreases from high to low (around $t = 9$ hours and 17 hours) there is also a sharp reduction in the flow rate, with only a gradual

increase over the following two hours. The liquid flow rate and water cut are both reasonably steady during the surges, other than during the first six hours, which may be due to test start up effects as discussed above. However, there is a significant difference in the gas flowrate in the high and low pressure periods. During periods of high pressure, the gas flow rate in standard units is approximately three times higher (top right plot), even though the GVF at line conditions is lower (bottom right graph): the gas volume is compressed by the higher line pressure.

In Figure 11, regular surges occur with a period of approximately 20 minutes, while the supply pressure remains relatively constant. In this example, the water cut of each surge varies significantly. The first three surges are oil free, followed by a large, oil-rich surge, with the oil content carrying over into subsequent surges. The regularity of the surge period suggests it arises from the extraction process.

Figure 12 shows another surge pattern: here, there is a six hour gap between consecutive surges, during which there is negligible flow, but no significant change in supply pressure. This is an example where further investigation would perhaps be warranted. The ten hour test period has proved insufficient to capture even two complete surges from the well: it is not possible to determine whether the pattern of flow is regular. Any estimate of 'average' flow rates for such a well would have low reliability unless the pattern of flow for the well had been established, and an appropriate testing period selected (e.g. to record a whole number of surge and gap cycles).

Figure 13 shows a well test in which the flow pattern appears steady, and then a surge occurs about four hours into the test. The surge is associated with a modest rise in supply pressure and a drop in temperature. It is not known whether this surge was the result of some adjustment to the production arrangements. Note that during the surge the water cut is significantly higher (lower right plot) but nevertheless that oil flow rate is increased significantly compared to the previous steady state behaviour (lower left plot).

Finally, Figure 14 shows a surge cycle, occurring roughly every hour: there is sufficient irregularity in the flow pattern that this may be a function of reservoir, rather than production effects. Arguably, this example could be placed in the ‘erratic’ category discussed in the next section.

7. ERRATIC WELL BEHAVIOUR AND WELL TEST OPERATION ISSUES

In a small number of cases, the well time series show erratic behaviour, suggesting the need for further investigation to ensure proper monitoring and management of the well. An example is shown in Figure 15, where the first two hours of the test feature a low water cut, and then after a brief surge the well produces only water. In other examples of erratic well behaviour not shown, large variations in the flow rate, water cut, GVF and/or temperature can be observed despite (typically) a relatively steady input pressure. Particular care needs to be taken to ensure that the results of such well tests are representative of well production: most obviously, longer tests might be carried out to reduce the influence of random fluctuations.

A further potential application of well test time series data is to verify the proper operation of the test itself. Some of the individual well test records appear to indicate, for example, that the fluid totalisation has been allowed to continue after the well supply to the NOG has been cut off, leading to an artificial lowering of the average flow rates calculated during the test. Visual or automated inspection of the time series should allow such incidents to be identified and dealt with appropriately.

8. SUMMARY

This paper has given examples of real-time well test data generated by a new commercial three-phase metering system based on Coriolis mass flow metering combined with water cut metering. The results demonstrate that patterns of well flow behaviour can be discerned that would not be visible through the operation of conventional well test separators. These patterns of behaviour may be helpful to reservoir operating companies to develop optimal testing strategies, reservoir management strategies, and identifying potentially problematic well tests.

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Accepted manuscript

Figure Captions

Figure 1: Figure 1: (right) conventional well test station, including separator. Note piping to handle multiple well production streams. (left) Mobile trailer carrying NOG system. Note piping extended from well test station, enabling NOG system to perform well tests.

Figure 2: Net Oil & Gas Skid Design

Figure 3: Net Oil & Gas Skid installed in mobile test unit, including small separator system on left

Figure 4: Steady well test profile: low water cut

Figure 5: Steady well test profile: high water cut

Figure 6: Short well test showing detail of impact of separator action on parameter time series

Figure 7: Long well test showing impact of separator action on parameter time series

Figure 8: Cycling well test profile

Figure 9: Well test profile: cycling pattern develops during course of test

Figure 10: Well test profile: regular flow surges driven by artificial pressure step changes

Figure 11: Well test profile: regular surges of flow with substantially varying water cut

Figure 12: Well test profile: irregular surges with extended periods of no flow

Figure 13: Well test profile: steady flow with surge

Figure 14: Well test profile: irregular flow surges

Figure 15: Erratic well test profile



Figure 1: (right) conventional well test station, including separator. Note piping to handle multiple well production streams. (left) Mobile trailer carrying NOG system. Note piping extended from well test station, enabling NOG system to perform well tests.

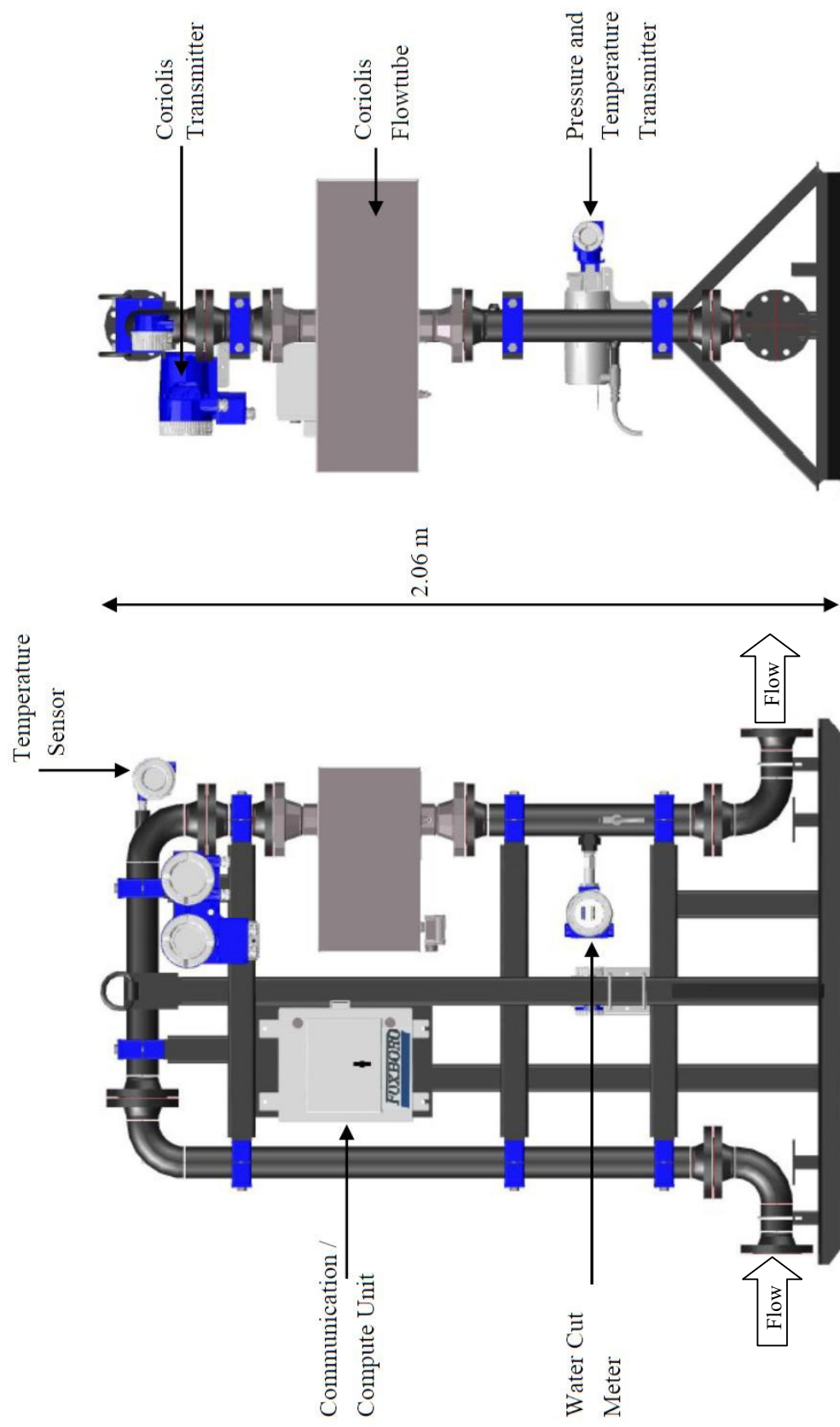


Figure 2: Net Oil & Gas Skid Design

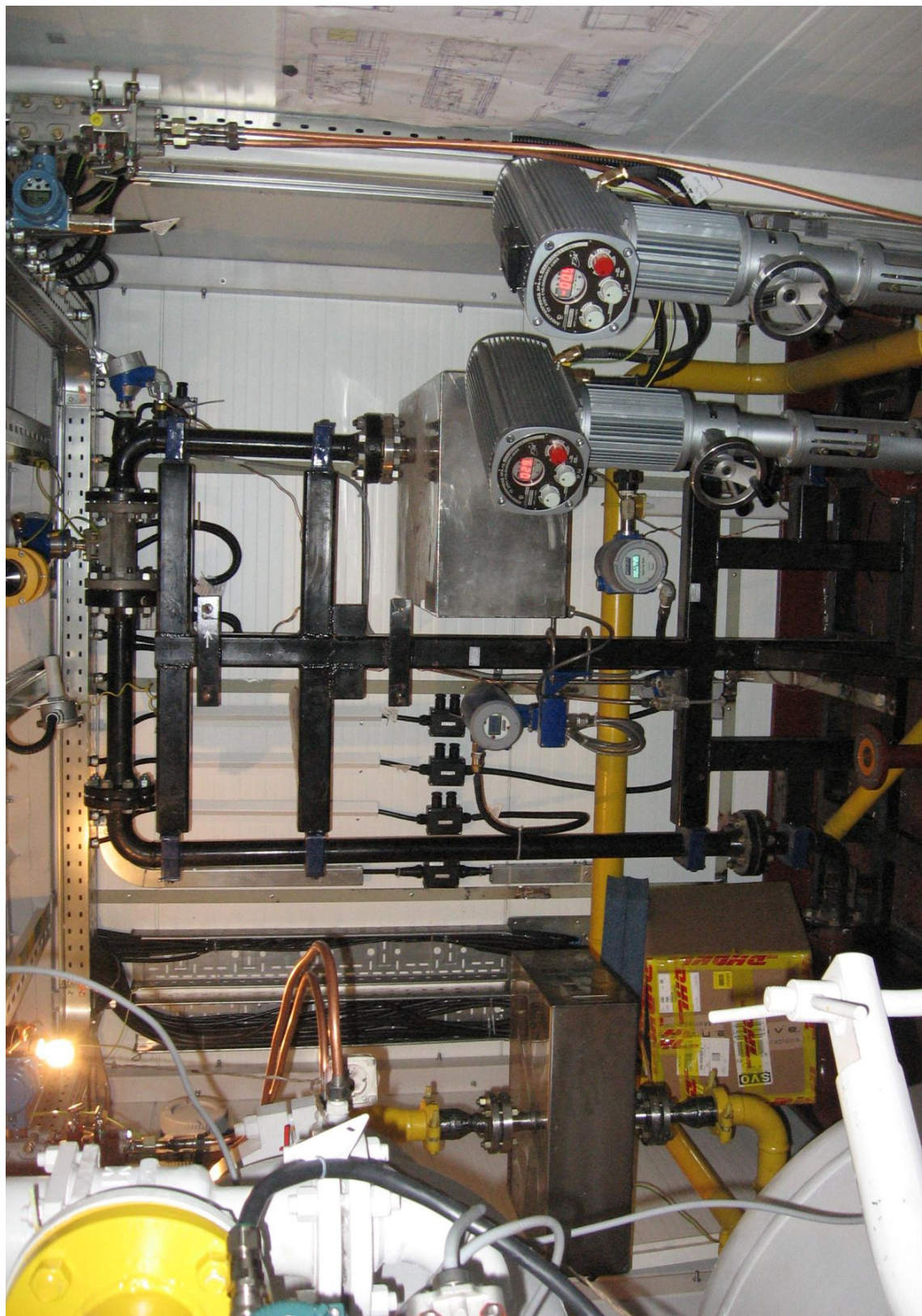


Figure 3: Net Oil & Gas Skid installed in mobile test unit, including small separator system on left

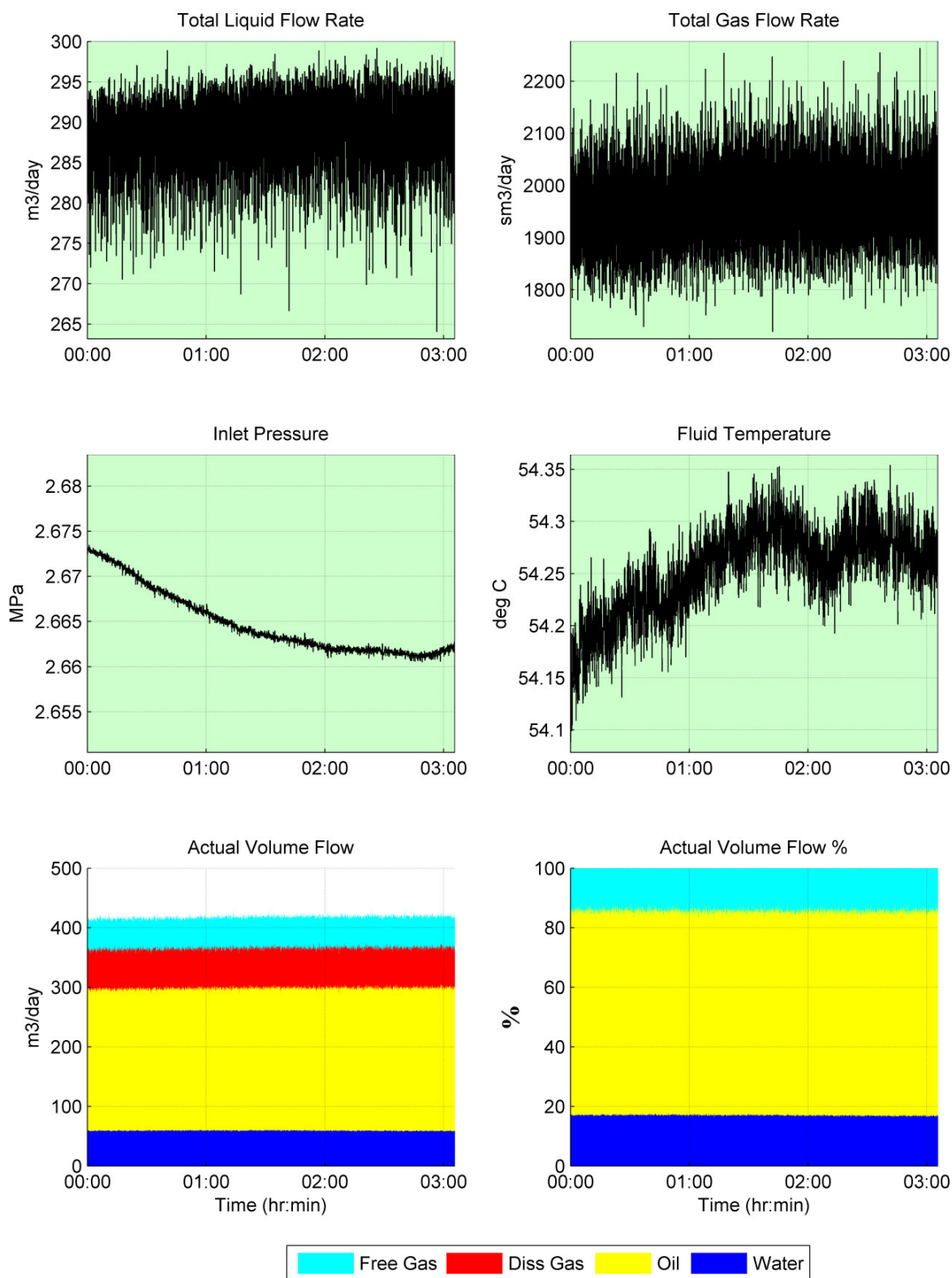


Figure 4: Steady well test profile: low water cut

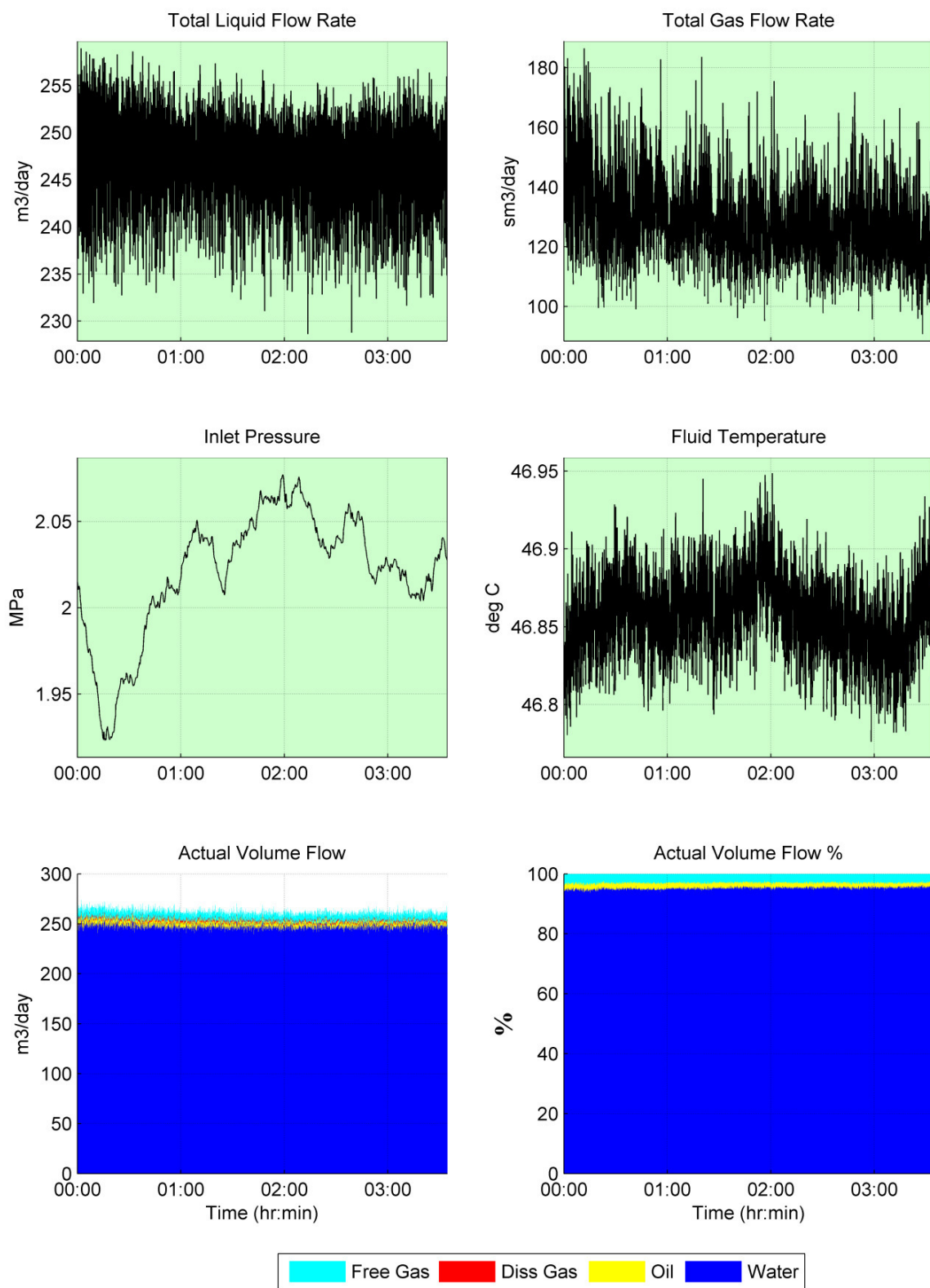


Figure 5: Steady well test profile: high water cut

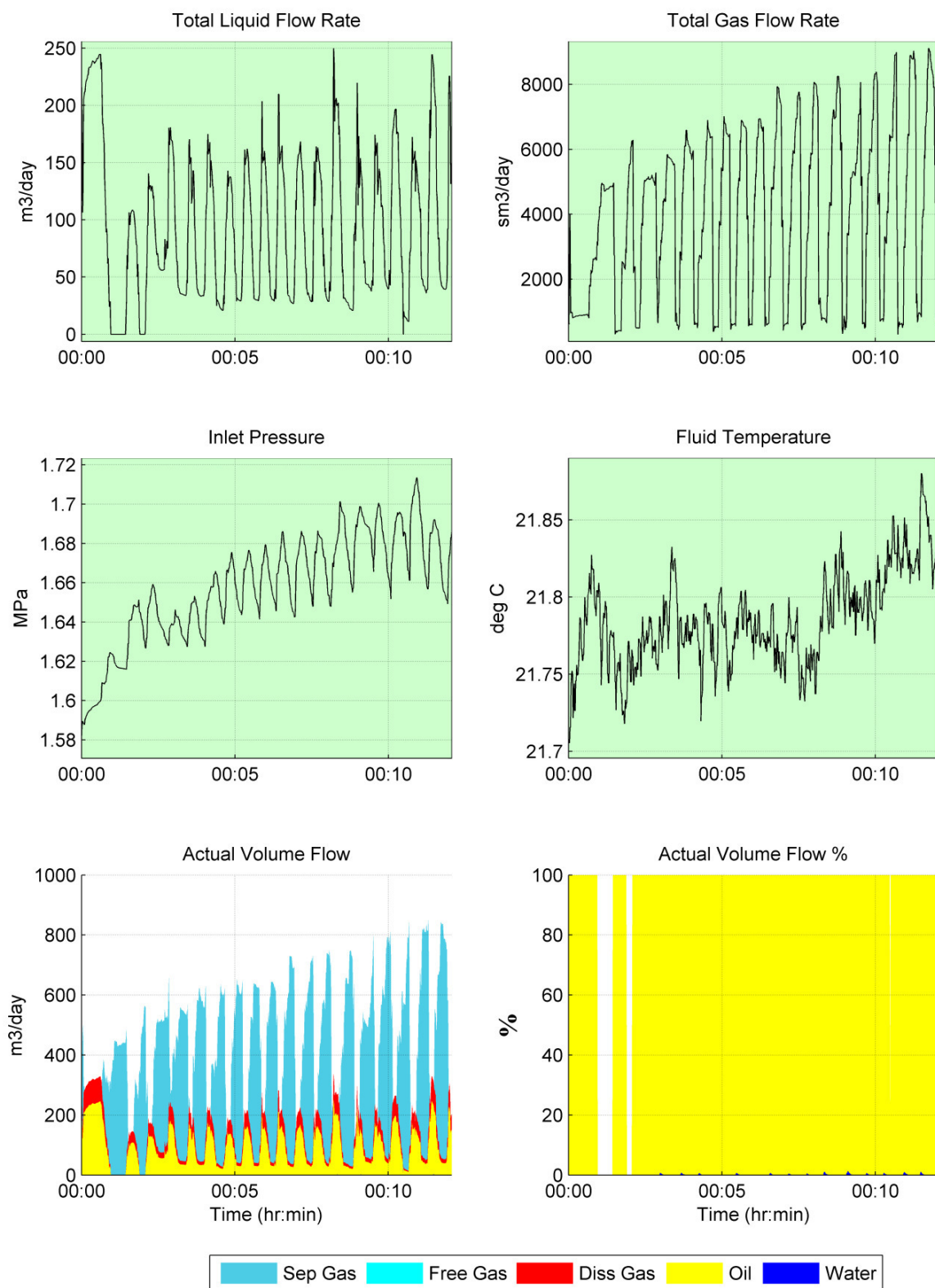


Figure 6: Short well test showing detail of impact of separator action on parameter time series

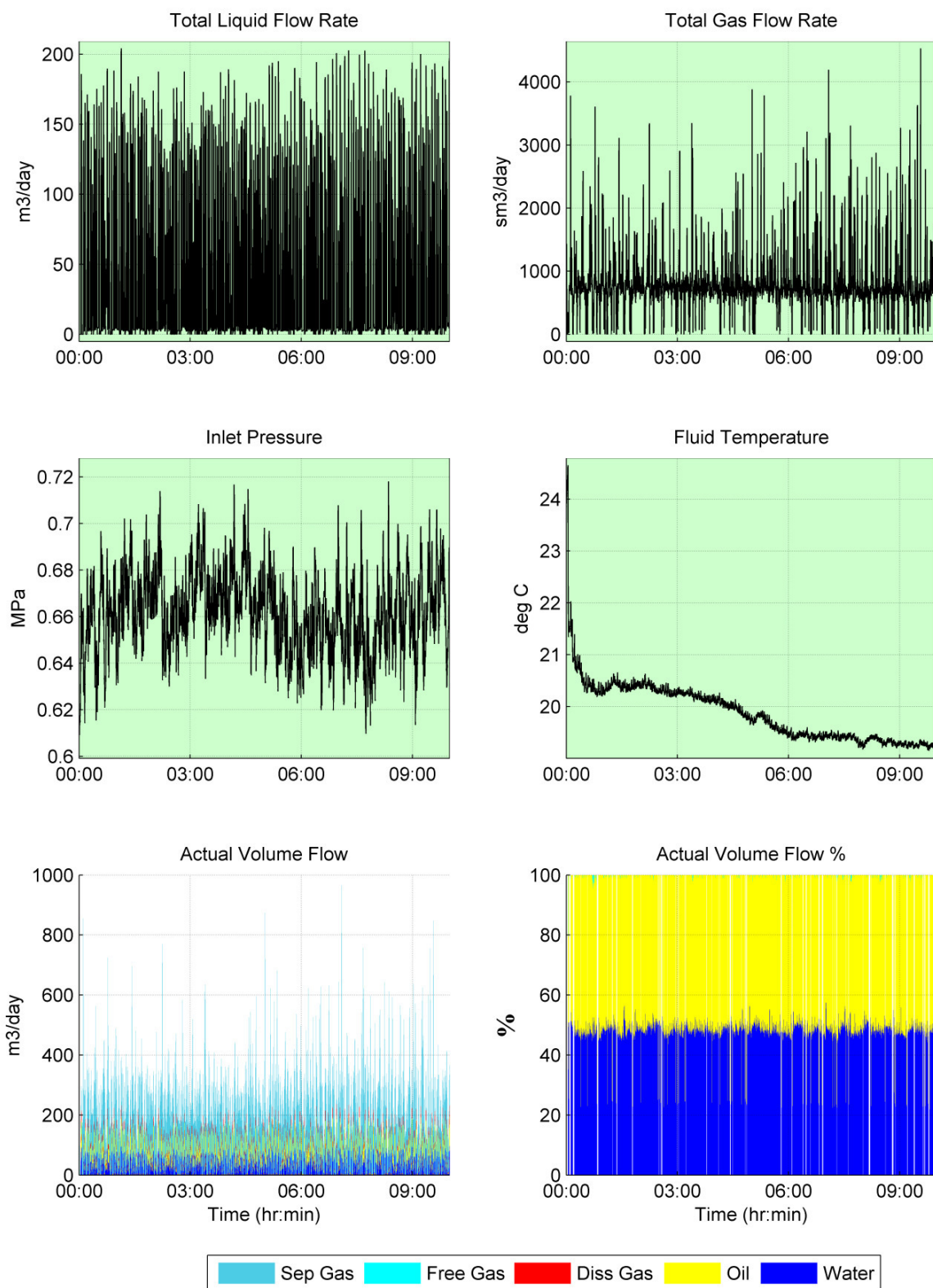


Figure 7: Long well test showing impact of separator action on parameter time series

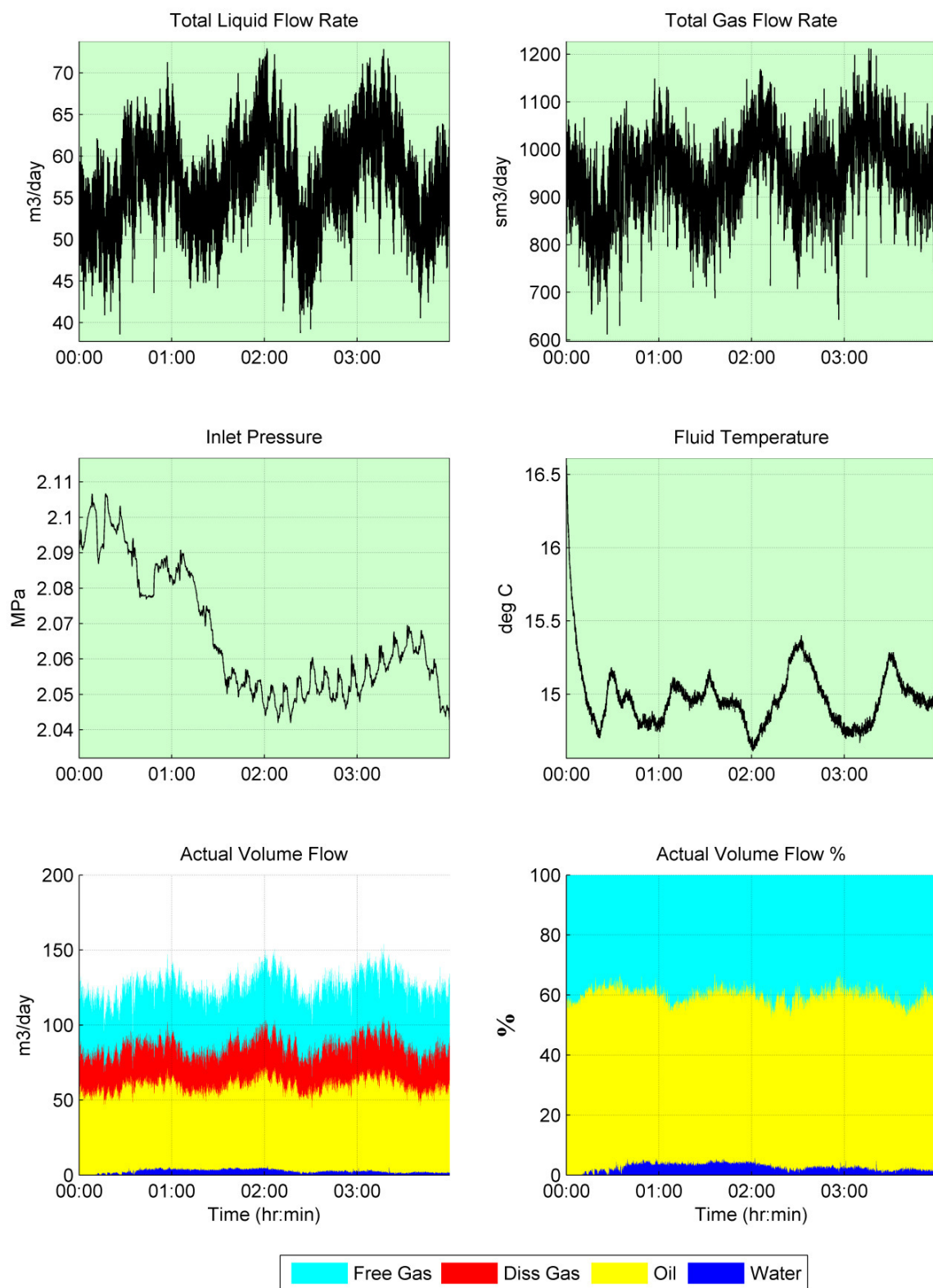


Figure 8: Cycling well test profile

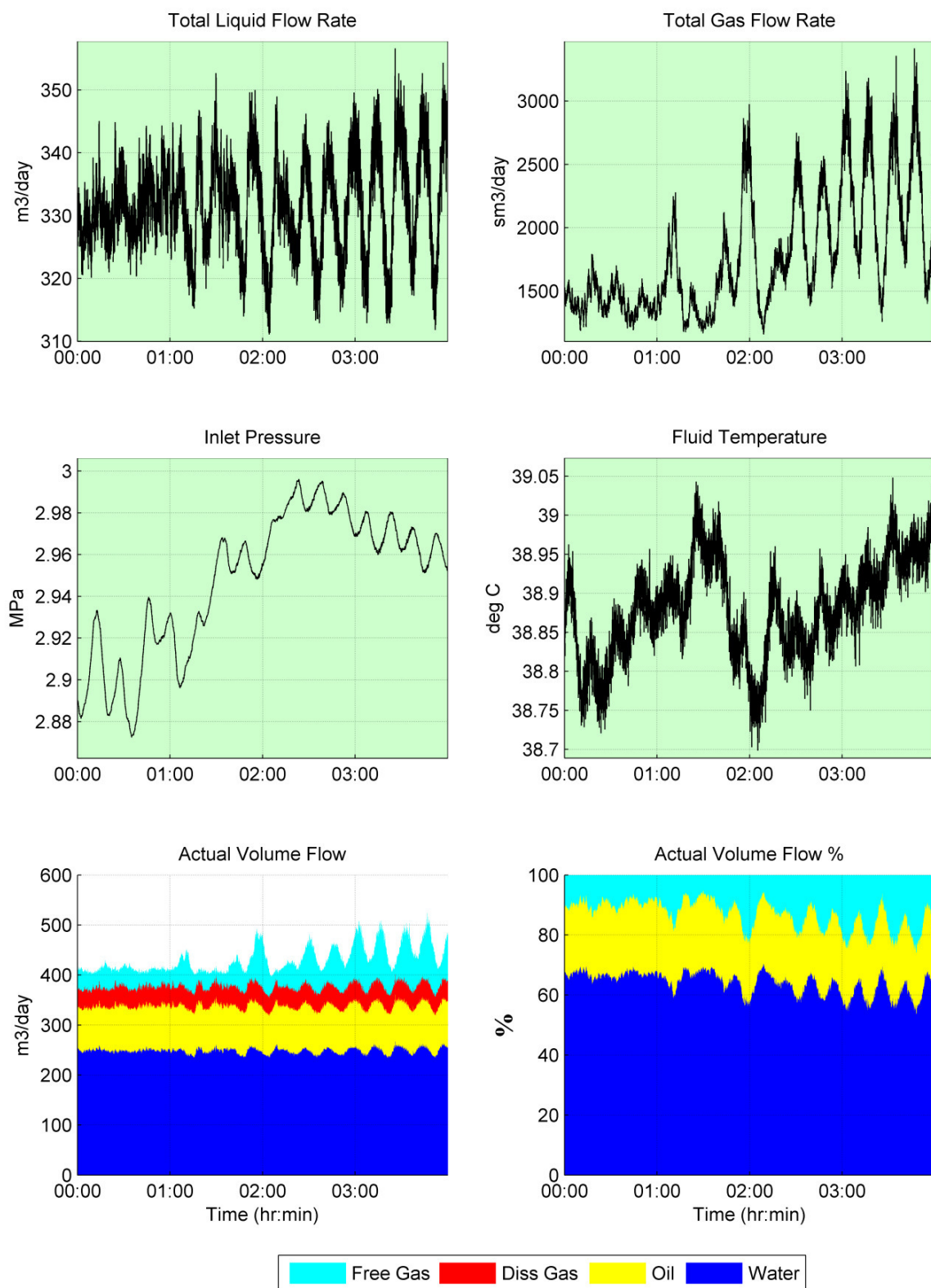


Figure 9: Well test profile: cycling pattern develops during course of test

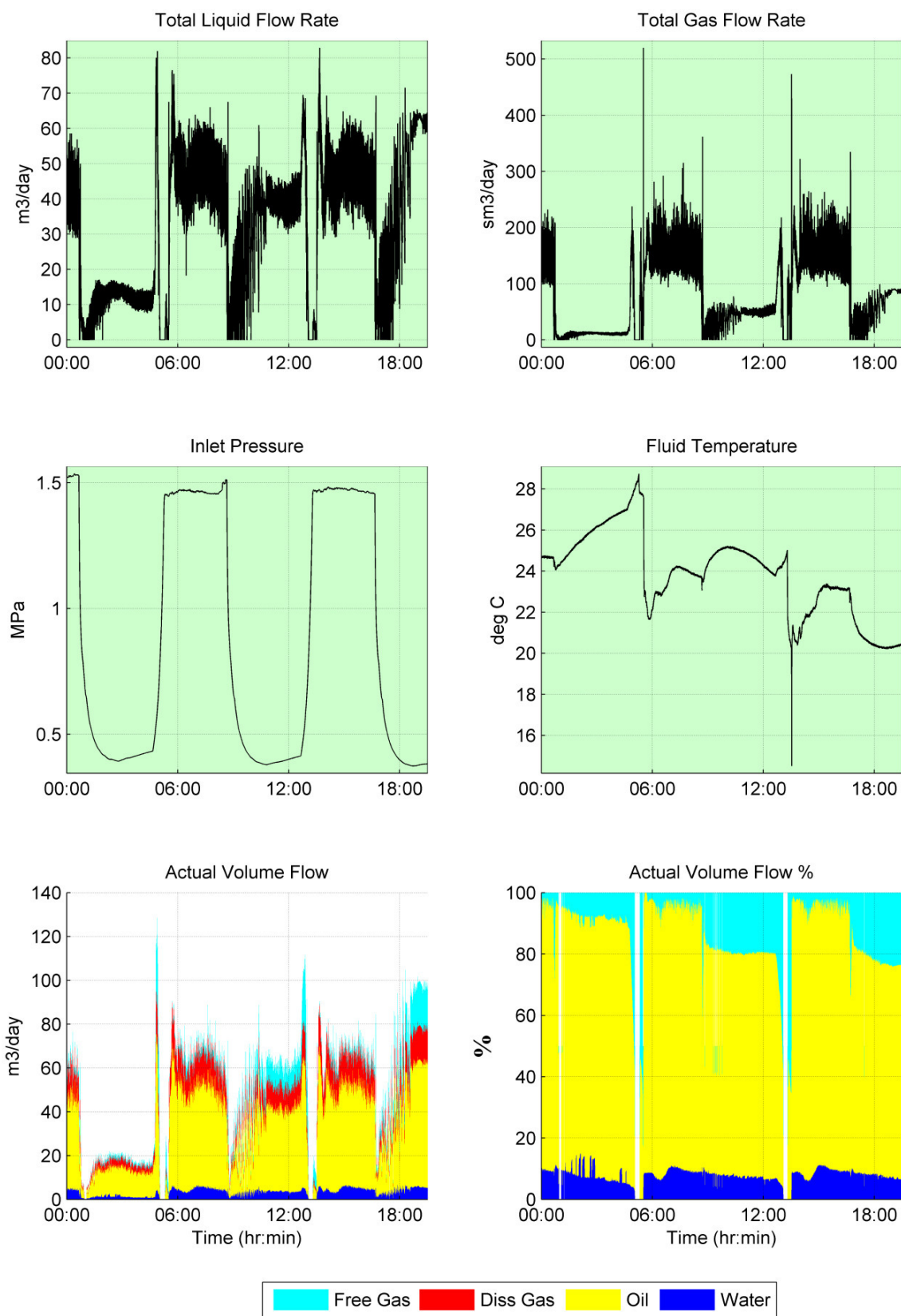


Figure 10: Well test profile: regular flow surges driven by artificial pressure step changes

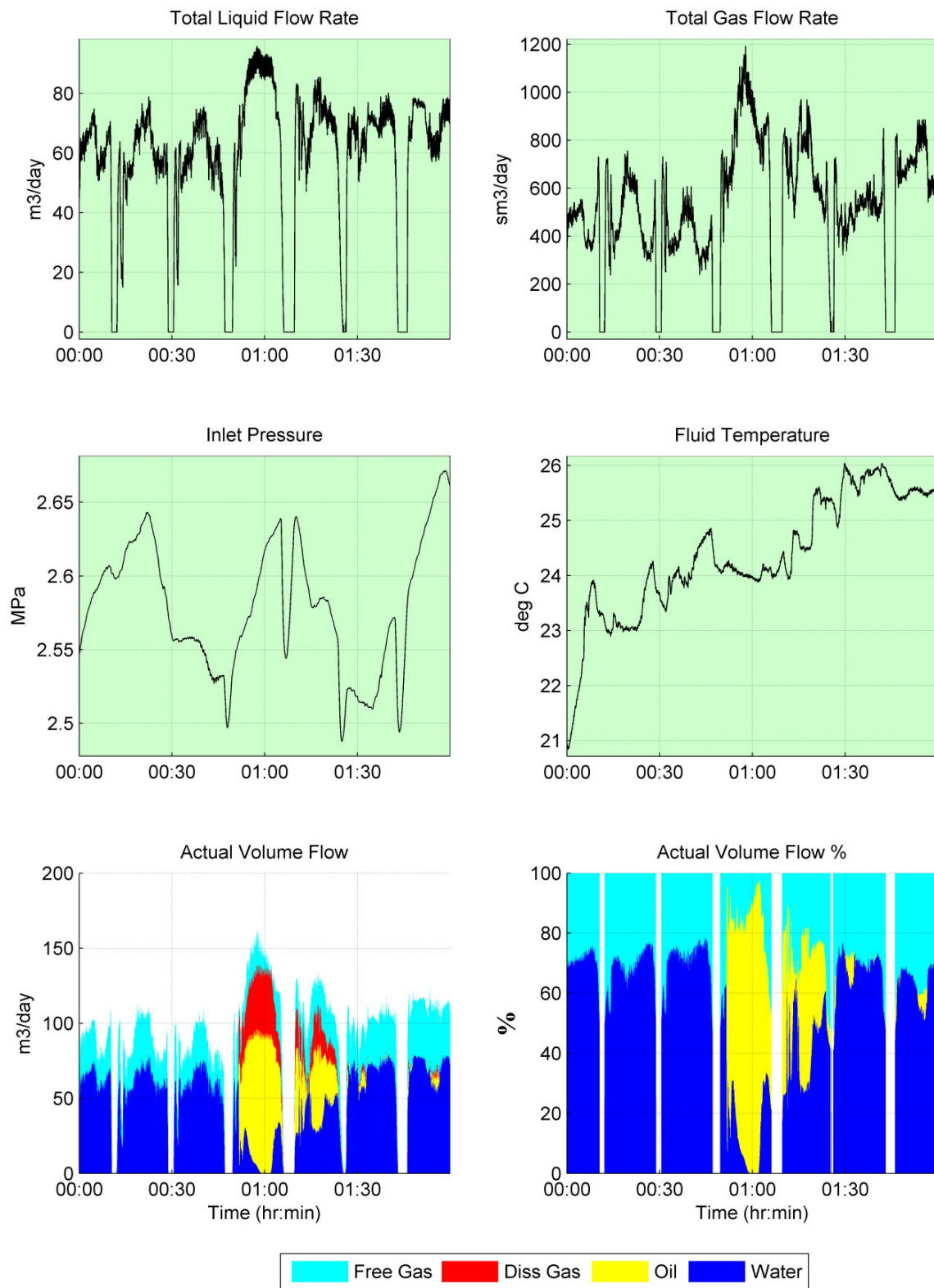


Figure 11: Well test profile: regular surges of flow with substantially varying water cut

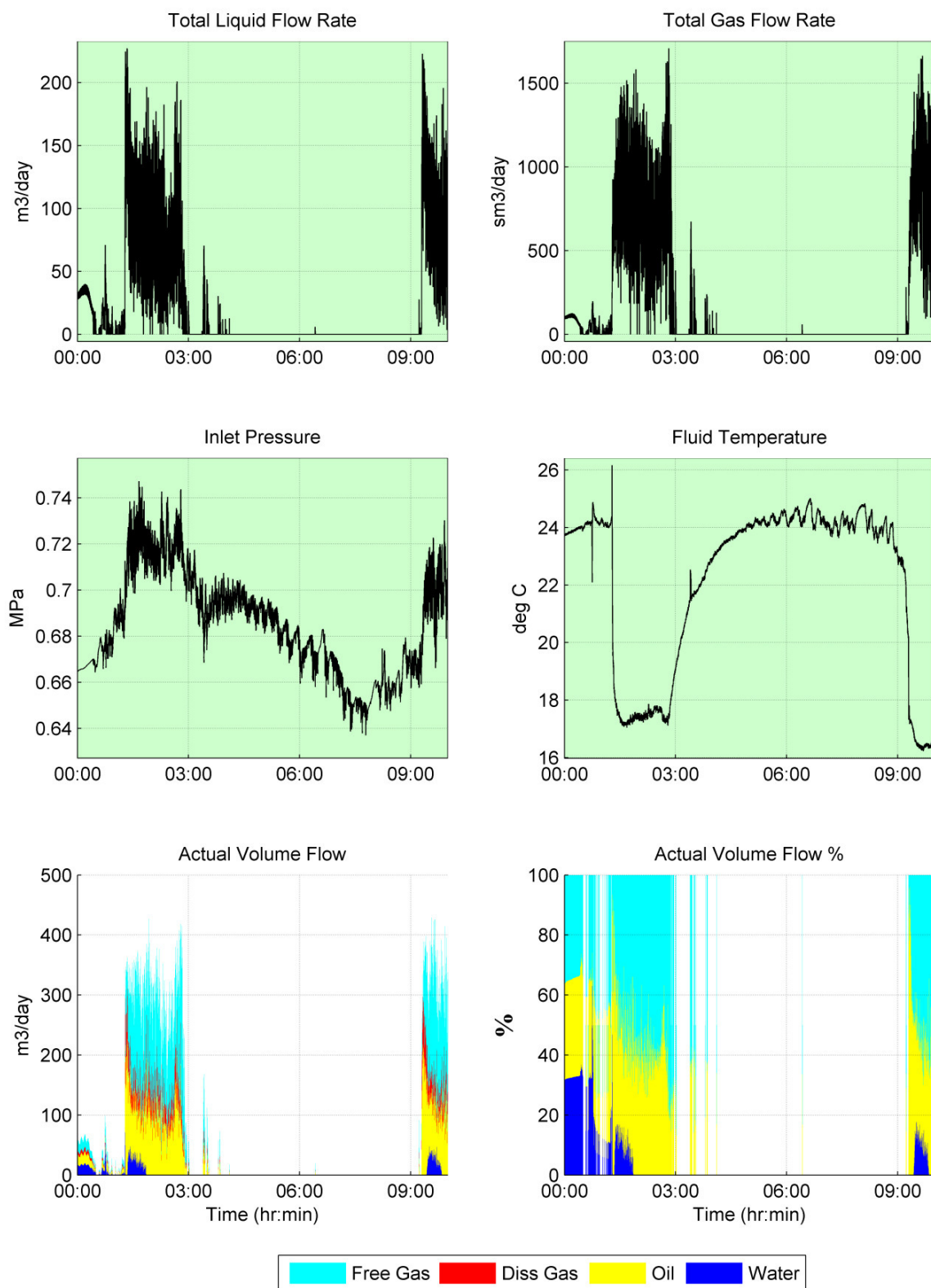


Figure 12: Well test profile: irregular surges with extended periods of no flow

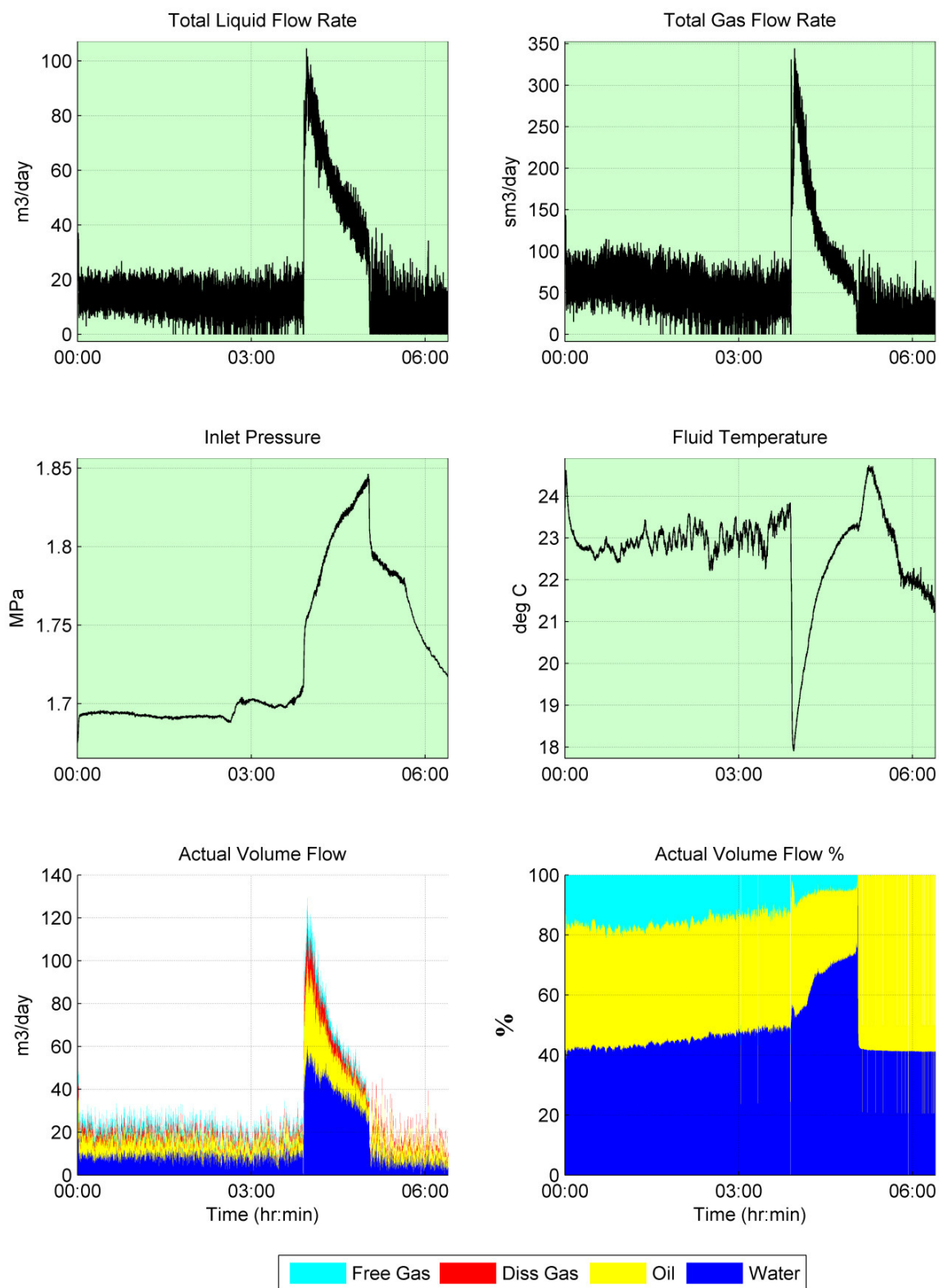


Figure 13: Well test profile: steady flow with surge

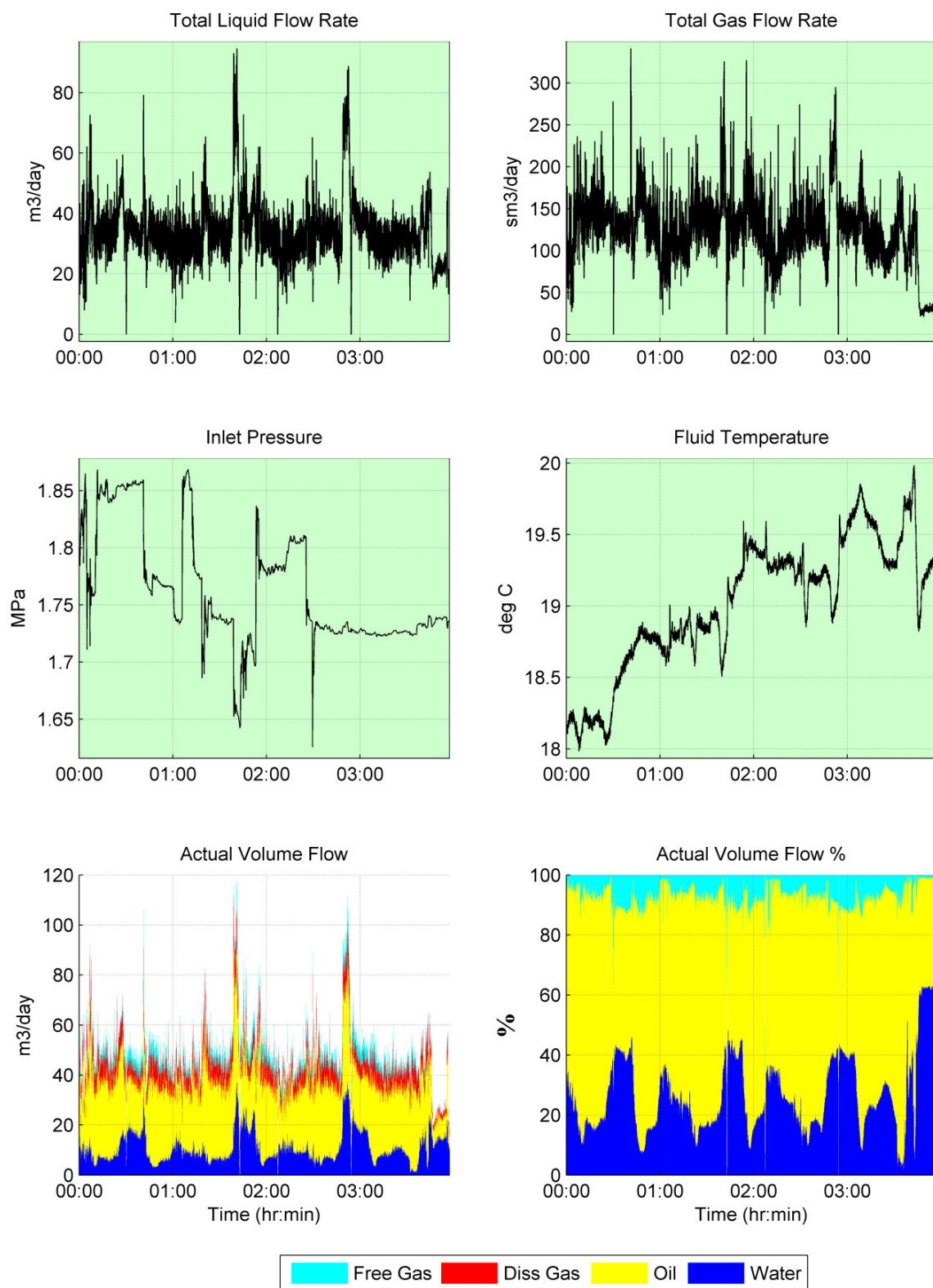


Figure 14: Well test profile: irregular flow surges

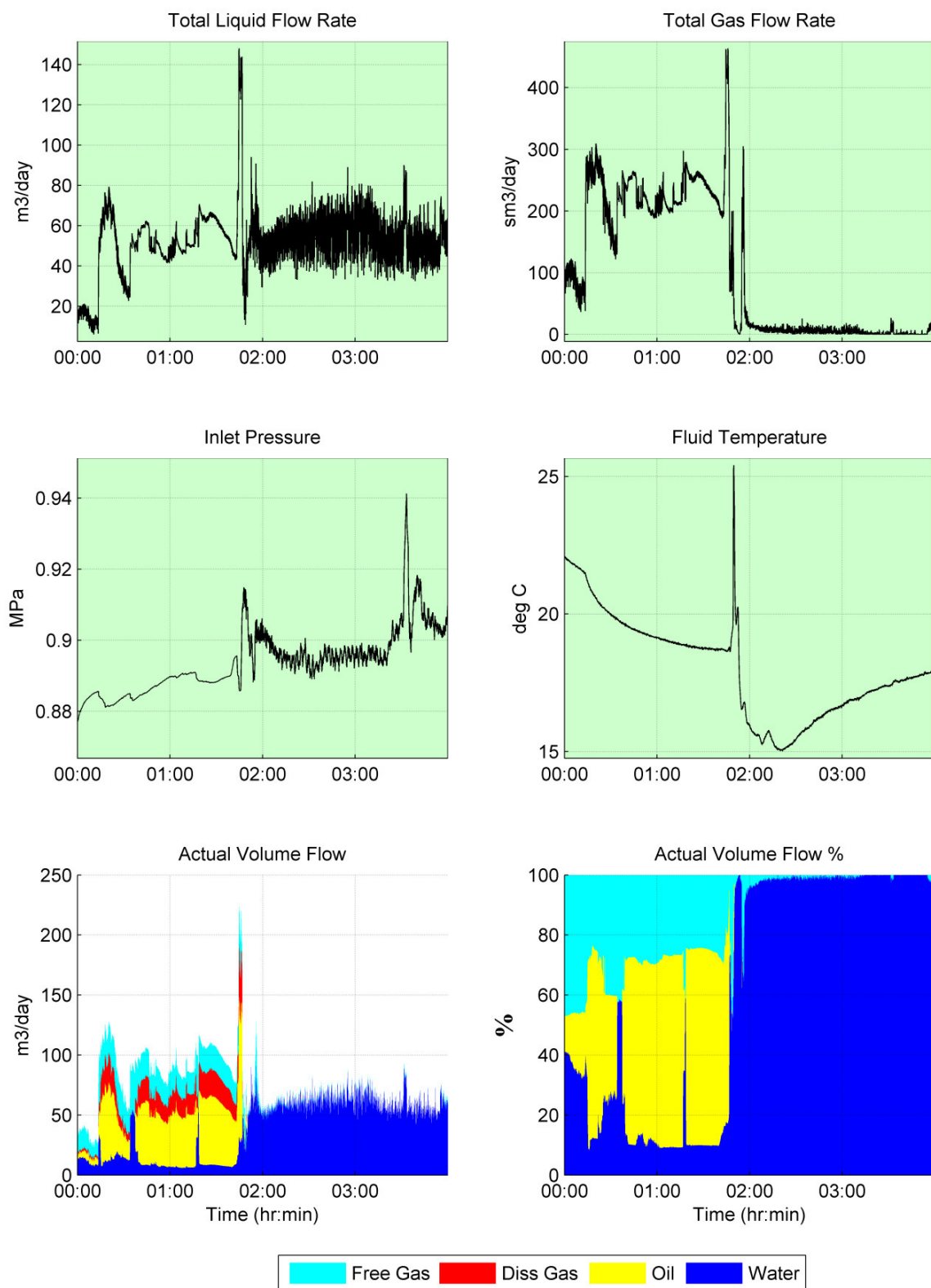


Figure 15: Erratic well test profile

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Highlights

- Examples are given of actual well tests monitored using a Net Oil & Gas skid
- Detailed time profiles of well behaviour are provided for several wells
- Different examples of well behaviour are indicated.