C-FER Technologies
200 Karl Clark Road
Edmonton, Alberta
Canada T6N 1H2
Tel 780.450.3300
Fax 780.450.3700
www.cfertech.com

Interim Testing Report

Laboratory Testing of Artificial Lift Systems for Low Pressure SAGD Applications

Confidential to
JIP Participants

Prepared by
J. Robles, MSc
K. Piers, PEng

Reviewed by
F. Alhanati, PhD, PEng

January 2006
P061

INTERIM TESTING REPORT

Laboratory Testing of Artificial Lift Systems for Low Pressure SAGD Applications

Confidential to
JIP Participants

Prepared by
J. Robles, MSc
K. Piers, PEng

Reviewed by
F. Alhanati, PhD, PEng

PROFESSIONAL ENGINEER ALBERTA
KELLY DEAN PIERS
1/31/06

PERMIT TO PRACTICE
C-FER Technologies
Signature
Date 2006 jan. 31
PERMIT NUMBER: P 04487
The Association of Professional Engineers, Geologists and Geophysicists of Alberta

January 2006
P061

PROJECT TEAM

Low Pressure SAGD Artificial Lift Test JIP	C-FER Project: P061
Name	**Responsibility**
Kelly Piers, PEng	Project Management/Vendor Interaction/System Installation
Jorge Robles, MSc	Flow Loop Design/Test Execution/Data Analysis
Paul Erickson	DAS development/Instrumentation/Testing Technologist
Shane Zunti	Instrumentation/Testing Technologist
Kerry Scott	Instrumentation

REVISION HISTORY

Low Pressure SAGD Artificial Lift Test JIP			C-FER Project: P061		
Revision	**Date**	**Description**	**Prepared**	**Reviewed**	**Approved**
1	September 29, 2005	Draft	JRV/KDP	FA	--
2	January 25, 2006	Final	JRV/KDP	FA	FA

NOTICE

1. This report was prepared as a deliverable for a Joint Industry Project ("JIP") entitled "Laboratory Testing of Artificial Lift Systems for Low Pressure SAGD Applications" conducted at C-FER Technologies (1999) Inc. ("C-FER"). Participants in this JIP currently are: ConocoPhillips Canada Limited, Deer Creek Energy Limited, Devon Canada Corporation, EnCana Oil and Gas, Imperial Oil Limited, Husky Oil Operations Limited, Innovation & Science (AERI), Nexen Inc., Paramount Resources, Petro-Canada Inc., Petrobras, Suncor Energy Inc. and Total E&P Canada Limited. All reasonable efforts were made to ensure that the work conforms to accepted scientific, engineering and environmental practices, but C-FER makes no other representation and gives no other warranty with respect to the reliability, accuracy, validity or fitness of the information, analysis and conclusions contained in this report. Any and all implied or statutory warranties of merchantability or fitness for any purpose are expressly excluded. The JIP Participants acknowledge that any use or interpretation of the information, analysis or conclusions contained in this report is at their own risk. Reference herein to any specified commercial product, process or service by trade name, trademark, manufacturer or otherwise does not constitute or imply an endorsement or recommendation by C-FER.

2. The information contained in this report includes information which is confidential and proprietary to the JIP Participants and information which is confidential and proprietary to C-FER. This report, including the information which is confidential and proprietary to C-FER, may not be copied, distributed, referenced, or quoted without the prior written approval of C-FER.

3. Any authorized copies of this report distributed to a third party shall include an acknowledgement that the report was prepared by C-FER and shall give appropriate credit to C-FER and the authors of the report.

TABLE OF CONTENTS

Table of Contents

Table of Contents

LIST OF FIGURES AND TABLES

Figures

List of Figures and Tables

List of Figures and Tables

List of Figures and Tables

List of Figures and Tables

Tables

EXECUTIVE SUMMARY

A number of operators have been searching for solutions in the form of new pump developments or improvements to existing Artificial Lift systems to contend with the very difficult operating environment that exists in Low Pressure Steam Assisted Gravity Drainage (LP-SAGD) applications. As a result, the JIP entitled "Laboratory Testing of Artificial Lift Systems for Low Pressure SAGD Applications" was launched in December 2003.

The objective of this JIP is to test a number of downhole pumping systems, at low intake pressures and low degrees of sub-cool, in a laboratory environment in order to prioritize and select candidates for further field trials.

The experimental program includes the following stages:

1. Tests with 100% oil at a reference temperature (baseline pump test): to establish a baseline for comparison with respect to pump performance information for subsequent tests;

2. Tests with 100% oil at different temperatures: to evaluate the combined effect of temperature on pump fit (particularly on positive displacement pumps) and fluid viscosity on pump hydraulic performance (particularly on dynamic pumps);

3. Tests with 100% oil and air: to evaluate the effect of produced free gas on the pump performance;

4. Tests with an oil/water mixture (~70% water) at different temperatures: to evaluate the effect of degree of subcool on pump performance; and

5. Tests with an oil/water mixture (~70% water) and air: to evaluate the effect of produced free gas on the pump performance.

The experimental matrix was adapted to each type of pumping system. However, as much as possible, all pumping systems were tested at similar levels of the different variables (fluid composition, pump intake pressures (PIP), temperatures, liquid rates and gal-liquid ratio).

Experimental Set-up

The experimental program called for the design and construction of a test loop with the ability to:

- Control fluid temperature between 60 and 200°C (+/- 2°C);

- Control pump intake pressure (PIP), between 200 – 2,070 kPa_g (+/- 7kPa_g);

- Handle liquid rates up to 800 m^3/d; and

- Achieve up to 20% Gas Void Fraction (GVF) at the pump intake.

Figure 1 provides a schematic of the flow loop.

The anticipated field operating conditions were replicated by installing the pumping systems in an 80 foot long section of 244 mm (9 5/8 inch) casing, at ~87 degrees of inclination (i.e. close to horizontal). An annulus separator was designed to allow for additional pump submergence. The separator consists of a 4 m long section of 152 mm (6-inch) pipe that is connected to the main casing section of the flow loop (downstream of the pump intake location).

The liquid and air flow rates are measured using a Coriolis mass flow meter. Pressure and temperature measurements are made using pressure and temperature transmitters with 4-20 mA output signals.

A heater allows for the fluid temperature to be controlled during testing in cases where the heat losses in the loop exceed the energy added by the pumping system. A heat exchanger allows for the fluid temperature to be reduced in cases where the energy provided by the pumping system exceeds the heat losses in the loop.

Air injection into the loop is provided by a radial air cooled booster. The air supply into the loop is regulated by a PID controller that operates an automatic control valve, based on the feedback from the corresponding Coriolis mass flow meter.

The Data Acquisition System (DAS) and control system were built using the LabView™ platform. The DAS allows for real time data capture of all loop parameters, at a frequency specified by the user.

Due to the multiple hazards inherent in the operation of a high temperature/high pressure test facility, an independent engineering firm with experience in steam generation projects (Eco-Technica Inc.) was hired to perform a Hazard and Operability (HAZOP) study and to provide the documentation required by the Alberta Boilers Safety Association (ABSA) for the operation of the facility. This resulted in a number of recommendations that were adopted by C-FER during the design and construction of the flow loop.

The design and construction of the flow loop was completed by the end of May 2004, and loop commissioning was completed by the end of June 2004.

Operational Procedures and General Testing Conditions

Tests were conducted under two different fluid conditions: 100% oil and an oil/water mixture. The oil was an ISO-460, with the following characteristics: a viscosity of 7cP at 200°C and 1,150 cP at 40°C; and a flash point (open cup) of 265°C. The oil/water mixture was made up of the same type of oil and fresh water, with an approximate water cut of 70 to 80%.

It was necessary to define "reference conditions" for testing, to allow for a fair comparison of results between the various pumping systems. Therefore, it was decided, with feedback from the Steering Committee (SC) that:

- The initial pump performance curves would be completed at a consistent level of pump intake pressure, or "Reference PIP". This intake pressure would be 700 kPa above the saturation pressure at each temperature level to be tested (e.g. PIP(t) = Psat(t) + 700 kPa]).

This PIP would also serve as the starting point for the "PIP reduction" tests.

- The "Reference delta-P" would be set at 3,000 kPa. This delta-P would, whenever possible, be used for all of the PIP reduction tests.

- For the oil/water mixture tests, a "reference pump speed" would be defined for each temperature, based on the speed required to deliver a specified flow rate (at the reference delta-P), as follows:

120°C	200 m^3/d
150°C	425 m^3/d
180°C	650 m^3/d
200°C	800 m^3/d

Table 1 Reference Liquid Rates for Oil/Water Tests

- An air liquid ratio (ALR) of 0.905 would be used to reproduce in the lab the same ranges of GVF (~15%) expected in the field.

At a high-level, the scope of the test program consisted of four different types of tests. Some of these tests were conducted with 100% oil, some with oil/water mixture and some with air injection. As well, some of the tests were conducted at one temperature only, while others were conducted at different temperatures. The types of tests were:

1. Pump baseline curve test;

2. Pump performance test (at reference PIP);

3. PIP reduction test (at reference delta-P); and

4. ALR sensitivity test.

Twin-screw System (Can-K)

A twin-screw pumping system, manufactured by Can-K, was tested in the flow loop during June/July 2004.

A separate report was prepared for this test, which was issued to the JIP Participants on August 13, 2004. For the sake of completeness, this report is included in Appendix A. In summary, only limited testing was completed with the pumping system, as unexpected increases in the torque required by the pumping system early on during the testing program forced the testing to be stopped.

PCP System with Elastomer Stator (Netzsch)

Netzsch supplied a DT226 elastomer stator PCP System for testing on September 29, 2004. The pumping system had a published pump capacity of 226 m^3/d/100 RPM and a maximum discharge pressure of approximately 9.0 MPa (1,305 psi).

Tests with 100% oil were conducted successfully up to the maximum temperature (200°C), with some exceptions as noted in the report.

During the process of preparing for the next stage of the test matrix (with oil/water mixture), a substantial quantity of elastomer material from the pump was found in the strainer immediately downstream of the pump discharge. Post-test analysis of the data showed possible evidence of deterioration in the pump hydraulic performance during the test with oil.

The SC agreed to have C-FER try to test with the oil/water mixture to obtain additional test data, starting with the two last temperature levels (180 and 200°C). However, soon after resuming testing, an additional pressure drop was observed across the strainer (indicating that more elastomer material was likely being deposited) and the test was concluded.

The main conclusions that resulted from the testing were:

- The predominant effect of temperature was to tighten the fit between the rotor and the stator, generally reducing slippage and improving volumetric capacity, up until the point of stator failure.

- From a volumetric efficiency standpoint, the pump showed a very good capacity to handle very low intake pressures during the 100% oil tests. For the range of viscosities corresponding to temperatures above 130°C (i.e. viscosities of less than 17 cP), the minimum NPSH required by the pump was close to zero.

- After completing the tests with 100% oil, it was found that significant elastomer material had been removed from the pump stator. Preliminary inspection of the pump at C-FER showed that chunks of elastomer were missing from different sections of the stator, both at the intake and discharge sides of the pump. Some initial de-bonding was also observed both at the discharge and intake of the pump.

ESP System (Woodgroup)

Woodgroup ESP (WG) provided an ESP system for testing on December 1, 2004. The system was comprised of a 41 stage TE 5500 pump, with a nominal operating rate of 875 m^3/d (5500 bpd), and a TR5-92 motor with a 150HP rating.

The test program was conducted as per the modified test matrix supplied to Participants, with some exceptions as noted in the report.

While testing at 180°C with the oil/water mixture, after obtaining only two test points for the pump curve (without air), a motor failure occurred. WG offered to repair the system and the SC agreed to carry on with the rest of the test program. The remaining tests were subsequently conducted according to the test matrix.

The ESP system was visually inspected by C-FER after removal from the flow loop, and there was nothing unusual to report.

The main conclusions that resulted from the testing were:

- During the oil tests, the effect of the viscosity on the pump flow rate and head was larger than that predicted by the Vendor's viscosity correction factors.
- Minimum PIP values for oil/water mixtures, without air, were very close to the saturation pressure (less than 5 psi above P_{sat}), with moderate deterioration in flow rate and head capacity (based on average values).
- The air injection had a negative effect on the minimum PIP achieved at all temperatures with the oil/water mixture. In addition, for the higher flow rates handled during testing, the air injection produced much more instability in the pump performance.

PCP System with Metal Stator (KUDU)

KUDU provided a 550MET675 metal stator PCP system for testing on May 9, 2005. The pumping system had a published pump capacity of 110 m^3/d/100 RPM and a maximum discharge pressure of approximately 6.6MPa (960 psi).

The test program was successfully completed with the 100% oil and the oil/water mixture, with changes to the test matrix as outlined in the report.

After the test program, C-FER performed a visual inspection of the top few stages of the rotor which showed some evidence of rotor wear.

The main conclusions that resulted from the testing were:

- The volumetric efficiency of the pump with 100% oil decreased noticeably at 200°C compared to initial tests at 60 and 150°C.
- For the oil/water mixture tests, the slippage was considerably higher than for the 100% oil tests (up to 250 m^3/d for delta-P's ranging from 2760 kPa to 3450 kPa (400 to 500 psi)).
- Low PIP values were obtained with both 100% oil and oil/water mixture.
- Additional data points taken near the end of the 100% oil test and at the end of the oil/water mixture test, suggested that the pump performance may have deteriorated during the test program, irrespective of fluid properties or temperature.

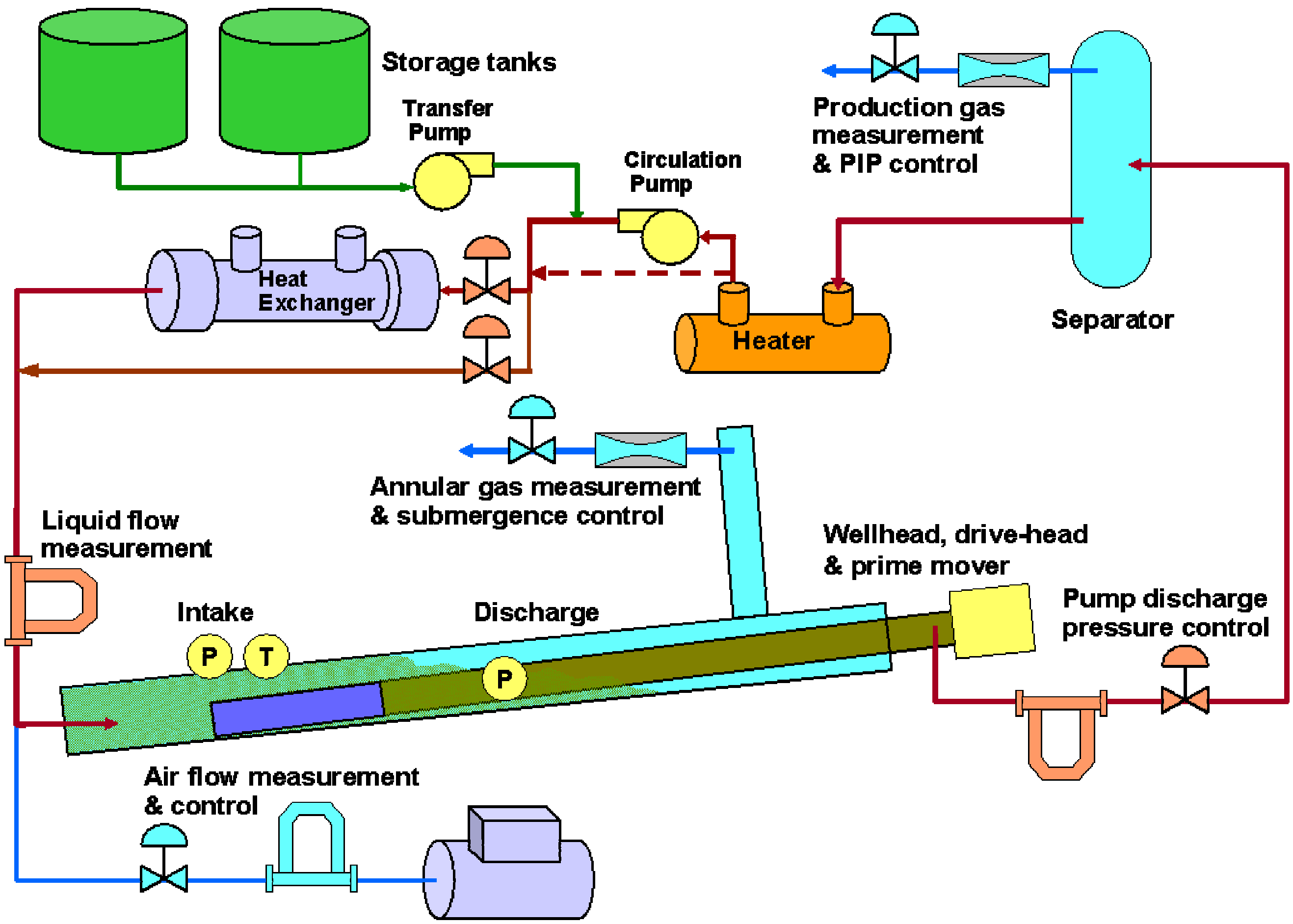


Figure 1 Flow Loop Schematic

1. INTRODUCTION

To date, most Steam Assisted Gravity Drainage (SAGD) pilot projects and field developments have used a combination of high-pressure steam injection and continuous gas lift to transport production fluids to surface. However, in large regions of the Athabasca oil sands where SAGD recovery techniques are currently being used or considered, the presence of a depleted or naturally low pressured gas bearing formation directly above the reservoir makes it necessary for producers to operate the producing and injection well pairs at much lower pressures.

In addition, the high cost of natural gas and the added energy required to generate high-pressure steam encourage producers to consider moving to lower steam injection pressures in an effort to reduce fuel costs. At these lower injection and production pressures, some form of artificial lift (AL) other than gas-lift is required to bring the produced fluids to surface.

Therefore, a number of SAGD operators have been searching for solutions in the form of new pump developments or improvements to existing AL systems to contend with this very difficult operating environment. It is uncertain if existing AL systems can operate efficiently and reliably at these difficult operating conditions, especially at low degrees of sub-cool (i.e. close to steam saturation conditions).

To help address this uncertainty, C-FER launched the JIP entitled “Laboratory Testing of Artificial Lift Systems for Low Pressure SAGD Applications” in December 2003, with the objective of testing a number of downhole pumping systems, at low intake pressures and low degrees of sub-cool in a laboratory environment, in order to prioritize and select candidates for further field trials.

The experimental program includes the following stages:

1. Tests with 100% oil at a reference temperature (baseline pump test): to establish a baseline for comparison with respect to pump performance information for subsequent tests.

2. Tests with 100% oil at different temperatures: to evaluate the combined effect of temperature on pump fit (particularly on positive displacement pumps) and fluid viscosity on pump hydraulic performance (particularly on dynamic pumps).

3. Tests with 100% oil and air: to evaluate the effect of produced free gas on the pump performance.

4. Tests with an oil/water mixture (~70% water) at different temperatures: to evaluate the effect of degree of sub-cool on pump performance.

5. Tests with an oil/water mixture (~70% water) and air: to evaluate the effect of produced free gas on the pump performance.

Introduction

The experimental matrix was adapted to each type of pumping system, as presented in the following sections. However, as much as possible, all pumping systems were tested at similar levels of the different variables (fluid compositions, pump intake pressures (PIP), temperatures, liquid rates and gal-liquid ratios).

As of January 2006, testing has been completed for the following pumping systems:

- Twin-Screw System (Can-K)
- PCP System with Elastomer Stator (Netzsch)
- ESP System (Woodgroup)
- PCP System with Metal Stator (Kudu)

2. EXPERIMENTAL SET-UP

2.1 Basis of Design

The experimental program called for the design and construction of a test loop with the ability to:

- Control fluid temperature between 60 and 200°C (+/- 2°C);
- Control pump intake pressure (PIP), between 200 and 2,070 kPa_g (+/- 7 kPa);
- Handle liquid rates up to 800 m^3/d;
- Achieve up to 20% Gas Void Fraction (GVF) at the pump intake;
- Allow for downhole gas (air and steam) separation at the pump intake while maintaining pump submergence;
- Control pump delta-P between 300 to 5,000 kPa, with discharge pressures up to 5,500 kPa_g;
- Handle water, oil and oil/water mixtures with viscosities up to 500 cP; and
- Accommodate downhole and surface driven systems.

2.2 Loop Design

Based on the requirements of the test program, several conceptual designs were evaluated taking into consideration the criteria of controllability, flexibility, safety and cost.

The requirement to test with water at temperatures above 100°C caused the need for a closed loop operation, where the pressure around the loop could be maintained above the steam saturation level. Figure 2.1 shows a schematic of the final loop design (a PID diagram of the loop is included in Appendix B), with the following characteristics:

2.2.1 Casing Section

The anticipated downhole operating conditions were replicated to the extent possible, by installing the pumping systems in an 80 foot long section of 244 mm (9 5/8 inch) casing, at ~87 degrees of inclination (i.e. close to horizontal). This casing section allowed sufficient length for all of the downhole and surface driven systems that were tested. In the case of rod driven systems, the rod string was long enough to absorb the eccentric motion of the rotor, without the need of a flexible connection. The inclination of three degrees with respect to horizontal was considered enough for the gas separated at the pump intake to flow towards the wellhead annulus.

2.2.2 Flow, Pressure and Temperature Measurement (Meters and Transmitters)

The liquid flow rate is measured close to the casing intake (upstream from the air liquid mixer) using a Coriolis mass flow meter. Note that this rate is equivalent to the rate handled by the pump only if there is no accumulation or reduction of fluid in the annulus.

A second Coriolis mass flow meter is located close to the pump discharge, upstream of the discharge pressure control valve (in order to minimize the effect of entrapped air on the flow measurement[1]).

A third Coriolis mass flow meter, located in the air injection line (upstream from the air liquid mixer), is used to measure the air injected at the bottom of the casing.

The intake pressure measurement point is located approximately 1 m from the bottom end of the casing, while the intake temperature measurement point is located right at the bottom end of the casing. The bottom of each pumping system was positioned the same distance from these measurement points, at approximately 1.5 m from the end of the casing. As a result, the reference intake pressure conditions were actually measured approximately 0.5 m below each pumping system, and the reference temperature conditions were measured approximately 1.5 m below each pumping system. Therefore, all pumping systems could be compared on a consistent basis, and any effects of the specific system completion (such as temperature increase or pressure drop at the pump intake) on the overall system performance could be taken into account.

To measure discharge pressure, a pressure connection was installed in the production tubing as close as possible to each pump discharge, and a capillary line was installed between this connection and the wellhead. In all cases, this pressure connection was within approximately 2 m of the pump discharge and below any rod centralizers. In this way, a reliable measurement was obtained without the need for a submergible high temperature transducer, instrumentation cable and connectors.

Pressure and temperature measurements were measured using transmitters with 4-20 mA output signals, which were sent to the Data Acquisition System (DAS).

2.2.3 Pressure Control (Control Valves and Separator)

The system controls the pump discharge pressure and delta-P by means of an automatic PID (Proportional-Integral-Derivative) controller, which operates an automatic control valve based on the feedback from the intake and discharge pressure measurements.

[1] It has been reported that GVF greater than 2% can produce substantial measurement errors in Coriolis meters. During the operation of the loop, it was found that this second meter gave a more accurate and stable reading of the liquid mass flow rate handled by the pump than the first flow meter.

The system also can be set to “manual mode”, where the percent opening of the valve is adjusted manually to maintain the desired range of delta-P. This was used in cases where it was difficult for the PID controller to deal with the interdependence between flow rate and delta-P during times of loop instability (such as surging characteristics of the flow due to air injection).

The separator, located after the discharge pressure control valve, serves two main functions: (a) controlling the “system pressure”, which indirectly controls the intake pressure; and (b) separating the air and steam vapour entrapped in the produced fluid. During conceptual design, it was decided to locate the separator after the pressure control valve to allow a more effective air-liquid separation process and to allow the use of a separator with a lower pressure rating. The separator pressure is controlled by a PID controller acting on the automatic control valve located at the top of the separator, based on feedback from a pressure transducer at the separator.

A Venturi meter is used to measure the gas flowing through the top of the separator. Under stable conditions, the air mass flow rate coming from the top of the separator equals the air handled by the pump.

2.2.4 Temperature Control (Heater and Heat Exchanger)

The heater allows for the fluid temperature to be raised before testing and to be controlled during testing in those cases where the heat losses in the loop exceed the energy added to the fluid by the pumping system.

The heat exchanger allows for the fluid temperature to be reduced in those cases where the energy provided by the pumping system exceeds the heat losses in the loop. A shell-tube exchanger was selected as the best option for this application, due to its competitive cost and flexibility to handle different fluids at high pressure. The process fluid is handled in the high-pressure tubing side, with city water being used in the shell side.

Different options were considered for temperature control. The final selection was made based on control flexibility, economics and safety. For the heating function, a heater with three heating elements was chosen, which allows manual selection of three different levels of power. This apparatus was combined with an on/off automatic control, allowing for fluid temperature to be reached and maintained between two predefined levels (giving rough temperature control).

Fine temperature control is achieved through the use of the heat exchanger. A bypass line and two control valves, wired to the same PID controller, allow for fine control of the temperature by controlling the fraction of process fluid diverted through the heat exchanger. A third control valve on the shell side of the exchanger allows for a rough adjustment of the water flow rate in the shell side. This combined temperature control system provides rapid response and allows an effective control of the Pump Intake Temperature (PIT).

An overnight temperature control feature allows for the fluid temperature in the loop to be maintained close to the testing point overnight, with the pumping system stopped. In the “overnight mode”, valve positions are set to allow fluid to bypass the pumping system and flow through the annulus. The fluid is circulated using the circulation pump, and an automatic on/off temperature control system allows for the fluid temperature to be maintained between two predefined levels. Normally, temperature variation overnight was set around 15°C. Due to safety considerations, the maximum overnight system temperature was set to a value equal or less than the maximum value reached during the previous day. Depending on the fluid viscosity and pressure drop in the system, the circulation pump delivers between 40 and 80 m^3/d.

2.2.5 Pump Submergence Control (Annulus Separator)

During conceptual design it was decided that the vertical distance between the pump intake and the top of the casing was not enough to allow proper control of the pump submergence. There was little room to prevent the conditions of pump-off or liquid carry-over, especially in those tests that required air injection. Therefore, an annulus separator was designed to allow for additional pump submergence.

The separator consists of a 4 m long section of 152 mm (6-inch) pipe that is connected to the main casing section of the flow loop (downstream of the pump intake location). The separator is inclined 45^{o}, and has a pipe opening at the top which allows gas to rise through a column of liquid.

A differential pressure transducer (DPT) is connected to the top and the bottom of the piping section, and its signal is used to control the fluid level in the separator, using a PID controller and a control valve installed in the piping at the top of the separator.

A Venturi meter is used to measure the gas flow through the top of the separator. Under stable conditions, the gas (air and steam vapour) mass flow rate coming from the top of this separator equals the gas separated downhole and bypassing the pump intake.

2.2.6 Air Injection and Control (Air Compressor and Control Valve)

Air injection into the loop can be supplied from two locations: 1) for low pressure requirements (up to 965 kPa), air supply is provided directly from C-FER's shop compressor with a maximum flow rate of 6,000 std m^3/d (150 scfm); and 2) for high pressure requirements (up 3,100 kPag), air supply is provided from a Bauer KWB-15-3EH radial air cooled compressor (booster) with a maximum flow rate of 3,000 std m^3/d (74 scfm). Both compressors are rated for eight hours of continuous service.

The air supply into the loop is regulated by a PID controller that operates an automatic control valve, based on the feedback from the corresponding Coriolis mass flow meter.

2.2.7 Data Acquisition System (DAS) and Master Control System (MCS)

The DAS and MCS were built using PC-based devices from National Instruments, and a customized application was developed for the flow loop under the LabView™ platform.

The DAS allows for real time data capture of all loop parameters, at a frequency specified by the user. For the purposes of generating the test data, this frequency was generally set to 1 Hz (i.e. one data point per second).

The MCS provides customized PID and ON/OFF controllers for all the critical variables around the loop (pump intake and discharge pressures, pump inlet temperature, annulus separator level, etc.) as well as safety protection during normal operations and overnight heating.

2.3 Description of Fluids

Tests were conducted under two different fluid conditions: 100% oil and an oil/water mixture.

2.3.1 100% Oil

The selection of the oil for the test program was based on the following criteria:

- Viscosity range (~10 cP at 230°C and ~450 cP at 20°C based on feedback from SCM#1);
- Flashpoint > 240°C;
- Ability to withstand heating cycles and a combination of water and/or air with a reasonable operating life; and
- Safe to use (from the environmental and health standpoints).

The search of an economic product with these properties proved to be much more challenging than anticipated. Finally a suitable product was found (from a supplier in USA) with the following characteristics:

- Naphthenic Bright Stock Oil, ISO-460, group II (low aromatics);
- Viscosity: 7 cP at 200°C and 1,150 cP at 40°C; and
- Flash Point (open cup): 265°C.

Figure 2.2 shows the lab data and the curve-fit correlation used to estimate the viscosity of the oil at different temperatures.

2.3.2 Oil/Water Mixture

The second fluid condition under which tests proceeded was an oil/water mixture (with an approximate water cut of 70%). As discussed during the project kick-off meeting, for this level of water cut C-FER did not expect any emulsion to be formed during the tests; however, the strict control of the rheology characteristic of the mixture was beyond the scope of this project. The target was to keep the average water cut of the oil/water mixture in the vicinity of 70 to 80%, and this was largely achieved. However, there was some inherent variability in the water cut during testing, because:

- Any time a PIP reduction step was performed, water (in form of steam) was lost from the system (through the annulus separator); and
- During the tests with air injection, some oil was also lost (carry over of oil drops with the air/steam stream).

Therefore, after each test, fluids were added to compensate for volume lost and to set the water cut within the desired range.

Figure 2.3 shows the charts used to estimate the water cut as a function of mixture density. Note that the density contrast is reduced with increasing temperature, thereby reducing the accuracy of the water cut estimation. For example, the density contrast of the oil and water is as low as 50 kg/m^3 at 200°C, and combined with the accuracy of the density measurement (~ +/-2 kg/m^3), the accuracy for 70% water cut estimation is approximately +/-5%.

2.4 Safety and Environmental Considerations

Due to the multiple hazards inherent to the operation of a high temperature/high pressure test facility, an independent engineering firm with experience in the area of steam generation projects (Eco-Technica Inc.) was hired to perform a Hazard and Operability (HAZOP) study and to provide the documentation required by the Alberta Boilers Safety Association (ABSA) for the operation of the facility.

The following is a short summary of the main actions and considerations taken to respond to the HAZOP and meet ABSA requirements:

- All the pressure vessels (separator, heat exchanger, heater) were registered with the Alberta Boilers Safety Association (ABSA).
- Certified procedures were obtained for the welding of the annulus separator onto the casing.
- Pipelines and fittings were hydrotested (at room temperature) at a pressure equal to 1.587 times the design pressure (as per ABSA's request).
- Pressure vessels and critical pipe sections were protected through pressure relief valves set at pressures at least 8% below the design pressure.
- An air suction system and exhaust fan was attached to the storage tanks to vent the fumes generated during testing.
- An Emergency Shutdown Valve (ESV) was installed, and a remote emergency shutdown button was located in the control room.

Experimental Set-up

- A holding tank was installed downstream of the shell side of the heat exchanger, to help detect any oil contamination in the water and prevent contamination of the disposal water.

- The riskiest equipment (e.g. well head and separator) was located in one of the C-FER "strong-wall" cells. Removable blast shields were used to create a somewhat confined area for the higher risk section of the loop.

- Access to the test cell during testing was limited and personal protective equipment was used anytime access to the test cell was required when the loop was at high (>60°C) temperature.

- A "fail-safe" protocol was used when overnight circulation was required in order to keep the system hot. This system was based on redundant measurements (e.g. from several pressure and temperature transducers or combining the flow switch and flow meter signals) and actions included sending a text message to C-FER technicians in case of emergency.

Experimental Set-up

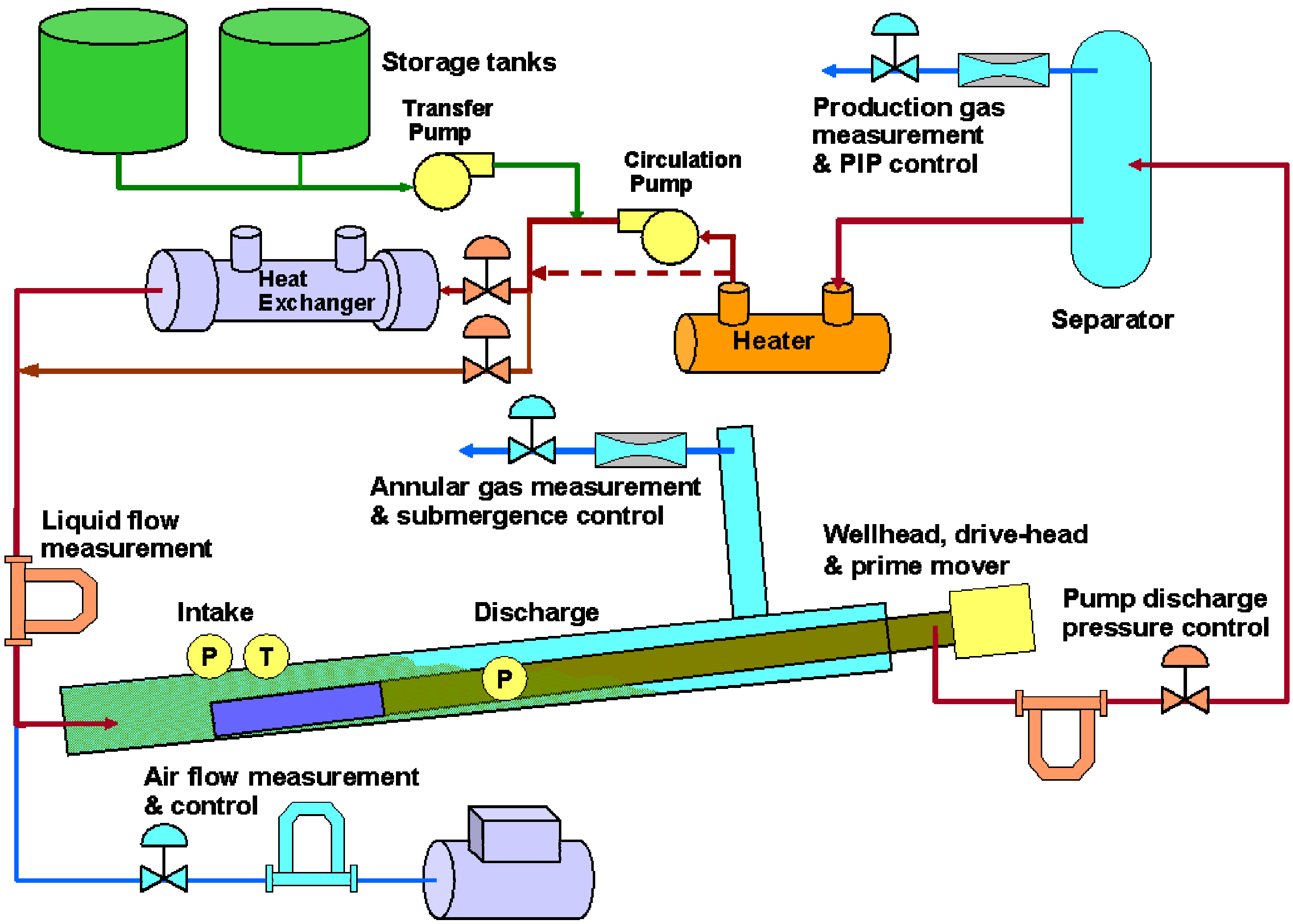


Figure 2.1 Flow Loop Schematic

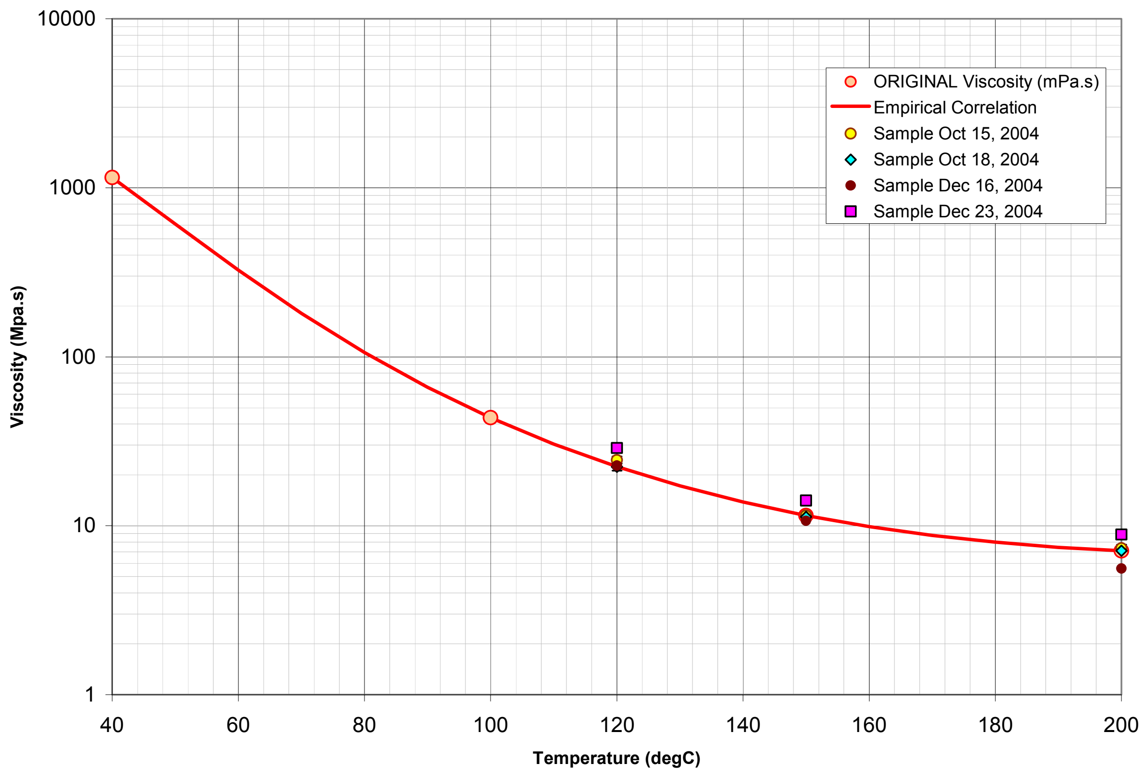


Figure 2.2 Viscosity of Oil

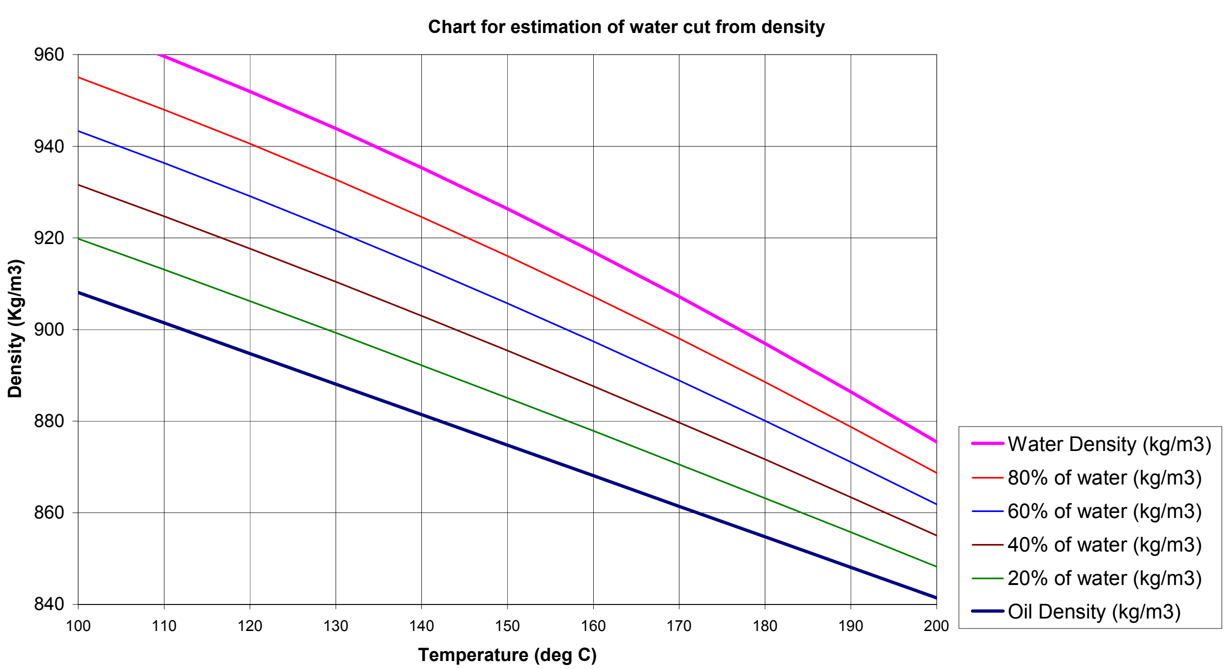


Figure 2.3 Charts for Estimation of Water Cut as a Function of Mixture Density

3. DESCRIPTION OF TESTING PROGRAM

This section describes the general operational procedures for the loop. Specific procedures, restrictions or exceptions related to each pump system are explained in more detail in the corresponding pump test results sections.

3.1 Definition of Reference Test Conditions

This section presents a brief explanation of the criteria used to define the different test procedures and conditions. Note that some procedures were applied to tests with both fluids (100% oil and oil/water mixture) while others are particular to only one of the test fluids.

3.1.1 Determination of Reference delta-P

There were three delta-P values that were relevant for the testing program:

- The design delta-P, which is used by the vendors to optimize the performance of their systems. It is related to the expected operation conditions used when ordering equipment for the field.

- The maximum delta-P, which corresponds to the maximum value of delta-P imposed on the pump. This was defined as 4,000 kPa at the onset of the JIP.

- The reference delta-P, at which the speed would be adjusted to achieve the corresponding rates at different temperatures, as established in Table 3.1.

Since positive displacement pumps (PDP) and dynamic pumps are affected differently by the delta-P, it was important to define a meaningful criterion that would allow a fair comparison between the different pumping systems and a proper interpretation of the results.

Based on the fact that ESP systems are designed to operate near their point of maximum efficiency, it was decided that the reference delta-P should be equal to the design delta-P and that this value should be set at 3,000 kPa.

It was also decided to use a slightly different experimental procedure for centrifugal and PDP's. For the PDP's, the goal was to cover a full range of delta-P's, from the minimum delta-P allowed by the test loop to 4,000 kPa. For centrifugal pumps, the goal was to set the minimum and maximum delta-P to cover most of the operational envelope specified by the Vendor (normally defined by the upthrust and downthrust conditions).

3.1.2 Determination of Reference PIP

It was decided, with feedback from the SC, that the initial pump performance curves should be completed at a consistent level of pump intake pressure, or "Reference PIP" (one for each different temperature level being tested), to allow for valid comparisons between the testing results at lab conditions and expected field conditions. The goal was to select a reference PIP that ensured that the baseline pump performance tests were carried out without any effects related to approaching saturation conditions (e.g. steam flashing). It would also serve as the starting point for the "PIP reduction" tests. A final consideration for the selection of the PIP reference was to try to obtain a GVF of at least 15% during the pump performance tests with air injection (to roughly correspond to expected field conditions based on a gas/oil ratio of 4 std m^3/m^3).

Two options were considered in this regard: 1) maintain a constant level of subcooling (e.g. 30°C) at each temperature; or 2) maintain a constant level of "overpressure" (pressure above saturation pressure). Note that due to the shape of the water saturation curve as a function of temperature (see Figure 3.1), the use of a constant level of subcooling produces a much larger level of "overpressure" at higher temperatures.

C-FER presented the Steering Committee (SC) with the results from "black-oil" simulations (steady state conditions) that showed that using a constant level of subcooling as a reference and a constant air/liquid ratio (ALR) would produce very different levels of GVF for each temperature. After a discussion with the SC, it was decided to use a constant overpressure [PIP(t) = Psat(t) + 700 kPa] and a constant ALR, which would correspond roughly to the 15% GVF (see Figure 3.2).

Note that for a fixed ALR, the in-situ GVF changes with the PIP (as shown in Figure 3.2). When the PIP approaches the saturation pressure, GVF increases exponentially. This is due to the behaviour of a multiphase system, where the air volume is affected by the partial pressure of the air, which shares the volume (of the gas phase) with steam at saturation conditions. Therefore, the partial pressure of the air is given by:

$$P_{air} = P - P_{steam} = P - P_{sat(t)}$$

This equation shows that when the fluid pressure approaches the saturation pressure, the partial pressure of the air trends to zero. This explains why the GVF increases exponentially as the fluid pressure approaches saturation conditions.

3.1.3 Determination of ALR

Simulations performed by C-FER suggested that the effect of temperature on natural gas solubility in produced fluids is minimal. In addition, the solubility of air in the oil/water mixture was neglectable. Therefore, it was reasonable to use a constant ALR as a control variable during the tests. This ALR[2] was defined as:

$$ALR = Q_{air}\ (sm^3 d) / Q_{liq}\ (\text{actual } m^3 d)$$

Using the target water cut of 70%, C-FER estimated that an ALR = 0.905 should be used to reproduce in the lab the same ranges of GVF expected in the field.

Figure 3.3 shows a comparison between the calculated GVF (simulated field condition) and ALR (lab condition), as a function of pressure and temperature. As shown, there is good agreement between the two parameters.

3.1.4 Determination of Reference Pump Speed and Flow Rate

For the pump tests with 100% oil, the pump speeds were selected based on discussions with the pump vendor. The goal was to characterize the performance of each system around the zone of interest of this project of 200 m^3/d to 800 m^3/d (in cases where the systems flow capacity exceeded the ranges specified in the test program) or within the limits of the system (in cases where the system did not allow for the entire flow rate range to be covered). Depending on the system, two or three different pump speeds were tested at each temperature for the 100% oil test program.

In the case of the oil/water mixture tests, it was decided during discussions with the SC that C-FER would use a criteria based on flow rate to determine a reference pump speed at which the system could deliver a specified flow rate, with a delta-P equal to the reference delta-P (3,000 kPa). As shown in Table 3.1, this flow rate was different at different operating temperatures, as follows:

120°C	200 m^3/d
150°C	425 m^3/d
180°C	650 m^3/d
200°C	800 m^3/d

Table 3.1 Reference Liquid Rates for Oil/Water Tests

The rationale behind the dependence of reference rate with temperature was based on Participants' expectations for well deliverability as a function of temperature. Once again, in those cases where the reference flow rate (as a function of temperature) was beyond the capacity of the pump, the test was performed at the maximum speed allowed by the Vendor.

[2] Note that the units are slightly different from the values used to report Gas Liquid Ratio (GLR) in the field (sm^3 of gas divided by m^3 of liquid at stock tank conditions). The rationale for this decision was to minimize the number of transformations applied to the variables monitored during testing (note that empirical correlations would be required in order to convert the actual liquid measurement to stock tank conditions)

3.2 Pump Test Types

At a high-level, the test program was designed to first obtain data points for each pumping system under a variety of different operating temperatures, delta-p, and speeds, which would enable the construction of "performance curves". Then, the remainder of the test program was to analyze the performance of the pumping system at low PIP levels. Some of these tests were to be conducted with 100% oil, some with oil/water mixture and some with air injection.

To achieve this, the test scope consisted of four different types of tests:

1. Baseline Pump tests (one temperature and one or more speeds);

2. Pump Performance tests at elevated temperatures (at reference PIP);

3. PIP reduction tests (at reference delta-P); and

4. ALR sensitivity tests.

In almost all cases, each data point was taken during a time when at least two minutes of stable conditions were achieved, according to the following criteria:

- PIP: variations of no more than +/- 1 psi (+/- 6.89 kPa); and

- Pump Intake Temperature (PIT): variations of no more than +/- 1°C.

3.2.1 Baseline Pump Tests (with 100% oil)

After the pumping system was installed, the loop was filled with oil at room temperature using an air operated diaphragm transfer pump. After enough volume of liquid had been transferred into the loop, the circulation pump and the heater were turned on until the target temperature for the baseline pump test was reached.

The baseline pump tests were conducted at the minimum temperature allowed by the pumping system and/or flow loop. The goal was to obtain test data that could be compared to either published pump curves for that pumping system (if they existed) or tests done internally by the pumping system manufacturer.

These tests were to be performed at the reference PIP. If the temperature for the baseline pump test was below 100°C, then the test could be performed right after the loop was filled with fluid. If the reference temperature was above 100°C, then sometimes it was required to vent (residual) steam from several of the high spots in the system before the test could be carried out.

3.2.2 Pump Performance Tests at Elevated Temperatures (with 100% oil, oil/water mixture and oil/water mixture with air)

At each temperature level defined in the test matrix for each pumping system, data points were gathered. For tests with 100% oil, data points were generated at different pump speeds, while for tests with the oil/water mixture data points were generated for one pump speed.

Pump performance tests with air injection were also performed for certain temperature levels. In these tests, the pump was operated at the reference PIP and at a constant ALR ratio of 0.905 m^3/m^3. (In some cases, the ALR ratio was increased further, up to levels as high as 20 s m^3/m^3). These tests were generally performed at the end of the PIP reduction tests (see next section), in order to prevent entrapped air bubbles from affecting subsequent tests.

3.2.3 PIP Reduction Tests (with 100% oil, oil/water mixture, and oil/water mixture with air)

The PIP reduction tests were carried out with both 100% oil and the oil/water mixture (with and without air injection). For tests with 100% oil, the PIP reduction tests were generally performed only at two different temperatures, while for tests with the oil/water mixture the tests were carried out at four different temperatures.

The procedure for the PIP reduction test evolved during the development of the project. The approach initially used was to reduce the separator pressure slightly (by adjusting the control valve at the discharge of the gas outlet), wait for stabilization of the PIP and then record a two-minute period of stable conditions. However, it was found that using this procedure required a lengthy period of time to reach the point where the pump performance was affected by the PIP reduction.

Therefore, the procedure was later modified to slowly reduce PIP in a continuous “ramp”. When the first signal of pump performance deterioration was observed, the separator pressure was maintained to obtain a stable PIP reading. After recording a two-minute period, the PIP was reduced further by another small amount and so on, until the minimum “performance limit” was reached.

This performance limit varied somewhat between pumping systems as outlined specifically in the testing results for each system. However, in general, it consisted of a certain reduction in flow rate or head capability of the pump, or flow instabilities in the pump that no longer allowed for the flow loop operation.

3.2.4 ALR Sensitivity Tests (with 100% oil and oil/water mixture)

This type of test was added after the SCM#2 as a possible alternative to the standard PIP reduction test. It was decided to add this test at only one temperature for each system (150 or 180°C, depending of the case).

Description of Testing Program

In this test, instead of fixing the ALR and reducing the PIP (as per the standard PIP reduction test), the PIP and delta-p were maintained at their "reference levels", and the ALR was increased (by increasing gas flow) until the performance limit of the system was reached.

3.3 Test Program Summary

In summary, unless specifically mentioned in the section for a specific pumping system, the order of testing was:

1. Tests with Oil
    a. Heat up to minimum temperature required by the pump;
    b. Obtain a pump performance curve at the first speed (maintaining a constant reference PIP);
    c. Conduct the PIP reduction test[3] (maintaining a constant reference delta-P);
    d. Repeat "b" and "c" for two other speeds;
    e. Repeat "b" through "d" (without air) for different temperatures up to 200°C; and
    f. Perform the ALR sensitivity tests for three different speeds at one temperature (e.g. 180°C).
2. Tests with Oil/Water Mixture (~70% water cut)
    a. Heat up to the first temperature (e.g. 120°C);
    b. Determine reference speed[4] for reference rate, according to Table 3.1;
    c. Obtain pump performance curve at reference speed (maintaining reference PIP constant);
    d. Conduct the PIP reduction test at the reference speed (maintaining reference delta-P constant);
    e. Repeat "c" and "d" with ALR = 0.905;
    f. Repeat "b" through "e" for different temperatures up to 200°C; and
    g. Perform the ALR sensitivity test at the reference speed at one temperature (e.g. 180°C).

---

[3] Only at temperatures specified in the experimental matrix.

[4] In case of limited pump flow rate capacity, the test speed was equal to the maximum speed allowed by the vendor.

Note that actual test procedures changed somewhat from system to system, due to inherent differences between each system and the experience gained during testing. For instance, for some systems all of the ALR sensitivity tests with 100% oil were performed at reference PIP, while for other systems additional data was acquired at lower values of PIP.

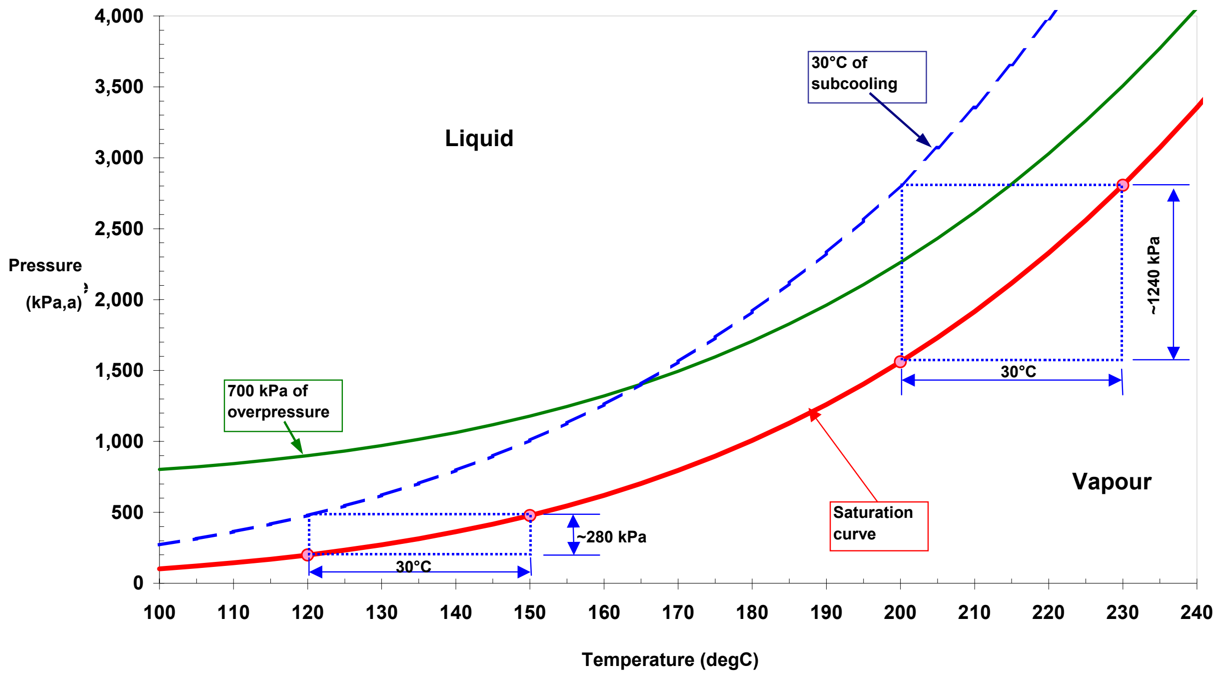


Figure 3.1 Effect of the Shape of the Saturation Curve on Subcooling – Overpressure Relationship

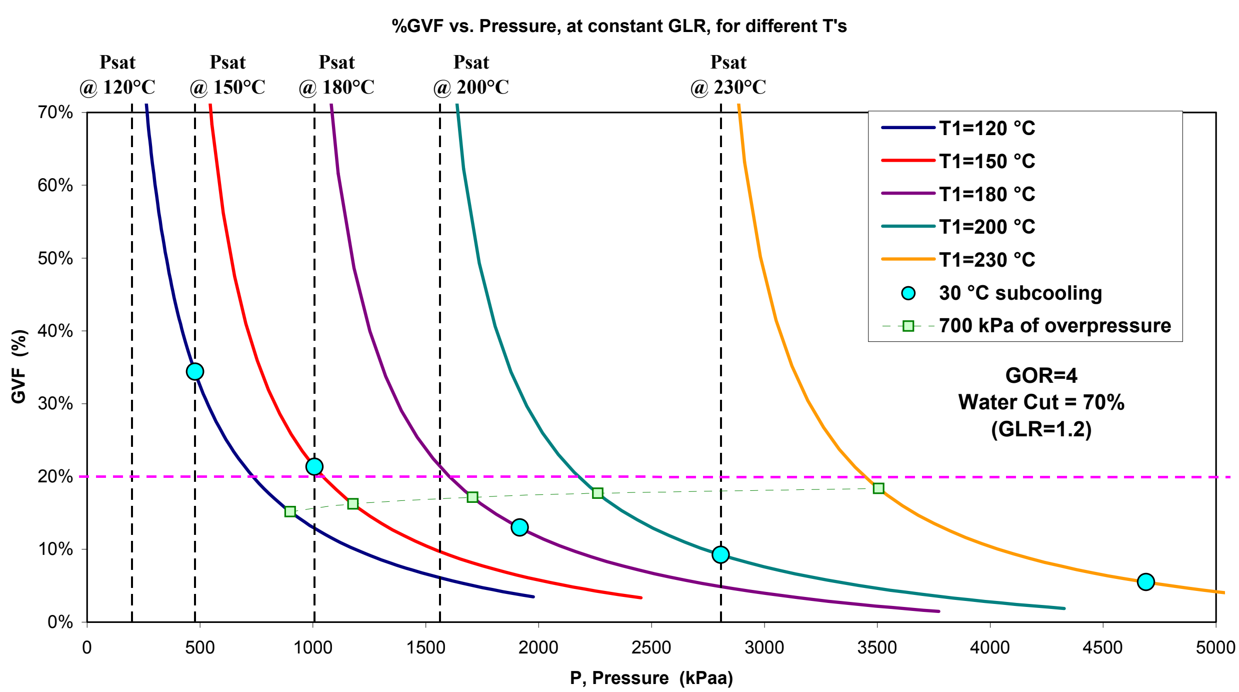


Figure 3.2 Illustration of Effect of PIP Reference Criteria on GVF Ranges at Field Conditions

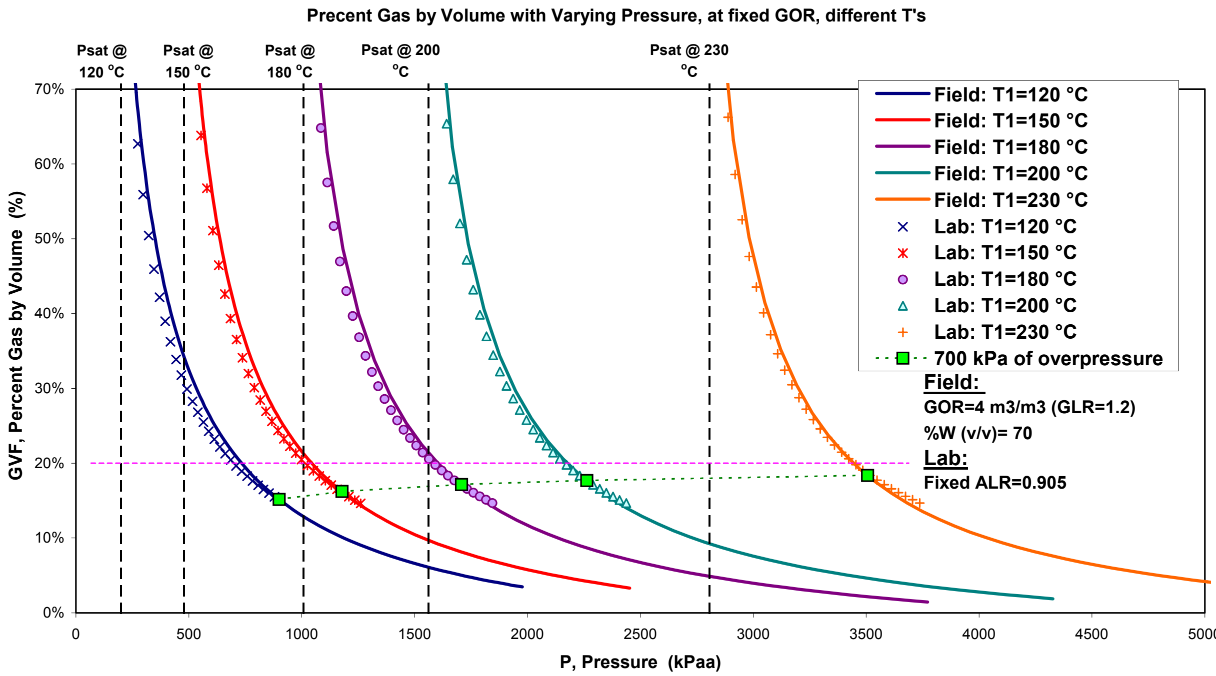


Figure 3.3 Comparison of GVF Ranges at Lab and Field Conditions

4. PCP SYSTEM WITH ELASTOMER STATOR (NETZSCH)

4.1 System Description and Technical Specifications

Netzsch supplied an elastomer stator PCP System for testing with the following specifications:

- Surface Horizontal Drive Unit
  - Internal 5.16:1 gear ratio;
  - Non-reversing brake;
  - Stuffing box with shaft packing suitable to 20 MPa (200 bar) and 250°C; and
  - Bottom connection: 79 mm (3-1/8 inch) x 3000 psi flange with r-31 ring gasket.
- DT226 Subsurface Pump (2 in 3 Multi-lobe) Stator
  - Production rate: 226 m^3/d at 100 RPM;
  - Maximum discharge pressure: 9,000 kPa (1305 psi);
  - At 40 bar delta-P, the pump would require 17.5 HP per 100 RPM;
  - Connection to 102 mm (4 inch) API tubing;
  - Housing OD: 127 mm (5 inches); and
  - Pump length: approximately 9.1 m (30 ft).
- Rotors
  - Two different size rotors, one rotor was undersized for 200°C temperature and the other was undersized for 120°C temperature;
  - Rotor threads for 38 mm (1.5 inch) API rod; and
  - The rotor maximum dimension was 80 mm (3.15 inches) and requires a minimum of 102 mm (4-inch) tubing in which to operate.

4.2 Installation and Commissioning

The PCP system arrived at C-FER on September 29, 2004. As indicated above, Netzsch provided two differently sized rotors, the larger one suitable for temperatures up to 150^{o}C and the smaller one (P22) for temperatures above 150°C. Based on feedback from the majority of the

Participants, it was decided to perform all tests with only the smaller rotor. The minimum operating temperature for this rotor was to be determined experimentally.

The drive head arrived without the agreed upon connection to C-FER's hydraulic motor, so C-FER fabricated an adapter to allow the motor to be used.

The pump also arrived without a tag bar, meaning that the pump would be installed without a standard intake. CFER advised the SC, and it was agreed that the preference would be to provide a pump intake as close as possible to field conditions, since this could affect pump system performance (especially regarding steam flashing and gas separation). Subsequently, EnCana provided a "bottom feeder" intake that was connected to the bottom of the pump. C-FER purchased the required adapters to connect the bottom feeder.

Netzsch recommend that 2 to 3 rod centralizers be used during testing. However, they did not provide centralizers with the system and did not know of any centralizers suitable for operation at 200°C. C-FER contacted Rod Guide Industries (RGI), who also did not have a suitable commercial product. However, they did have an untested compound that was apparently good for continuous service up to 200°C and were willing to mold three centralizers free of charge for use with the Netzsch test. After consultation with the SC and Netzsch, it was decided to proceed with using the RGI centralizer.

4.3 Testing Program

4.3.1 Test Matrix

Since the rotor was designed for temperatures above 150°C, the tests originally planned for 120°C were substituted for tests at the minimum temperature at which the pump could operate.

After discussions with Netzsch, an additional restriction was imposed for the PIP reduction tests to try to limit the stator decompression rate. This was done by trying to limit the rate of intake pressure reduction to 207 kPa/min (30 psi/min).

The intended test matrix for this system is shown in Table 4.1.

PCP System with Elastomer Stator (Netzsch)

	OIL		OIL/WATER	
T (°C)	NO AIR	WITH AIR	NO AIR	WITH AIR
Min (*)	• Pump curve and PIP reduction for 3 RPM's	• N/A	• Pump curve at reference RPM • PIP reduction	• Pump curve at reference RPM • PIP reduction
150	• Pump curve for 3 RPM's	• N/A	• Pump curve at reference RPM • PIP reduction	• Pump curve at reference RPM • PIP reduction
180	• Pump curve for 3 RPM's	• ALR Sensitivity for 3 RPM's	• Pump curve at reference RPM • PIP reduction	• Pump curve at reference RPM • PIP reduction • ALR Sensitivity
200	• Pump curve and PIP reduction for 3 RPM's	• N/A	• 1 RPM (Reference) • PIP reduction	• 1 RPM (Reference) • PIP reduction

(*) To be determined experimentally. Criteria: Efficiency at minimum delta-P = 80%

Table 4.1 Summary of Test Matrix for Netzsch Pumping System

4.3.2 Test Program Summary

Tests with 100% oil were conducted successfully up to the maximum temperature (200°C). Table 4.2 shows the actual pump test data that was generated for the Netzsch system, which was very close to the original test matrix. Comments regarding the minor changes between the intended test matrix and the actual test matrix are included later in this section.

T°C	Pump speed (RPM)	Pump performance curve	PIP reduction with 100% oil	ALR sensitivity
130	100	4 points	-	-
	150	Full	Full	-
	200	@193 RPM[5]	Full	-
150	100	Full	Single point	Up to ~13 m^3/m^3
	150	Full	Single point	-
	200	Full	Full	Up to ~21 m^3/m^3 Additional: PIP reduction and "closed annulus" test
180	100	Full	Single point	-
	150	Full	Single point	-
	200	Full	Full	-
200	100	Full	Single point	-
	150	Full	Single point	-
	200	Full	Full	-

Table 4.2 Summary of Tests Carried Out for Netzsch System (with 100% oil)

PCP System with Elastomer Stator (Netzsch)

During the process of preparing for the next stage of the test matrix (with the oil/water mixture), a substantial quantity of elastomer material from the pump was found in the strainer immediately downstream of the pump discharge. Post-test analysis of the data showed possible evidence of deterioration in the pump flow capacity during the test with oil.

The SC agreed to have C-FER proceed with trying to test with the oil/water mixture to obtain some additional test data, starting with the two last temperature levels (180 and 200°C). However, soon after resuming testing, an additional pressure drop was observed across the strainer (indicating that more elastomer material was likely being deposited into it) and the test was concluded.

4.4 Test Results and Analysis

4.4.1 Pump Curves with 100% Oil

As mentioned, the first step of the test program was to determine the minimum operating temperature for this rotor. The criterion was a volumetric efficiency greater than 80% at 100 RPM and at the minimum delta-P possible in the flow loop (open choke).

This temperature was determined to be close to 130°C, with a volumetric efficiency of approximately 85% at 275 kPa (40 psi) of delta-P (see Figure 4.1). At this temperature, for 100 RPM a maximum delta-P of approximately 1,516 kPa (220 psi) was achieved (with very low volumetric efficiency). At 150 RPMs, the maximum delta-P achieved was about 3,310 kPa (480 psi).

Figure 4.2, Figure 4.3 and Figure 4.4 show the flow rate (Q) versus delta-P pump curves for the 100% oil tests at 100, 150 and 200 RPM, respectively[5]. An analysis of the results shows how the temperature has a combined effect on the pump performance. At a given pump speed (for example at 100 RPM as shown in Figure 4.2) the maximum flow rate (at minimum delta-P) was reduced when the temperature was increased from 150 to 200°C. This is likely due to the thermal expansion of the elastomer, which reduces the effective size of the cavity and therefore the volumetric capacity of the pump.

Figure 4.5 shows a summary of the torque readings for all the tests with oil. The thermal expansion phenomenon described above also has an effect on the pump torque. Since the effective volumetric capacity of the pump is reduced as the elastomer expands, the slope of the torque versus delta-P curve (which represents the hydraulic component of the torque) is also reduced, as shown in Figure 4.6.

[5] At 130°C, the maximum RPM test was performed at 193 RPM rather than 200 RPM, due to a calibration range limit set for the speed transducer that could not be reset without interrupting the test. The results presented for 200 RPM at 130°C were extrapolated (linearly) from the experimental data at 193 RPM. Later, the RPM sensor was recalibrated for all other tests.

On the other hand, the results illustrate that as the elastomer expands, the rotor-stator fit tightens, which reduces the slippage and improves pump performance at higher levels of delta-P. In the flow rate (Q) versus delta-P charts, the effect of the temperature on the cavity size is reflected in the (extrapolated) y-intercept of the pump curve, while the effect on the pump fit is shown by the change in the slope of the curve. Note that there was a "reversed" trend in the slope of the curve when the temperature was increased from 180 to 200°C. Some of the theories considered to try to explain this behaviour were the reduction in the fluid viscosity and the softening of the elastomer due to the temperature increase. However, based on data analysis and post-test observations (see Section 4.4.5), it is likely that this reversed trend was due to deterioration of the pump stator.

Figure 4.7 shows the volumetric efficiency based on the theoretical (reference) pump capacity[6]. Figure 4.8 shows the theoretical slippage based on the following equation:

Theoretical slippage = RPM * (Pump reference capacity) – Actual pump rate

However, due to the possible changes in the size of the pump cavities with temperature as mentioned before, this representation may not reveal the actual pump slippage. Figure 4.9 shows an alternative representation for the slippage, based on the extrapolated flow rate at zero delta-P (at the same temperature and RPM):

Slippage = flow rate @ zero delta-P (extrapolated) – actual flow rate

This definition for slippage is equivalent to the practice of setting the pump volumetric efficiency at 100% for zero delta-P. Note in Figure 4.9 how the curves obtained at different speeds at the same temperature tend to collapse using this definition, suggesting that the slippage was more affected by the delta-P and the temperature than by the pump speed.

There are two exceptions to this "clustering" behaviour, corresponding to the pump curves at 100 RPM for 130 and 150°C. There doesn't appear to be a simple explanation for this; however, one possibility could be that the larger residence time of the fluid inside the pump (due to the lower flow rate achieved at 100 RPM) led to a larger increase in temperature and subsequent decrease of viscosity. The more pronounced dependence of viscosity with temperature at lower temperatures and the existence of a looser rotor/stator fit at 130°C may also help explain why this effect was more evident at this temperature.

The "reversed" trend mentioned before regarding the effect of temperature on the slope of the pump curves is again observed in Figure 4.9. As it will be discussed in Section 4.4.2, there was some evidence suggesting that damage occurred to the pump after the 100% oil test at 180°C. Comparing the plots corresponding to 130, 150 and 180°C, apparently the positive effect of the

[6] The vendor reported a theoretical volumetric capacity of 2.26 m^3/d/RPM, which led to efficiencies above 100%. Thus, the reference volumetric capacity used for this report was 2.375 m^3/d/RPM, based on the extrapolation (at zero delta-P) of the best experimental performance (at 150°C and 200 RPM).

change in rotor/stator fit due to elastomer thermal expansion was larger than the negative effect of viscosity reduction on pump efficiency (i.e. the pump exhibited higher slip at lower temperatures).

4.4.2 PIP Reduction Tests with 100% Oil

When performing the first PIP sensitivity test at 130°C and 200 RPM, the data showed that the pump was able to produce fluid with little reduction in volumetric efficiency, down to near zero intake pressure. Originally the test matrix called for a progressive PIP reduction at each speed, in order to determine the minimum intake pressure required by the pump. After observing the result of the first test, the procedure was modified slightly (to reduce the total testing time) as follows:

- At 200 RPM, and maintaining delta-P at its reference value (3,000 kPa), the intake pressure was reduced from the PIP reference value at a slow constant rate to a value close to saturation pressure; and
- While maintaining the PIP at this level, the pump's RPM was reduced to 150, and then to 100, to obtain the corresponding flow rate values at this minimum PIP value.

The justification for this change was that any effect of the low PIP in pump performance was expected to be more pronounced at maximum RPM, where the frictional pressure drop due and any cavity fillage difficulties would likely be more severe. Therefore, if no effect was detected during the PIP reduction at maximum speed, no effect would be expected at lower speeds. The additional points for the lower speeds were acquired basically to maintain completeness in the experimental data.

Figure 4.10 and Figure 4.11 summarize the results for the PIP reduction tests (at 200 RPM) in terms of flow rate and volumetric efficiency, respectively. Note how the pump was able to handle very low intake pressures with little effect on the performance, until the test at 180°C. However, there is evidence that the reduction observed in the pump flow rate at this temperature was due to pump elastomer deterioration rather than hydraulic phenomenon at the pump intake (e.g. cavity fillage).

Figure 4.12 shows the flow rate, pump torque and the pump delta-P as the PIP was reduced for the test at 180°C. The additional curve shows the expected torque, based on data from the pump performance tests. Note that when the PIP was reduced from 22 to 9 kPa (155 to 64 psig), there was a considerable reduction on the flow rate (even though the delta-P had also dropped somewhat). There was a good match between the calculated and measured torque for the first two values of PIP; however, for the third value (PIP = 64 psig) the measured torque was ~50% above the calculated value. This suggests that some mechanical problem in the stator began to occur at this point. By the time the minimum PIP (3 psig) was achieved, the torque returned to values closer to normal, but the final flow rate was ~10% below the initial value.

In Figure 4.13, the data points obtained for the PIP reduction tests are plotted along with the pump performance curves with 100% oil. Note how most of the PIP data points lay very close to the corresponding pump performance curve at the same temperature, except for the case at

180°C. This may be another indication of some damage to the pump stator during the PIP reduction test at 180°C.

4.4.3 ALR Sensitivity Test with 100% Oil

The ALR Sensitivity Test was performed at 150°C (instead of 180°C) in order to reduce the loop heating time (as reported to the Participants before the testing). This test was carried out after all the pump performance and PIP reduction tests had been finished (in order to avoid any effect of small bubbles that could remain entrapped in the oil).

As shown previously in Figure 4.2, the flow rate at 100 RPM and 150^{o}C was low (e.g. approximately 50% volumetric efficiency) for pump delta-P's below 2.5 MPa (360 psi). Therefore, there was concern about performing the ALR sensitivity test at the reference delta-P (3 MPa), and it was decided to perform the ALR sensitivity test at a low delta-P of 260 kPa (38 psi).

The data showed that the downhole separation efficiency was close to 100% (i.e. all the air injected was bypassing the pump intake), as shown in Figure 4.14 and Figure 4.15. This was concluded because there was little effect on the pump liquid flow rate compared to the performance without air, and there was no evidence of air flow at the gas outlet of the main separator.

The high separation efficiency was discussed with the SC Chairperson, and it was agreed that C-FER should proceed with an ALR sensitivity test at a higher pump speed (200 RPM), and increase the ALR until a significant reduction in the volumetric efficiency of the pump was observed (maintaining the same reference PIP).

At 200 RPM it was possible to maintain the reference delta-P. C-FER proceeded to gradually increase the air injection up to 2,680 sm^3/d (65 scfm), which corresponded to an ALR of more than 20 s m^3/m^3. A moderate negative effect on liquid flow rate was noticed. It was then decided to lower the PIP to try to reach the performance limit of the downhole gas separator (bottom feeder), while maintaining pump delta-P. Later analysis of this data revealed a slow but steady reduction in liquid flow rate as shown in Figure 4.16 (a drop of about 40 m^3/d in 70 minutes). Note however that this change was occurring even before air injection.

Since it appeared that most of the air was still bypassing the pump intake, the Chairperson also suggested an additional test, consisting of maintaining an air rate corresponding to a GVF of up to 15% and then closing the annulus to force all the injected gas through the pump. The objective was to try to establish a stable condition were the pump would be pumping fluid and air at the same time (as opposed to a surging condition).

Initially, air was injected into the bottom of the casing at a rate corresponding to less than 10% of GVF. As shown in Figure 4.17, there was no major effect on the pump performance for about ten minutes, at which time the reading from the Coriolis flow meter (FT02) became very erratic. This was interpreted as an indication of the air/liquid interface reaching the intake of the bottom feeder. As stable operation under these conditions was not possible, the test was stopped. The system was shut down while maintaining a decompression rate of less than 207 kPa/min (30 psi/min).

Figure 4.18 and Figure 4.19 show the volumetric efficiency at 100 and 200 RPM as a function of ALR and GVF, respectively. Please note that the reference values of delta-P used at each speed were different. Observe how the efficiency was much more affected at 200 RPM than at 100 RPM as the ALR was increased. To verify that this was indeed an effect of the injected air, an additional data point was extracted from the data recorded at 200 RPM after the ALR test had finished. As observed in Figure 4.18 the flow rate did not return to its original value, indicating that the pump may have suffered some physical deterioration during this test.

4.4.4 Testing Attempt with Oil/Water Mixture

After testing with the 100% oil was complete, the flow loop strainers were inspected. A substantial quantity (~600 g) of small and medium pieces (up to 7 cm in length) of elastomer from the pump was found in the strainer immediately downstream of the pump discharge, as shown in Figure 4.20. The strainer upstream of the pump intake only contained a few small pieces of elastomer.

Due to this finding, the data was reviewed to try to quantify when the damage to the pump may have started. After a review of the pump volumetric efficiency data and the pressure losses in the loop section containing the strainer, it appears that the damage started after the initial performance tests at 180°C, during the PIP reduction test. During this test there was the first indication of reduced efficiency, and after this test there appeared to be a gradual and progressive decline on the volumetric efficiency of the pump[7].

It had been previously noted that the slippage (reduction in efficiency at higher delta-P) observed at 200°C was larger than at 180°C, but this had been interpreted at the time as a temperature effect on the mechanical properties of the stator elastomer (i.e. softening of the elastomer) or viscosity reduction of the oil. However, this increase in slippage coupled with the stator material found in the strainer, now indicated that the performance deterioration was likely due to stator damage.

After receiving approval from the SC, an attempt was made to test the Netzsch system with the oil/water mixture; however, soon after resuming testing a pressure drop increase was observed across the section of the flow loop containing the strainer (indicating that more elastomer material was likely being deposited into the strainer). The discharge strainer was again inspected, and significant additional elastomer material was found. Therefore, the test program was interrupted.

---

[7] Note that the conclusions are based on preliminary examination of data only, and more thorough analysis can be performed at the request of the SC.

PCP System with Elastomer Stator (Netzsch)

4.4.5 Post-test Observations

After the pumping system was removed from the flow loop, a preliminary inspection at C-FER showed that chunks of elastomer were missing from different sections of the stator, with no apparent preference toward the intake or discharge sides of the pump. Some initial de-bonding was also observed both at the discharge and intake of the pump; however, at least in those specific sections, the loss of elastomer chunks did not extend through the whole thickness of the stator.

Although Netzsch had mentioned that they planned to perform a teardown on the pump and report the results to the JIP, they have not yet provided any information to C-FER regarding any teardown results to date.

No problems were experienced with the Netzsch drive unit (stuffing box and gear box) during testing.

Post-test inspection of the three rod centralizers supplied by RGI showed that very little wear had occurred on the two centralizers closest to the drive, while moderate wear (apparently associated to impact) had occurred on the lowest centralizer, which was located approximately 20 ft above the rotor. RGI personnel informed us about their plans to perform some additional analysis on the rod centralizers and report back; however, no information was received by C-FER regarding this analysis so far.

4.5 Conclusions

- The test program for 100% oil (with and without air) was concluded successfully. Deteriorating pump stator condition prevented the continuation of testing with the oil/water mixture.
- The predominant effect of temperature was to tighten the fit between the rotor and the stator, generally reducing slippage and improving volumetric capacity, up until the point of stator failure.
- From a volumetric efficiency standpoint, the pump showed a very good capacity to handle very low intake pressures during the 100% oil tests. For the range of viscosities corresponding to temperatures above 130°C (i.e. viscosities of less than 17 cP), the minimum NPSH required by the pump was close to zero.
- In addition to the characterization of the pump, the tests with air showed very high gas separation efficiency at the pump intake/annulus with the bottom feeder, for the specific test conditions tested.
- After completing the tests, it was found that significant elastomer material had been removed from the pump stator. In reviewing the test data, it appears that hydraulic performance of the pump had been deteriorating during testing.

PCP System with Elastomer Stator (Netzsch)

- Preliminary inspection of the pump at C-FER showed that chunks of elastomer were missing from different sections of the stator, both at the intake and discharge sides of the pump. Some initial de-bonding was also observed both at the discharge and the intake of the pump.
- Preliminary inspection of the three rod centralizers supplied by RGI showed only minor wear, with the most pronounced wear on the centralizer closest to the pump.
- No leakage or friction problems were experienced with the Netzsch drive unit (stuffing box and gear box).

PCP System with Elastomer Stator (Netzsch)

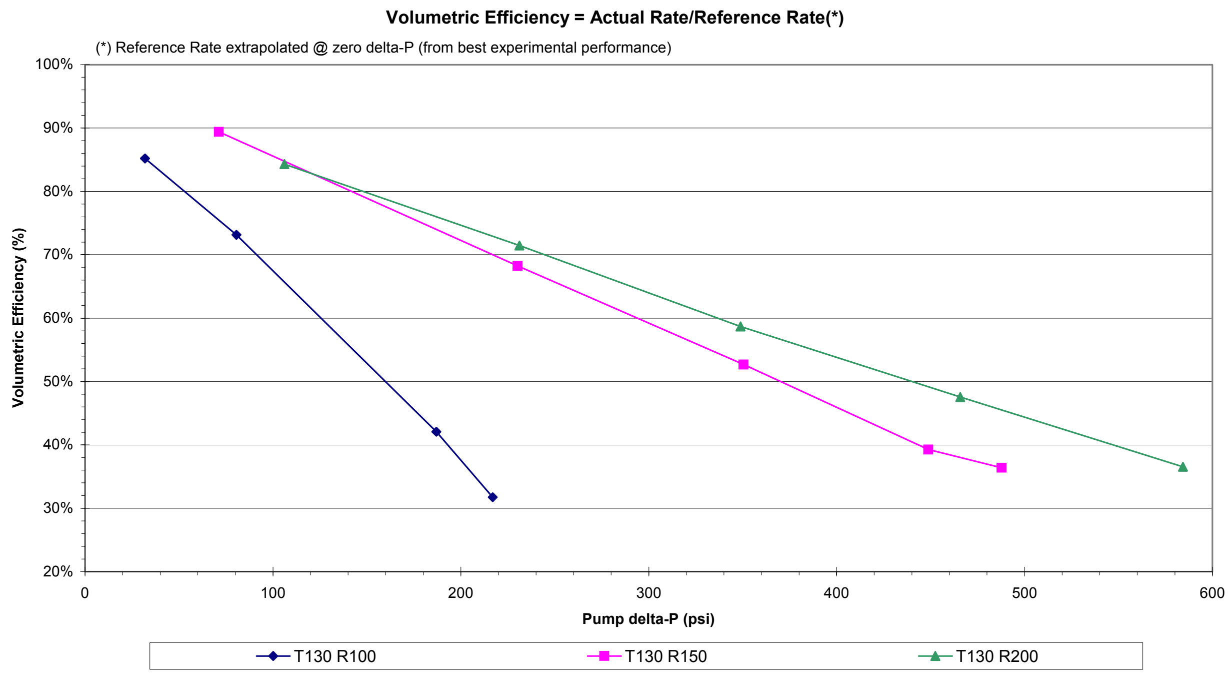


Figure 4.1 Netzsch - Pump Efficiency at 130°C with 100% Oil

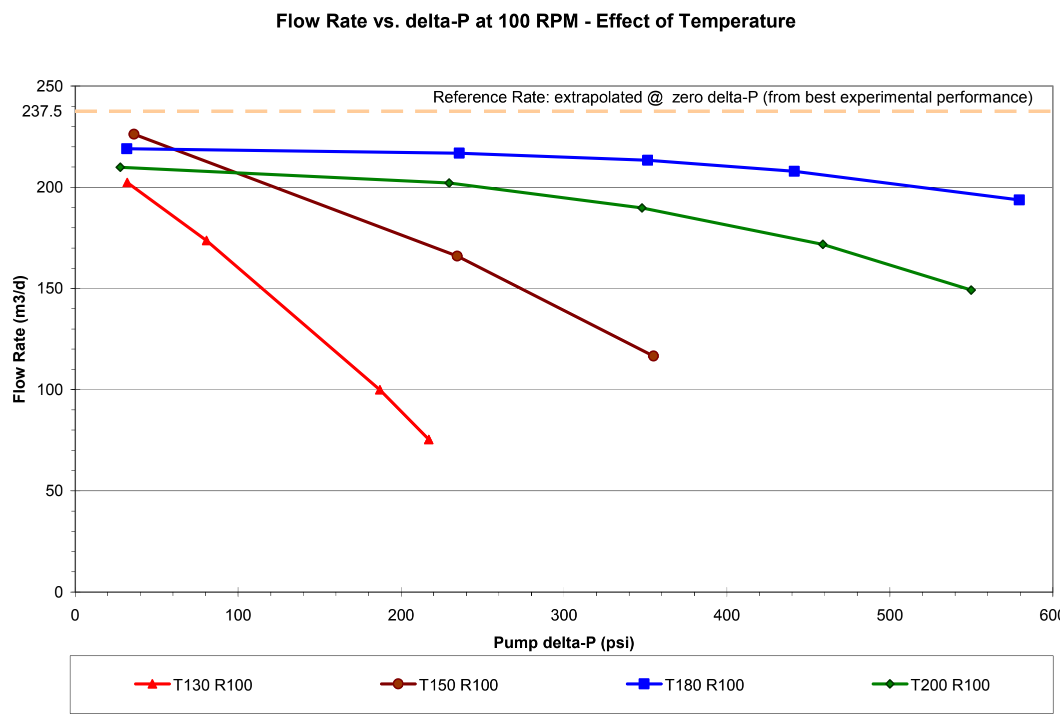


Figure 4.2 Netzsch - Pump Curves at 100 RPM, Effect of Temperature with 100% Oil

PCP System with Elastomer Stator (Netzsch)

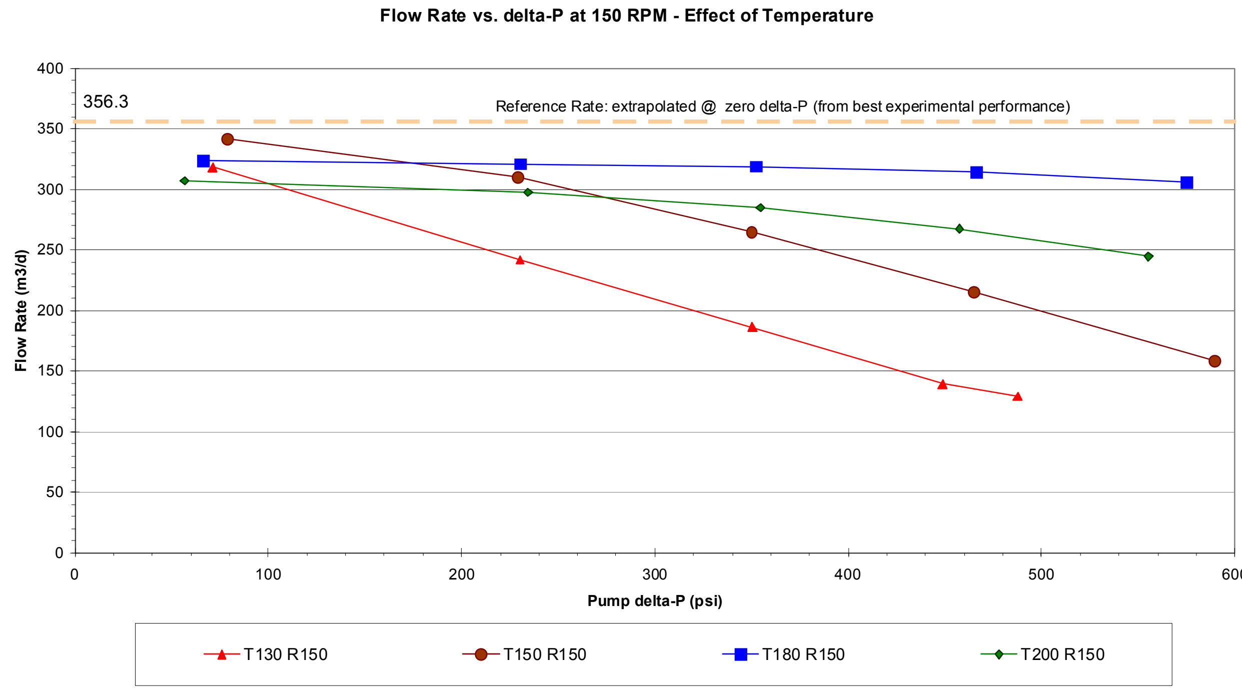


Figure 4.3 Netzsch - Pump Curves at 150 RPM, Effect of Temperature with 100% Oil

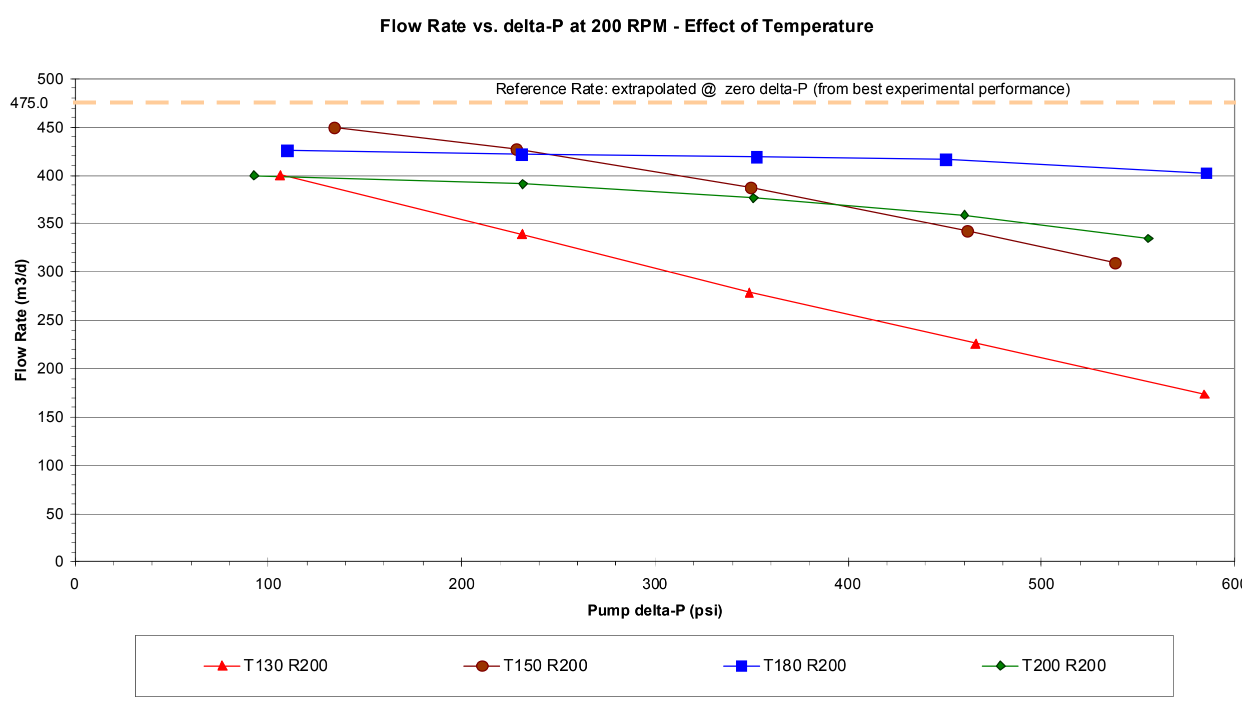


Figure 4.4 Netzsch - Pump Curves at 200 RPM, Effect of Temperature with 100% Oil

PCP System with Elastomer Stator (Netzsch)

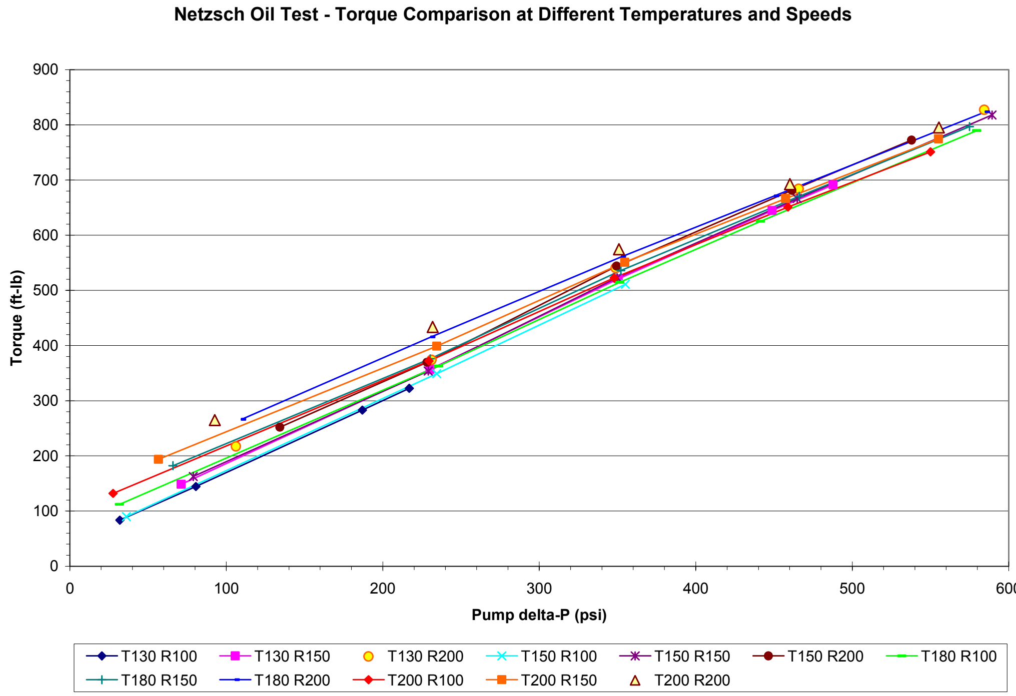


Figure 4.5 Netzsch - Effect of Temperature and Speed on Torque with 100% Oil

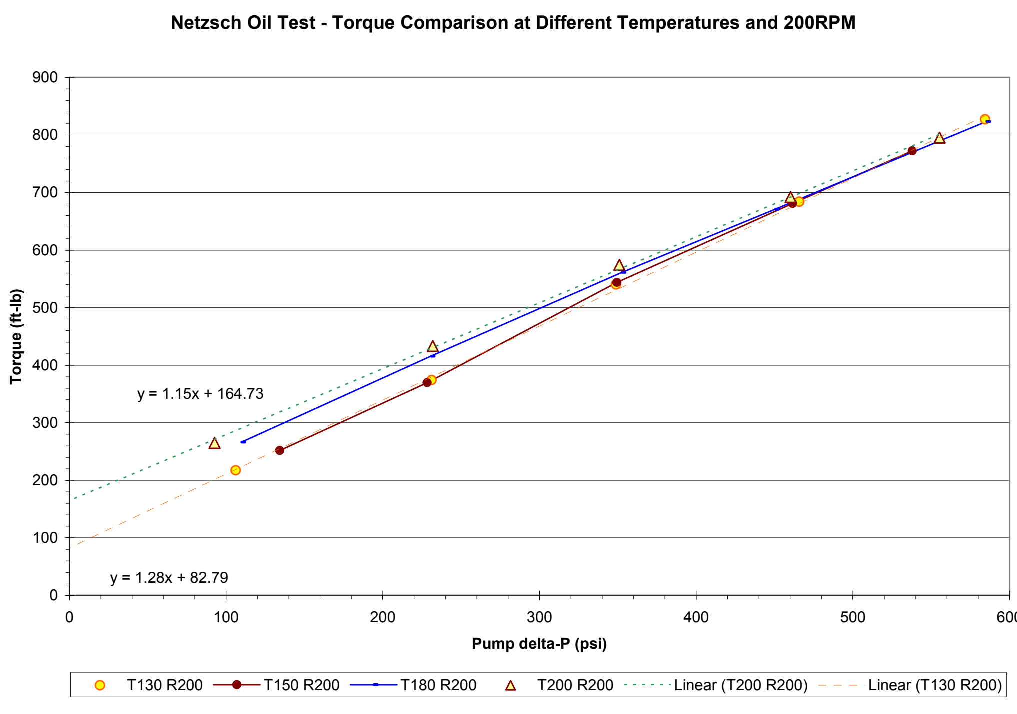


Figure 4.6 Netzsch - Effect of Temperature on Torque at 200 RPM with 100% Oil

PCP System with Elastomer Stator (Netzsch)

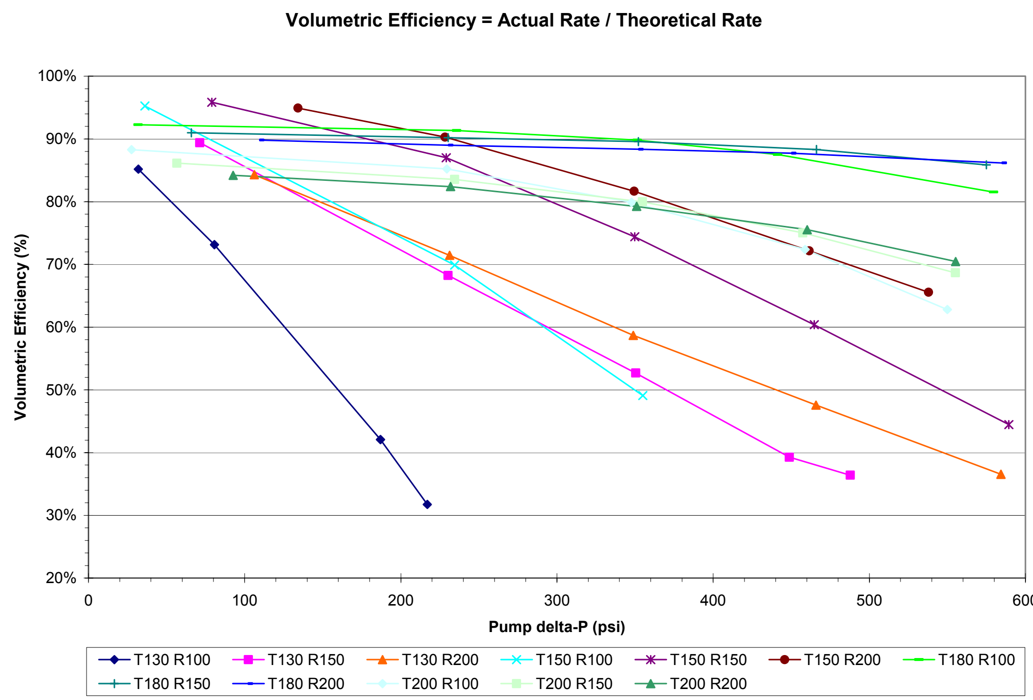


Figure 4.7 Netzsch - Volumetric Efficiency for all Conditions for 100% Oil

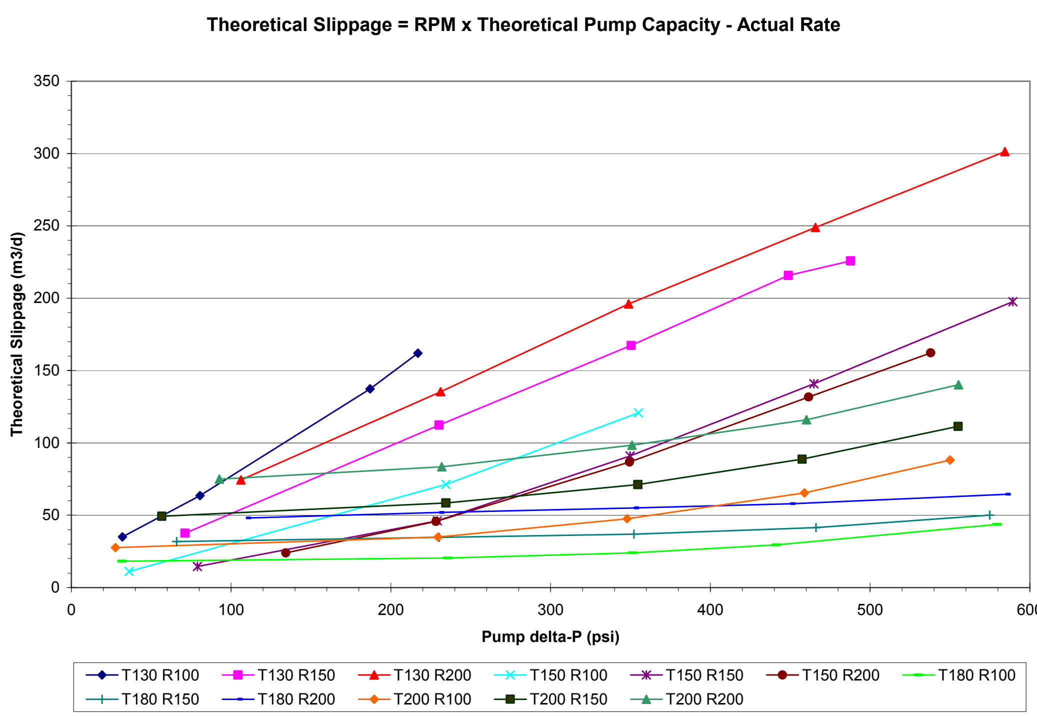


Figure 4.8 Netzsch - Theoretical Slippage (Based on Theoretical Rate) with 100% Oil

PCP System with Elastomer Stator (Netzsch)

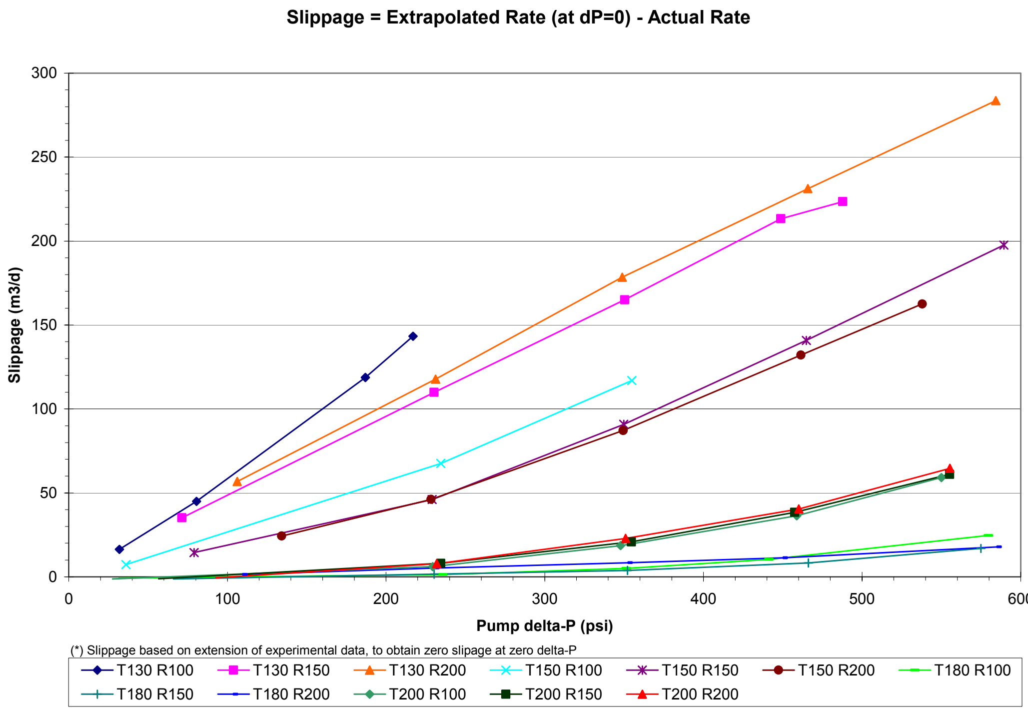


Figure 4.9 Netzsch - Slippage Based on Maximum Rate (Extrapolated at delta-P = 0) with 100% Oil

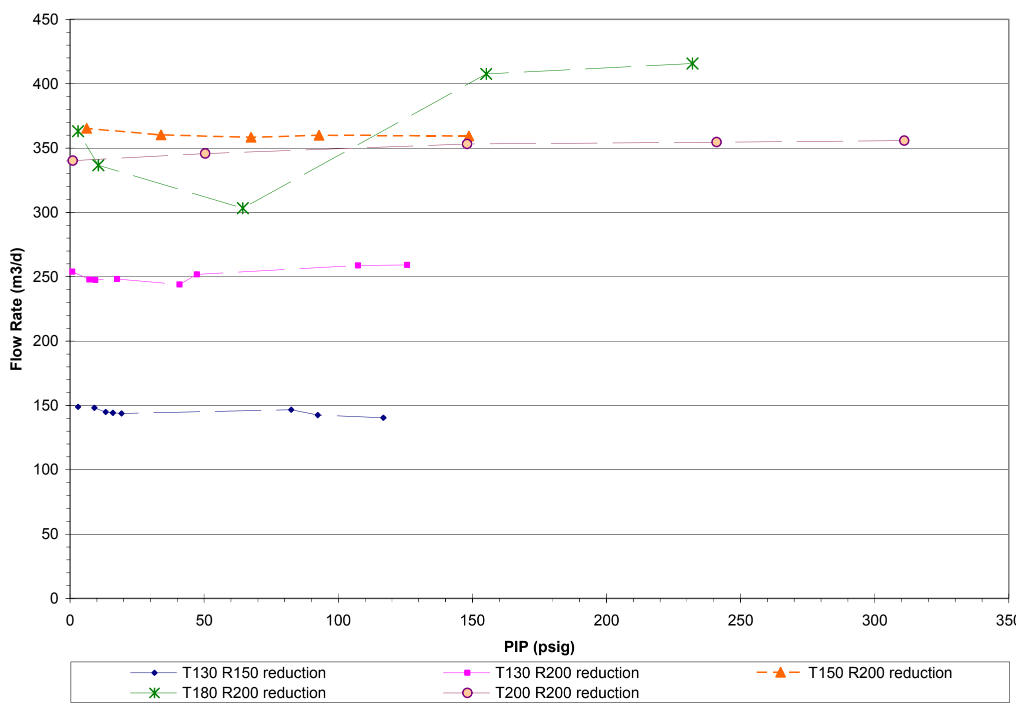


Figure 4.10 Netzsch - Effect of PIP Reduction on Flow Rate with 100% Oil

PCP System with Elastomer Stator (Netzsch)

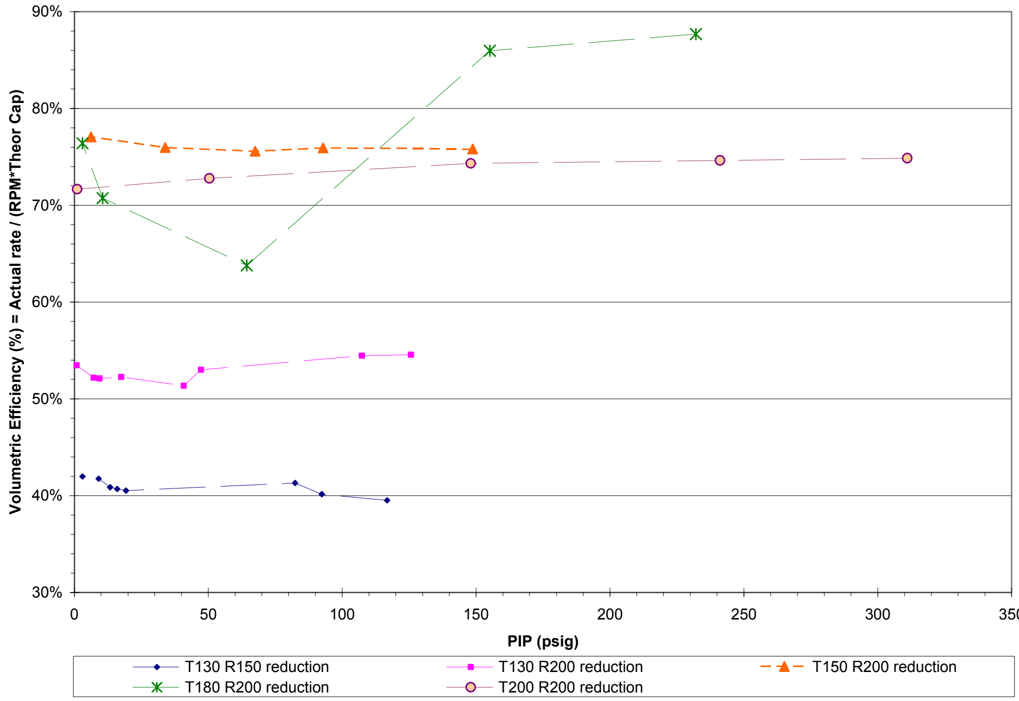


Figure 4.11 Netzsch - Effect of PIP Reduction on Volumetric Efficiency with 100% Oil

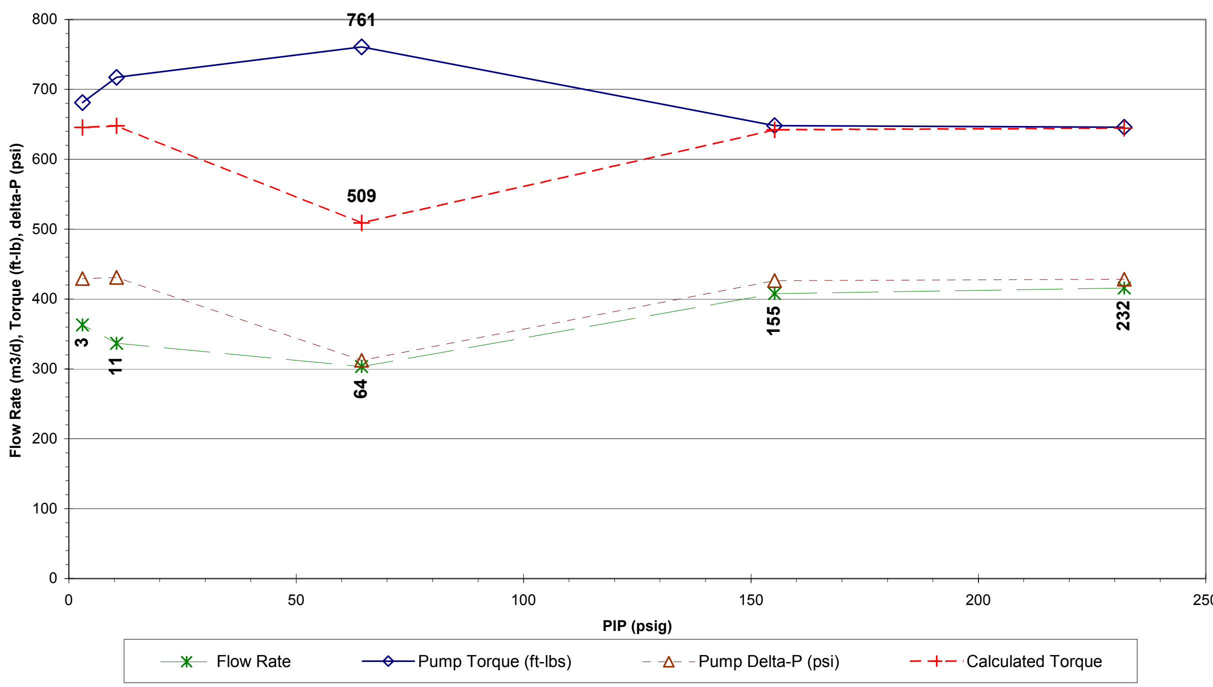


Figure 4.12 Netzsch - Strange Behaviour with PIP Reduction at 180°C with 100% Oil

PCP System with Elastomer Stator (Netzsch)

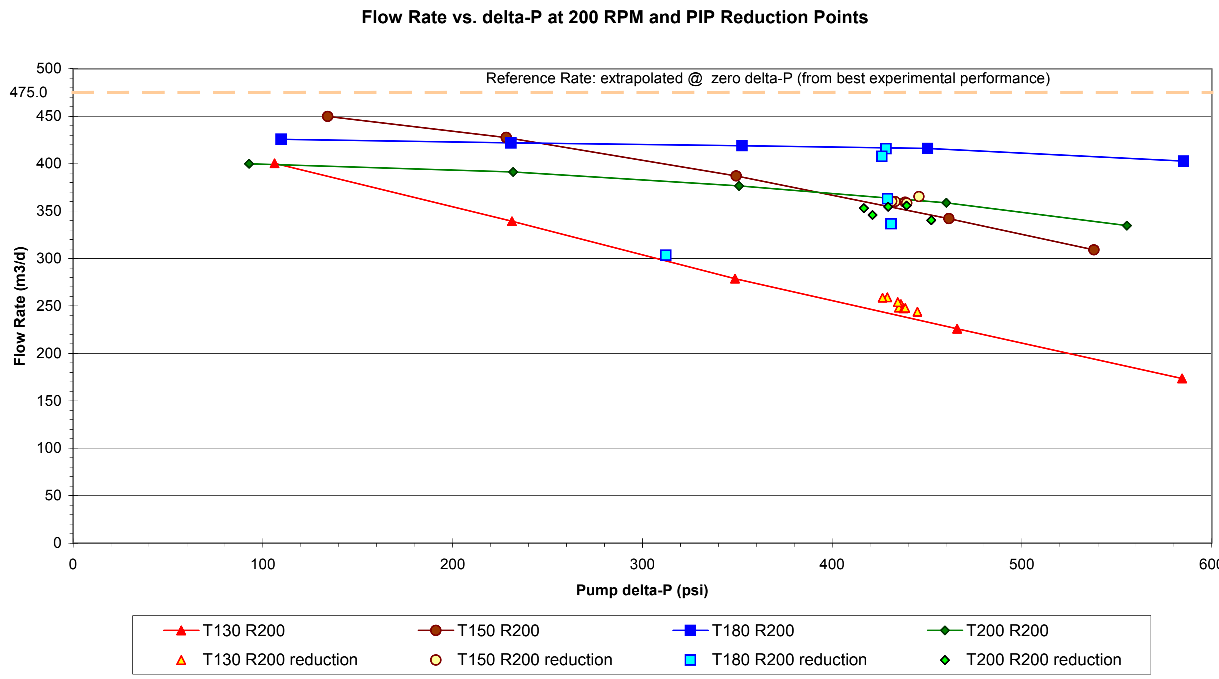


Figure 4.13 Netzsch - PIP Reduction and Pump Performance Results with 100% Oil at 200 RPM

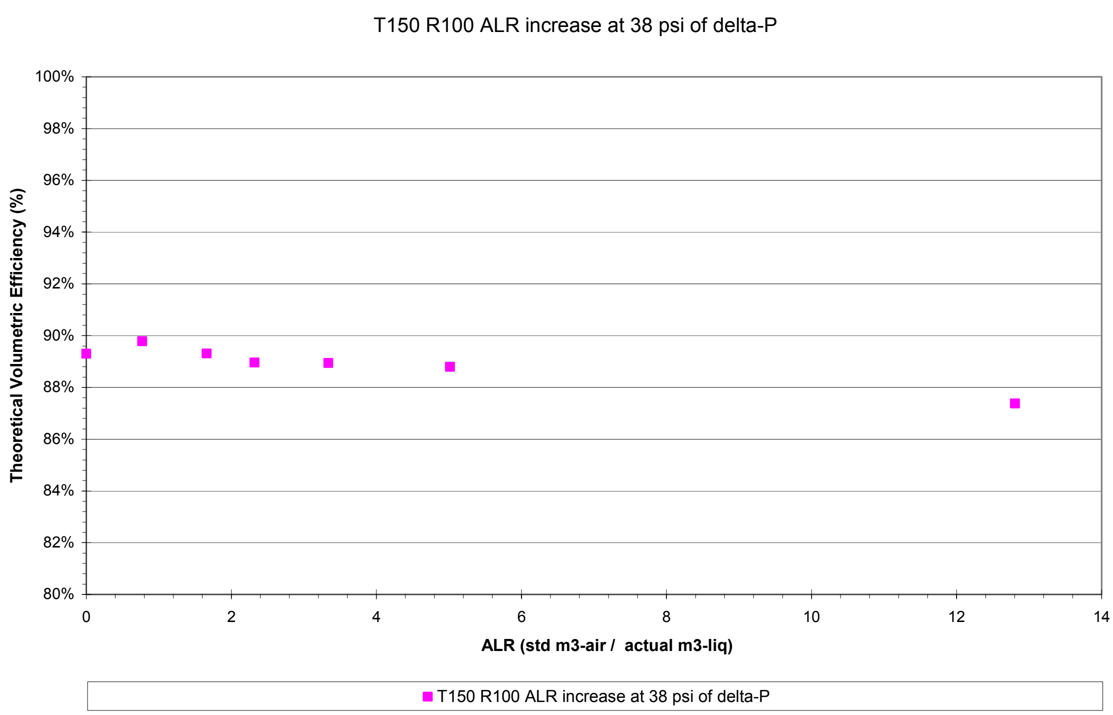


Figure 4.14 Netzsch - Effect of ALR Increase on Volumetric Efficiency at 150°C and 100 RPM with 100% Oil

PCP System with Elastomer Stator (Netzsch)

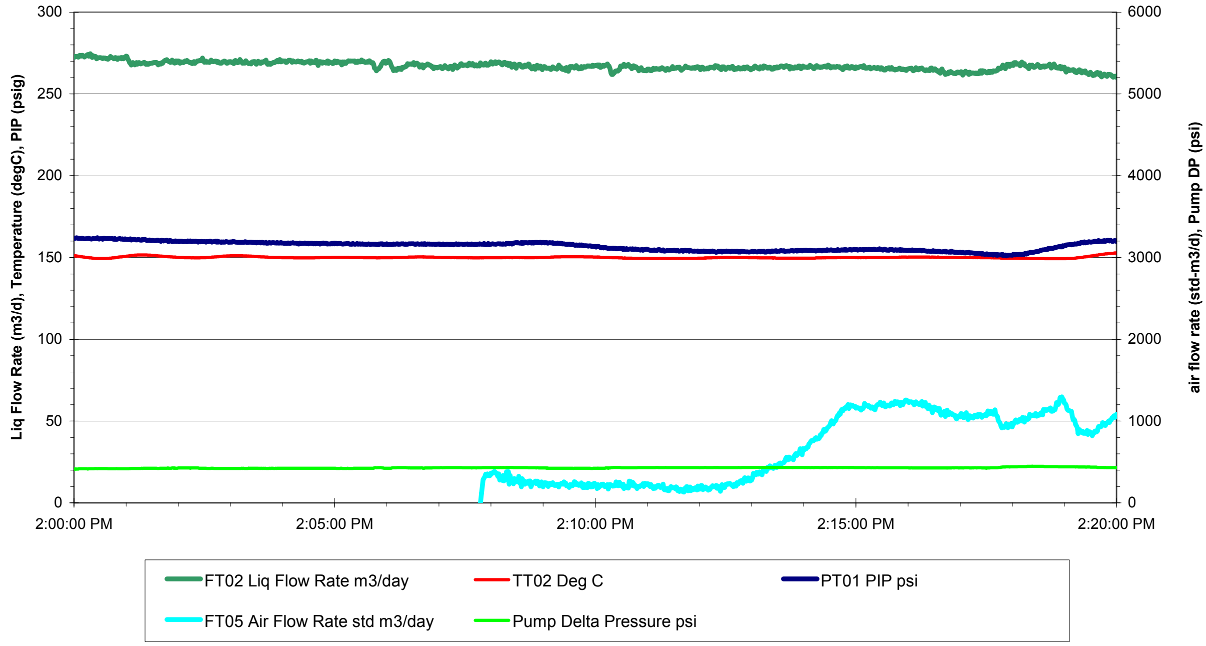


Figure 4.15 Netzsch - Historic Data Showing Mild Effect of Air Injection on Pump Performance for 100% Oil

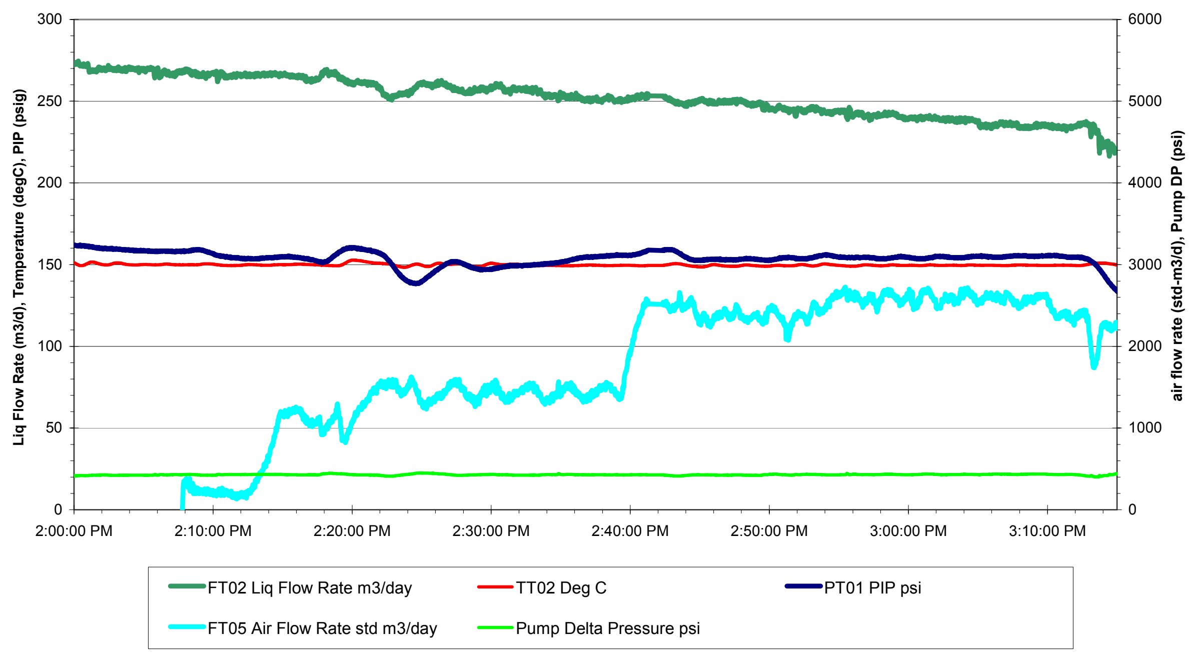


Figure 4.16 Netzsch - Historic Data Showing Slow but Continuous Deterioration on Pump Performance during ALR Test for 100% Oil

PCP System with Elastomer Stator (Netzsch)

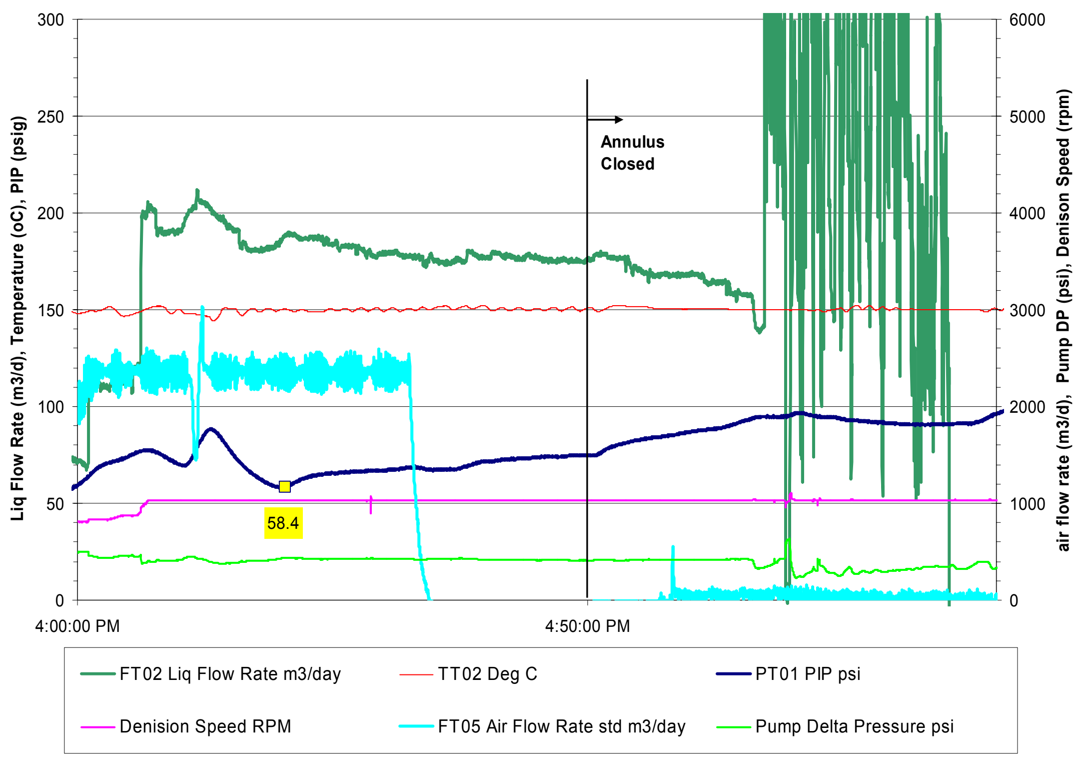


Figure 4.17 Netzsch - Historic Data of "Closed Annulus" ALR Test for 100% Oil

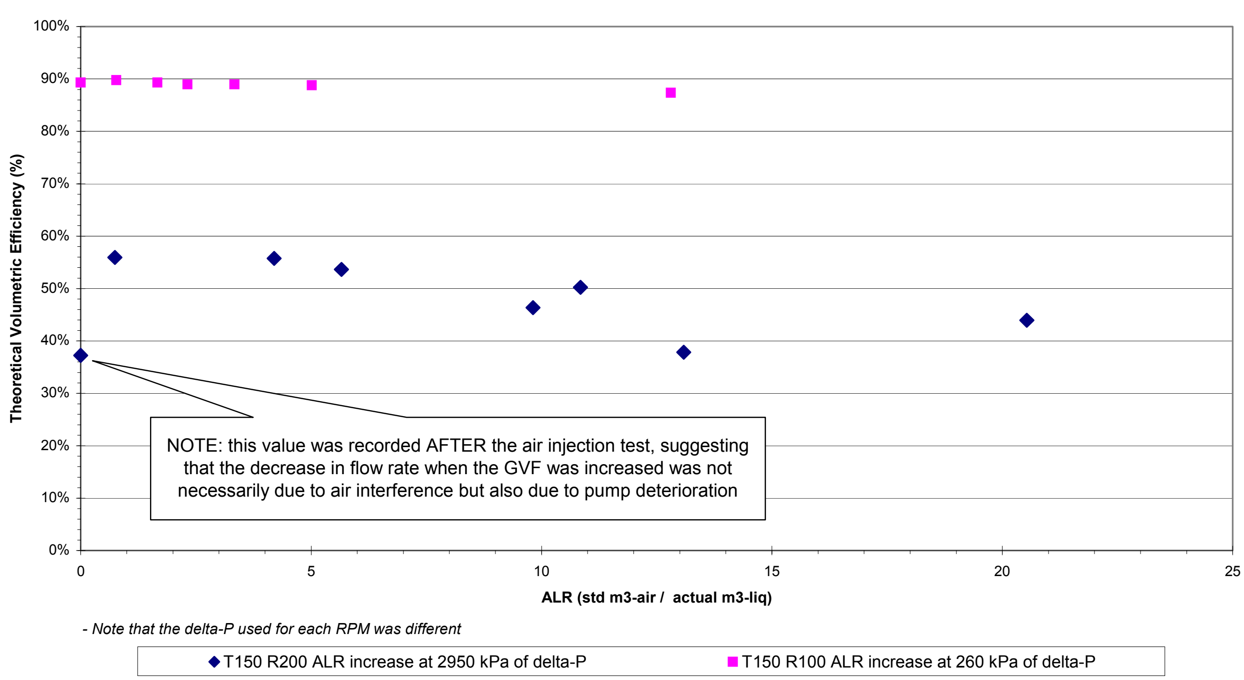


Figure 4.18 Netzsch - Volumetric Efficiency Versus ALR at 150°C with 100% Oil

PCP System with Elastomer Stator (Netzsch)

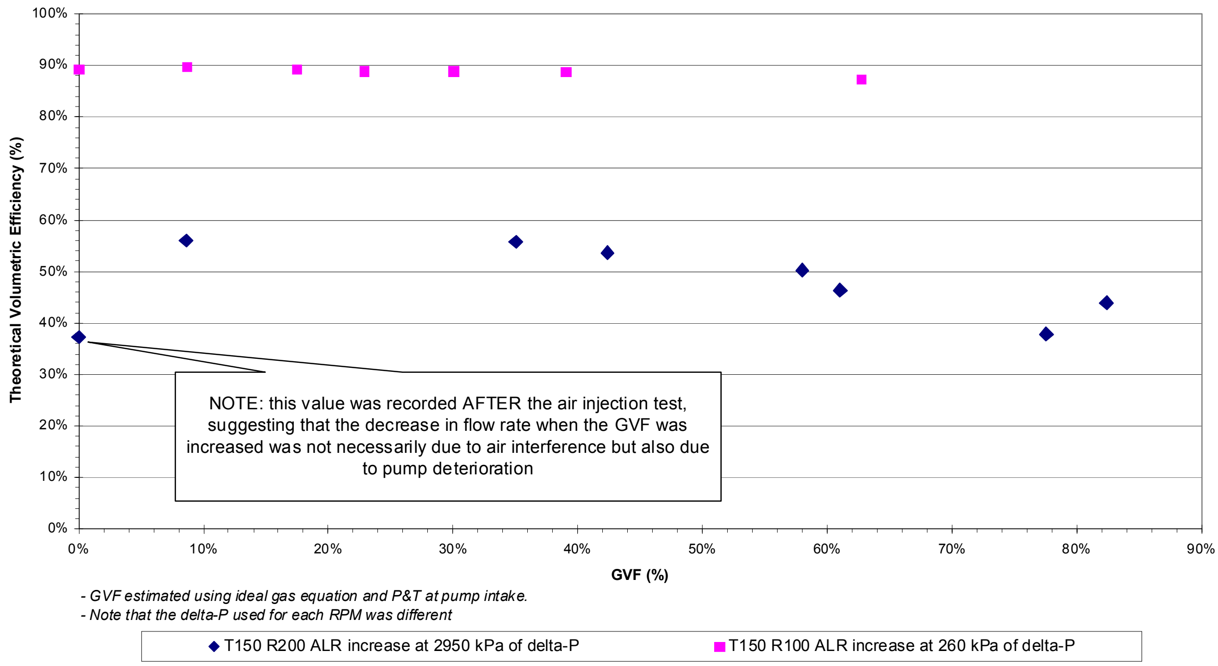


Figure 4.19 Netzsch - Volumetric Efficiency Versus GVF at 150°C with 100% Oil

Figure 4.20 Netzsch - Elastomer Material Found in the Strainer after Testing with 100% Oil

5. ESP SYSTEM (WOODGROUP)

5.1 System Description and Technical Specifications

Woodgroup ESP (WG) provided the following components for testing:

- Pump (TE 5500 AR CMP 41/13B #07 XHT);
  - 538 Series, 41 stages
  - Nominal flow rate 875 m^3/d (5500 bpd)
- Intake (BOTTOM FEEDER TG SST);
- Seal (TR5-AR 2PB/2LAB XHT HL CCW);
- Motor (TR5-92XHT UT);
  - 150HP 2350V 49A
- Cable (MLC TR5-XHT LEAD #4 MNL 100' (ENG));
- BIW mandrel for wellhead feedthrough; and
- Variable speed drive (VECTOR SERIES NEMA 3 W/OPT)
  - 225 KVA.

5.2 Installation and Commissioning

WG was unable to locate a generator, so C-FER sourced a 225 KW skid unit.

After discussions with WG and StreamFlo, it was decided that the existing wellhead could be utilized if: 1) a new bore (3 inches) was machined into it, and 2) a custom BIW mandrel sleeve was designed and fabricated, to allow the mandrel to be located above the wellhead (since the wellhead has no dognut). C-FER designed this sleeve and contracted out the machining and welding.

The ESP system arrived at C-FER on December 1, 2004, in sections, and the motor/seal/intake/pump assembly was performed at C-FER by WG and C-FER technicians.

One item of note is that WG advised that the oil in their seal section would have to be refilled if a cooling of more than 160°C were experienced. This impacted the operational procedures, since the test program called for testing up to 200°C with 100% oil and then performing a fluid change to an oil/water mixture, where the pumping system was going to cool to 0°C or less. This meant that the pumping system had to be pulled out of the loop between the 100% oil tests and the oil/water mixture tests.

ESP System (Woodgroup)

Some issues delayed testing:

- WG supplied the VSD without an interface board, so current and frequency signals could not be tied into the DAS. WG later provided the board, which was installed by C-FER technicians.

- C-FER ordered a new batch of oil from the US supplier, but the new oil appeared to have a lower viscosity. (This new batch was required to top up the system for the 100% oil test.) Therefore, a decision was made not to use the new oil until it had been tested to verify its viscosity. C-FER tried instead to skim oil off the oil/water mixture tank; however, some water also entered the loop and time was spent trying to remove it.

- Due to the cold temperatures during that week (-20°C), some heat tracing of instrumentation lines were needed. As well, the heat exchanger water tank had to be relocated inside the building. The generator also shut down for half a day.

- When the ESP system was turned on at 60°C, an excessive pressure drop was observed across the air/liquid mixer at the casing entrance. To avoid draining the loop to inspect the mixer, it was decided to install a bypass line around the mixer.

- The circulation pump experienced a seal leak and needed to be pulled from the loop to be repaired.

As mentioned above, an excessive pressure drop had been observed across the air/liquid mixer and as a temporary fix C-FER had installed a bypass line around the mixer. However, even with the small diameter bypass, there was still a noticeable pressure drop through that section. There was a risk of not been able to achieve the maximum PIP specified at 200°C with the oil/water mixture. Therefore a decision was made to remove the custom air/liquid mixer from the entrance of the casing. The negative effect of this action was that it likely reduced the mixing efficiency of the air and liquid streams going into the casing entrance.

5.3 Experimental Program

5.3.1 Test Matrix

Table 5.1 summarizes the intended experimental matrix for this system:

	OIL		OIL/WATER	
T (°C)	NO AIR	WITH AIR	NO AIR	WITH AIR
Min (*)	• Pump curve and PIP reduction for 3 RPM's	• N/A	• Pump curve at reference RPM • PIP reduction	• Pump curve at reference RPM • PIP reduction
120	• Pump curve for 3 RPM's	• N/A	• Pump curve at reference RPM • PIP reduction	• Pump curve at reference RPM • PIP reduction
150	• Pump curve for 3 RPM's	• N/A	• Pump curve at reference RPM • PIP reduction	• Pump curve at reference RPM • PIP reduction
180	• Pump curve for 3 RPM's	• ALR Sensitivity for 3 RPM's	• Pump curve at reference RPM • PIP reduction	• Pump curve at reference RPM • PIP reduction • ALR Sensitivity
200	• Pump curve and PIP reduction for 3 RPM's	• N/A	• 1 RPM (Reference) • PIP reduction	• 1 RPM (Reference) • PIP reduction

(*) To be determined experimentally. Criteria: minimum flow rate and maximum current limits

Table 5.1 Summary of Test Matrix for WG

The following is a summary of the operational constraints that were agreed with WG prior to testing:

- Maximum cooling rate: 1°C/min;
- Maximum allowed system cool down from maximum test temperature (delta-T) = 160°C (beyond this point it would be necessary to pull the system out and refill the oil chamber);
- Minimum allowed flow rate (required to cool down the motor): 350 m^3/d for long periods and 250 m^3/d for short periods (i.e. less than ten minutes)[8]; and

[8] This additional flexibility in the minimum acceptable flow rate for short periods was agreed upon with WG during the conduction of the 100% oil tests.

ESP System (Woodgroup)

- Maximum motor current draw (established at the VFD): 310 Amps.
- The criteria for stopping testing was based on the minimum liquid flow rate requirements established, as well as current and head fluctuations (as an indication of pump surging and/or other stability problems).

According to the Pump Test Types section (see Section 3.2), the PIP reduction and ALR sensitivity tests were to be conducted while maintaining the reference delta-P at different values of fluid temperature and pump speed. However, due to the principle of operation of an ESP, it was not possible to use the same reference delta-P specified in the original matrix (3,000 kPa) for all frequencies, as illustrated in Figure 5.1 (i.e. the pump would operate outside its envelope).

Note also that the original test program specified target flow rates (for oil/water mixture) as a function of temperature, as shown in Table 3.1. However, the flow rate of 200 m^3/d was out of the operational range, and the point of 425 m^3/d at the edge of the range for this pumping system. Notice also that, because the test points were to be at the "reference DP", some of the points would be significantly away from the best efficiency point range for the pump.

Therefore, it was apparent that a modified methodology would be required for the ESP pumping system that was being provided for testing. After discussion with the vendor, it was agreed:

1. To start the PIP reduction test with 100% oil near the point of maximum efficiency at each frequency; and
2. To attempt to maintain a constant liquid flow rate during the PIP reduction and ALR sensitivity tests and to monitor the actual delta-P.

However, during testing, the second item was found to be impractical and difficult to implement. Therefore, it was decided to conduct the PIP reduction and the ALR sensitivity tests while maintaining a constant opening of the discharge pressure control valve downstream of the pump, and monitor both liquid flow rate and delta-P.

5.3.2 Test Program Summary

The test program was conducted as per the modified test matrix supplied to Participants, with the following exceptions:

- Originally, the agreement with the Vendor was to perform the 100% oil tests at VFD frequencies of 38, 50 and 60 Hz; however, during testing it was not possible to achieve 60 Hz due to a current limit in the VFD (established by the Vendor at 310 Amps). For that reason, the maximum frequency was reduced to 55 Hz and the mid value was changed to 46.5 Hz. Nevertheless, note that for the first set of curves (100% oil at 120°C), the mid frequency test was carried out before the current limit was detected; therefore, the original mid frequency (50 Hz) was used in that case.
- During the experimental determination of the minimum operating temperature, the flow rate was less than half of what was estimated by WG at 60°C; therefore, this test was limited to a very short period because of minimum flow rate concerns for proper motor cooling. In

another attempt to determine the minimum possible operating temperature, it was found that operation was not possible below approximately 93°C (corresponding to a oil viscosity of ~60 cP). This limitation was in part due to problems in maintaining a constant temperature and PIP with the flow loop.

- When trying to perform the tests with the oil/water mixture, with a water cut around 70%, it appeared that a highly viscous emulsion was formed, as evidenced by the pump performance and the pressure drop measured across the different sections of the loop. A decision then was made to try to decrease the emulsion viscosity by increasing the water cut. This was successful, as evidenced by much better pump performance and much lower pressure drops. The corresponding water cut for the rest of the tests ranged from 75 to 80%. Tests were performed at 120 and 150°C and 38 Hz, with and without air. At both temperature levels, the PIP reduction tests were performed successfully.

- While testing at 180°C, after obtaining only two test points for the pump curve (without air), a motor failure occurred. WG offered to repair the system and the SC agreed to carry on with the rest of the test program for the oil/water mixture. The tests were subsequently conducted according to the test matrix.

5.4 Results and Analysis

5.4.1 Pump Curves with 100% Oil

The first step in the test program with 100% oil was to determine the minimum operating temperature (maximum viscosity) for the ESP system. WG had provided pump performance curves obtained using their pump simulation software and viscosity correction factors for C-FER's testing oil at 60 and 120°C (estimated to be 325 and 120 cP respectively). Based on these curves, it appeared possible to operate at 60°C.

However, during testing at 60°C (at 38 Hz), the flow rate was less than half of that estimated by WG's curves. Therefore, the performance test was limited to a very short period because of the concern of not achieving sufficient flow rate for a proper motor cooling.

Another attempt was made (at the end of the test program with 100% oil) to determine the minimum operating temperature for the system, and it was found that it was possible to operate under somewhat stable conditions at ~93°C (corresponding to an oil viscosity of 60 cP). Two partial pump curves were generated at 38 and 46.5 Hz at this temperature.

The testing was limited to two frequencies due to difficulties in maintaining temperature and stability in PIP at the highest frequency, which was causing excessive testing times. This instability may have been produced by the large sensitivity of the viscosity to temperature changes at this operating temperature, as follows:

- When the viscosity was high, the pump performance deteriorated and the total flow rate decreased.

ESP System (Woodgroup)

- When the rate decreased, the residence time of the fluid around the motor increased, generating a temperature rise in the fluid. This produced a decrease of viscosity of the fluid entering the pump.
- When the pump received the lower viscosity fluid, its performance improved and the produced flow rate increased.
- The larger flow rate caused a reduction on the residence time of the fluid around the motor, producing a decrease in the temperature and an increase in the viscosity of the fluid entering the pump, causing the cycle to repeat.

A more detailed analysis of this transient phenomenon is beyond the scope of this project. Nevertheless, the data obtained during these tests was useful in evaluating the accuracy of the Vendor's viscosity correction factors and simulation algorithms for pump performance with viscous fluids. Figure 5.3 shows a comparison of the experimental data collected by C-FER during testing versus estimates based on the Vendor's viscosity correction factors for 60 and 120°C. The results suggest that the viscosity correction factors used by the Vendor underestimated the effect of this parameter on pump performance.

The next section of the test program was to obtain the pump performance curves at different temperatures and frequencies. Pump curves (five points per curve) were obtained for three different frequencies (38, 46.5 and 55 Hz), at 120, 150, 180 and 200°C, except that at 200°C and 55 Hz, only four test points were obtained, due to maximum discharge pressure limitations.

Figure 5.4, Figure 5.5 and Figure 5.6 show the results at different temperatures for 38, 46.5 and 55 Hz, respectively. Note how the difference in performance between 93 and 120°C was more evident at 46.5 Hz than 38 Hz, suggesting that the negative effect of the high viscosity is larger at higher speeds. This could be a result of two factors: (1) at lower flow rates the pressure drop in the vicinity of the pump intake is smaller and, (2) at low speed the residence time of the fluid flowing around the motor is longer, producing a larger temperature increase which reduces the viscosity of the fluid entering the pump.

When WG supplied their estimated pump performance plots for this pump at 60 and 120°C they stated that the viscosity correction factors should be unimportant for fluid temperatures above 120°C. Figure 5.7 and Figure 5.8 compare the actual performance to simulations at 120 and 200°C. At 200°C the actual performance is quite close to the simulated level; however, at 120°C there is a significant difference between the actual and the theoretical values, especially when considering the flow rate (i.e. the maximum head was achieved, but the maximum rate was lower).

5.4.2 PIP Reduction and ALR Sensitivity Tests with 100% Oil

Originally the test matrix called for performing PIP reduction tests at: (1) the minimum temperature and (2) at 200°C. However, due to the instability problems observed at minimum temperature described in the previously, it was decided to use 120°C as the lowest reference temperature for the PIP reduction test.

ESP System (Woodgroup)

There were also some problems experienced in maintaining the required stable values of PIP and temperature during the PIP reduction at 200°C; therefore, PIP reduction data for the 100% oil tests were obtained only at the following conditions: 38, 46.5 and 55 Hz for 120°C; 55 Hz for 150°C; and 38 Hz for 180°C. The following table summarizes the set of initial conditions used for the PIP reduction tests:

T°C	Freq. (Hz)	Initial delta-P (kPa)	Initial Head (m)	Initial Flow Rate (m^3/d)
120	38	1,800 (261 psia)	206	540
	46.5	2,600 (377 psia)	302	640
	55	3,500 (508 psia)	405	770
150	55	4,160 (603 psia)	492	787
180	38	1,985 (288 psia)	240	550

Table 5.2 Starting Conditions (Flow Rate and delta-P) for PIP Reduction Tests with 100% Oil

Figure 5.9 shows the starting conditions in a head versus total flow rate graph. The idea was to try to start these tests at conditions close to the centre of the operational envelope for the pump.

The fact that the PIP reduction tests were not performed either at constant delta-P or at constant flow rate (but at constant valve opening) caused some difficulty in comparing results from different operating conditions. Therefore, to assist with the interpretation of the results, a new parameter "delta-P ratio" was defined as the ratio between the actual measured delta-P at a given PIP and the delta-P corresponding to the same rate, but at reference PIP. This ratio helps show performance degradation of the pump as the PIP is reduced on a "normalized" basis. Figure 5.10 helps illustrate how the "delta-P ratio" is calculated, and Figure 5.11 shows an example of this parameter as a function of PIP.

Figure 5.12 summarizes the results for all the PIP reduction tests with 100% oil in terms of the "delta-P ratio". Note how there is an increasing effect of PIP reduction as the PIP approaches water saturation conditions at each testing temperature (120, 150 and 180°C). Since the oil used for the testing had a flash point above 240°C, it is suspected that this reduction in pump performance may be due to traces of water present in the oil. This is an interesting observation: if this trend is valid for general conditions, then even a small amount of steam could cause a substantial reduction in pump performance.

The test program also called for performing ALR sensitivity tests at three frequencies at 180°C; however, after performing the test at 38 and 46.5 Hz, a small leak in a control valve late in the day required the shutdown of the flow loop. After observing that ALR values as high as 2.5 std m^3/m^3 for the 38 and 46.5 Hz tests did not produce any effect on the pump performance (Figure 5.13), it was decided to skip the test at 55 Hz and resume testing the following day at the next temperature level.

Additional air injection data (not included in the original test program) was obtained at 120°C, where a more evident effect of air injection on pump performance was recorded. Note that (as explained before) the reference initial conditions (delta-P and flow rate) for each temperature were different; therefore, the curves in Figure 5.13 should be used only to illustrate the effect of

ALR on pump performance for each condition and not for comparing performance results at two different temperatures.

Figure 5.13 shows that, for the oil tests at 180°C and high PIP, the effect of injected air on pump performance was small, indicating high gas/liquid separation efficiency at the target rates. At 120°C, the effect of air was somewhat more noticeable, indicating a negative effect of the higher viscosity on the separation efficiency. The results are presented again using the parameter "delta-P ratio" used for the interpretation of the PIP reduction data. Figure 5.14 shows the same set of results expressed in terms of GVF[9].

5.4.3 Pump Curves with Oil/Water Mixture

As reported above, at the initial water cut (around 70%), it appeared that a tight viscous emulsion was formed, which was causing operational problems. Therefore the water cut was increased, which allowed for much better pump performance and much lower pressure drops. The corresponding water cut for the rest of the tests ranged from 75 to 80%.

Pump curves with the oil/water mixture were created for 120, 150, 180 and 200°C. For 120 and 150°C, the tests were performed at 38 Hz. At 180°C, the reference frequency to obtain a flow rate of 650 m^3/d at a delta-P of 3,000 kPa (435 psi), was determined to be 44.7 Hz. At 200°C, the reference frequency to obtain 800 m^3/d at 435 psi (3,000 kPa) of delta-P was determined to be 48.2 Hz.

Since the tests at 120 and 150°C were both performed at 38 Hz, it is possible to compare the results at these two temperatures, as shown in Figure 5.15 (delta-P versus Q) and Figure 5.16 (head versus Q). In both cases, the pump performance curve with oil at 200°C was included as a reference for a fluid of known viscosity (7 cP). Note that, as shown in Figure 5.16, the pump curves collapse to a cluster.

The results for 180 and 200°C are at different frequencies; therefore, the performance as a function of temperature is more difficult to compare for these temperatures. These results are presented in Figure 5.17 (delta-P versus Q) and Figure 5.18 (head versus Q).

5.4.4 PIP Reduction Tests and ALR Sensitivity Test with Oil/Water Mixture

Figure 5.19 illustrates the modified starting conditions for the PIP sensitivity tests with the oil/water mixture.

The starting delta-P and rates for 180 and 200°C remained as per the original matrix (650 m^3/d and 800 m^3/d, and 3,000 kPa); and the corresponding frequencies, F(180) and F(200), were determined experimentally.

---

[9] Note that the GVF was based on the following assumptions: the air behaves as an ideal gas, the air is at the same temperature as the liquid, and no water is present

ESP System (Woodgroup)

However, due to the limitations of the pump operational range described in Section 5.3.1, the tests for 120 and 150°C were both performed at 38 Hz, and in both cases a reference flow rate of 425 m^3/d (the rate originally corresponding to 150°C) was used. The starting delta-P was determined experimentally, based on the head of the ESP at 38 Hz for that rate (425 m^3/d) at each temperature.

The following table summarizes the modified reference conditions for the oil/water mixture tests:

T°C	Frequency (Hz)	Reference PIP (kPa, a)	Reference delta-P (kPa)	Ref Flow Rate (m^3/d)
120	38	899 (130 psia)	determined experimentally	425
150	38	1,178 (171 psia)	determined experimentally	425
180	determined experimentally	1,707 (248 psia)	3,000 (435 psia)	650
200	determined experimentally	2,262 (328 psia)	3,000 (435 psia)	800

Table 5.3 Modified Conditions for Tests with Oil/Water Mixture

Figure 5.20 summarizes the effect of PIP reduction on pump performance for all temperatures, with and without air injection. The minimum PIP remained very close to saturation pressure for all temperatures without air. However, there was a significant effect of air injection on the performance, evidenced by deterioration of performance at pressures above the saturation pressure. This supports the theory that the presence of gas reduces the partial pressure of the steam, producing evaporation at pressures above saturation conditions.

Figure 5.21 shows an example of the behaviour of the variables during the PIP reduction test (at 180°C, 44.7 Hz), in order to illustrate the increased instability in pump performance without air. Notice the fluctuations in the delta-P that defined the minimum PIP limit.

Referring to Figure 5.22 and Figure 5.23, note that there was little apparent effect of the injected air (and temperature) in the pump performance (for the oil-water mixture) at 120 and 150°C. The performance curve with 100% oil at 200°C and 38 Hz was included as a reference. Note how all the curves obtained at 38 Hz collapse in a single cluster when expressed in terms of head[10] (Figure 5.23). As shown in Figure 5.24 and Figure 5.25, the effect on performance is slightly larger at higher temperatures (180 and 200°C), which were at slightly lower mixture viscosity and higher flow rates, likely allowing for increased entrainment of air in the liquid stream.

However, it should be noted that these performance plots are based on averaged test data (typically a ~2 minute period), and this masks another important difference in the test performance with and without air, that being operational stability. For example, at 180°C,

[10] Head was calculated using the formula: $h = \Delta P/(\rho * g)$, using the density reading from the Coriolis meter downstream of the pump discharge.

maintaining a constant air injection rate was difficult, especially at high gas rates. This was mainly due to surging in the liquid flow rate, which produced variations in the pump intake, pump discharge and separator pressures. Figure 5.26 illustrates the fluctuations in the test variables, especially at high liquid rates and low PIP values.

In Figure 5.27, error bars (based on one standard deviation) have been included to illustrate the difference in stability between tests with air and without air injection at 180ºC. Figure 5.28 and Figure 5.29 show a similar comparison, at 200°C. The data suggest that the stability of the pumping system should also be taken in to consideration when assessing suitability, as it may have an impact on long term pump performance and run life expectation.

Note that at 180 and 200°C (at reference flow rate and intake pressure), an ALR of 0.9 could not be achieved due to booster capacity limitations. The following table summarize the average ALRs during the pump performance and PIP reduction tests with air injection:

T°C	Freq. (Hz)	Avg. ALR during Pump Performance Test (m^3/m^3)	Avg. ALR during PIP Reduction Test (m^3/m^3)
120	38	0.90	0.95
150	38	0.90	0.92
180	44.7	0.78	0.70
200	48.2	0.61	0.61

Table 5.4 Average ALR for Tests with Oil/Water Mixture

Finally, a test with increasing ALR levels was conducted at 180°C. At the start of this test, air injection was stopped to obtain the reference starting point. For this test, the air injection rate was "ramped up", (trying to maintain PIP as constant as possible), as shown in Figure 5.30. The air injection did not have a considerable effect on the pump performance up to an ALR = ~0.72. However, upon increasing ALR further, pump operation became unstable and the delta-P and flow rate decreased dramatically. Stability could not be restored.

During this test, it was observed that the flow of injected air was considerably affected by the cycling of the air supply compressor. An attempt was made to bypass some air from the booster, to enable the booster to remain "on" at all times; however, this was not successful. Since there was concern that the surging and flow rate instability could damage the motor of the ESP (preventing testing at 200°C), a decision was made to slowly decrease the ALR and conclude this portion of the test. Figure 5.30 shows that the pump performance recovered when the ALR was reduced and approached a value of ~0.89 m^3/m^3.

5.4.5 Post-test Observations

The WG system was visually inspected after removal from the flow loop. There was nothing unusual to report.

5.5 Conclusions

- The test program was successfully completed with the 100% oil. During testing with the oil/water mixture a downhole seal failed, requiring a pull and re-assembly of the pumping system. The system was subsequently re-installed, and the test program with oil/water mixture was completed.

- During the oil tests, the effect of the viscosity on reducing the pump volumetric capacity was larger than that predicted by the Vendor's viscosity correction factors.

- At lower temperatures there was a noticeable effect of air on pump performance, suggesting that the higher oil viscosity negatively affected gas separation efficiency.

- Minimum PIP values for oil/water mixtures and no air were very close to the saturation pressure (less than 5 psi), with moderate deterioration in rate and delta-P capacity (based on average values). The criteria to stop the PIP reduction was the stability of the ESP, rather than the flow rate limit specified by the vendor (350 m^3/d).

- The air injection had a negative effect on the minimum PIP achieved at all temperatures. This supports the theory that the presence of gas reduces the partial pressure of the steam, producing evaporation at pressures above saturation conditions. In addition, for the higher flow rates handled during testing, the air injection produced much more instability in the pump performance.

ESP System (Woodgroup)

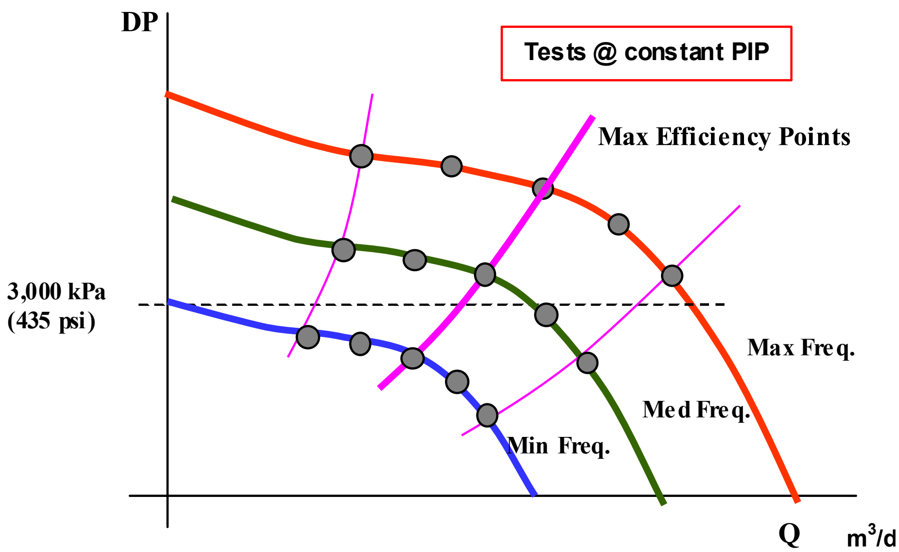


Figure 5.1 WG - Illustration of Testing Points

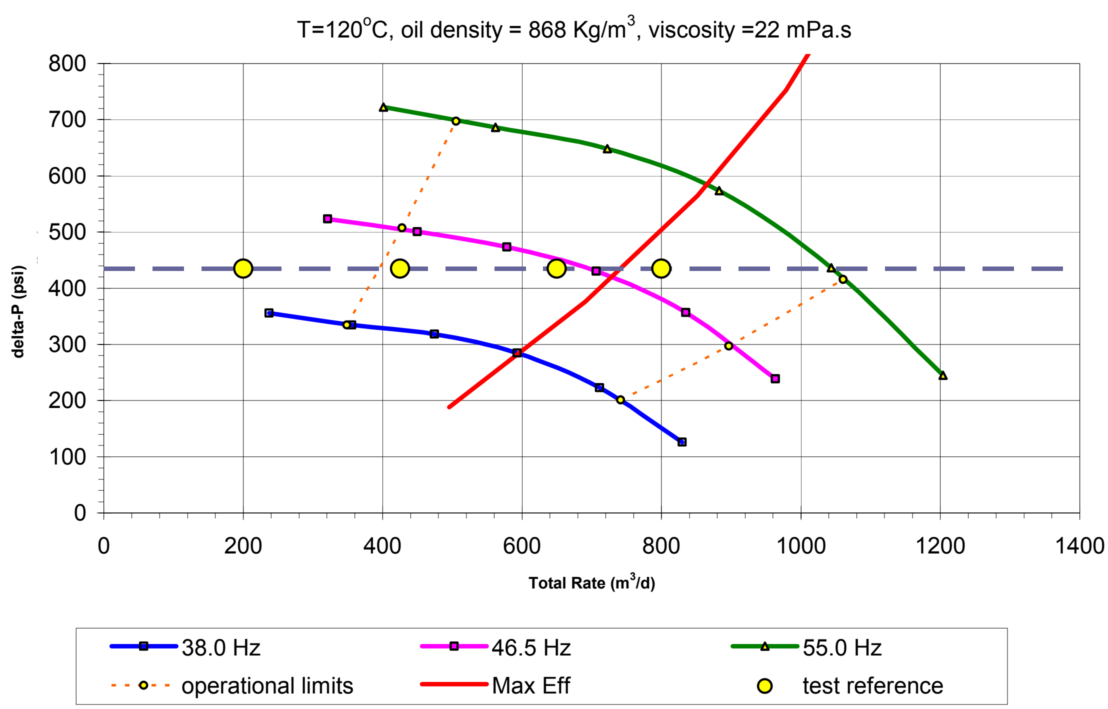


Figure 5.2 WG - Reference Rates

ESP System (Woodgroup)

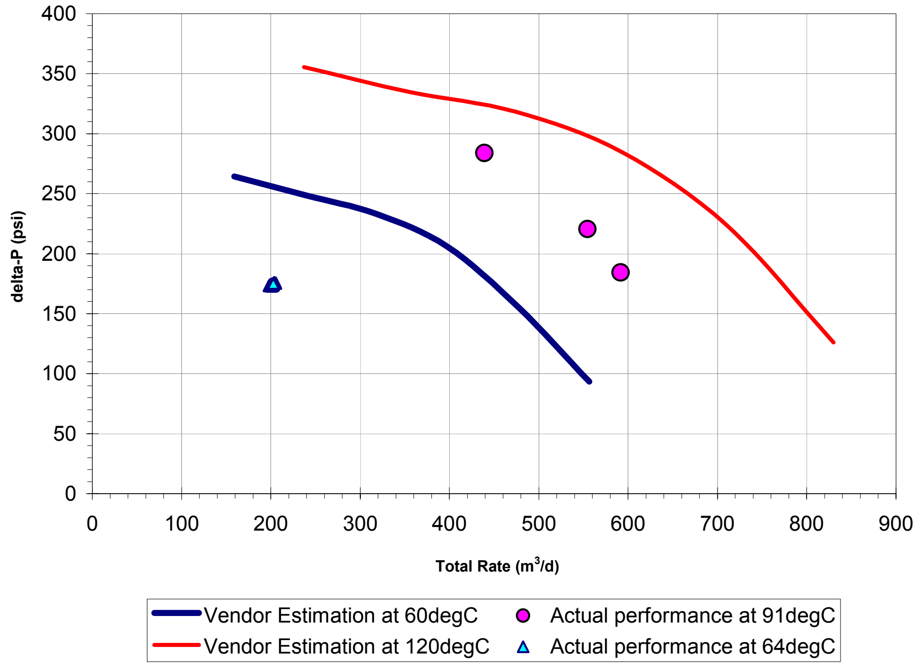


Figure 5.3 WG - Pump Performance with 100% Oil at Low Temperature

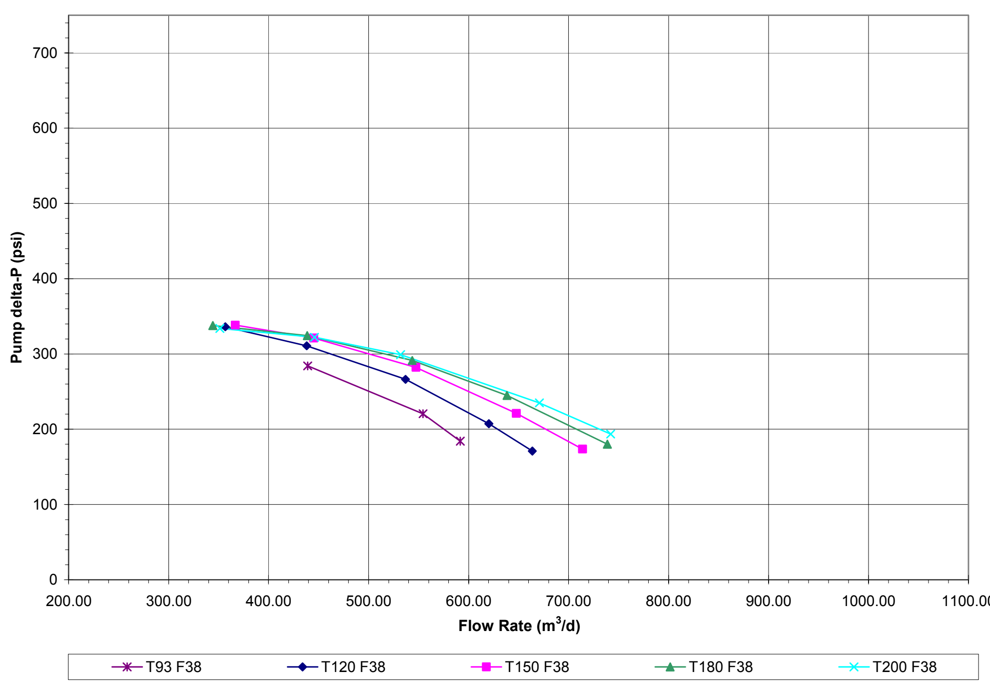


Figure 5.4 WG - Pump Curves at 38 Hz with 100% Oil

ESP System (Woodgroup)

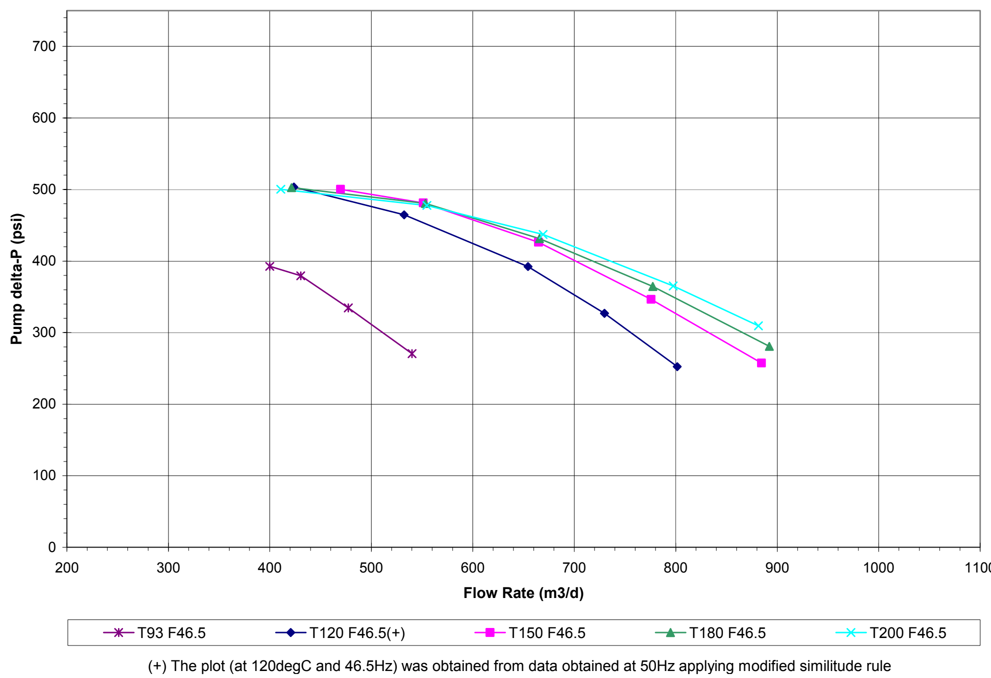


Figure 5.5 WG - Pump Curve at 46.5 Hz with 100% Oil

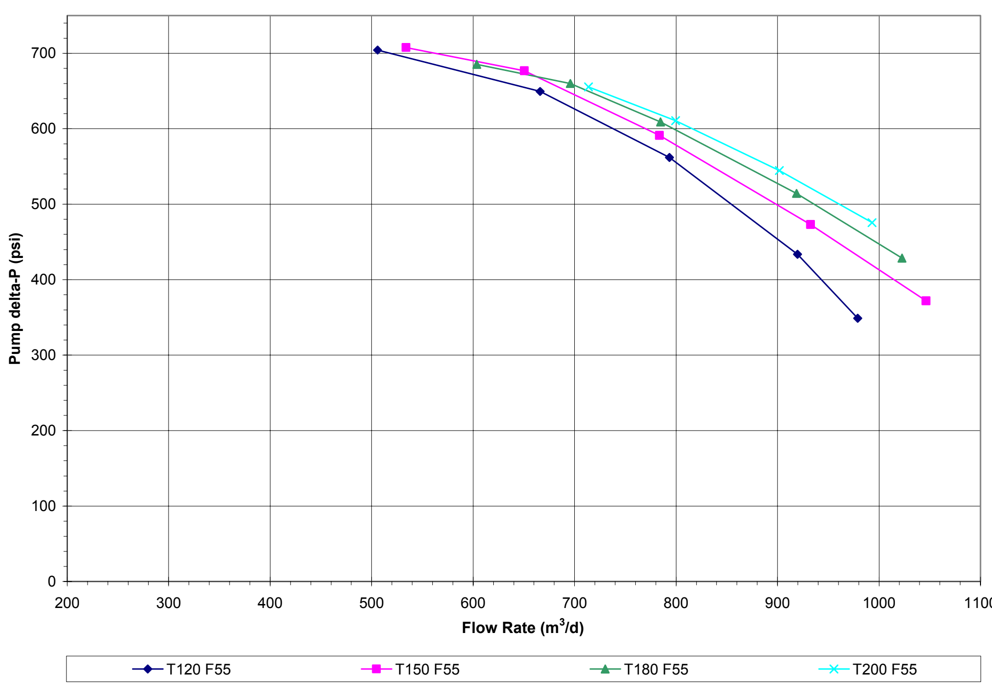


Figure 5.6 WG - Pump Curve at 55 Hz with 100% Oil

ESP System (Woodgroup)

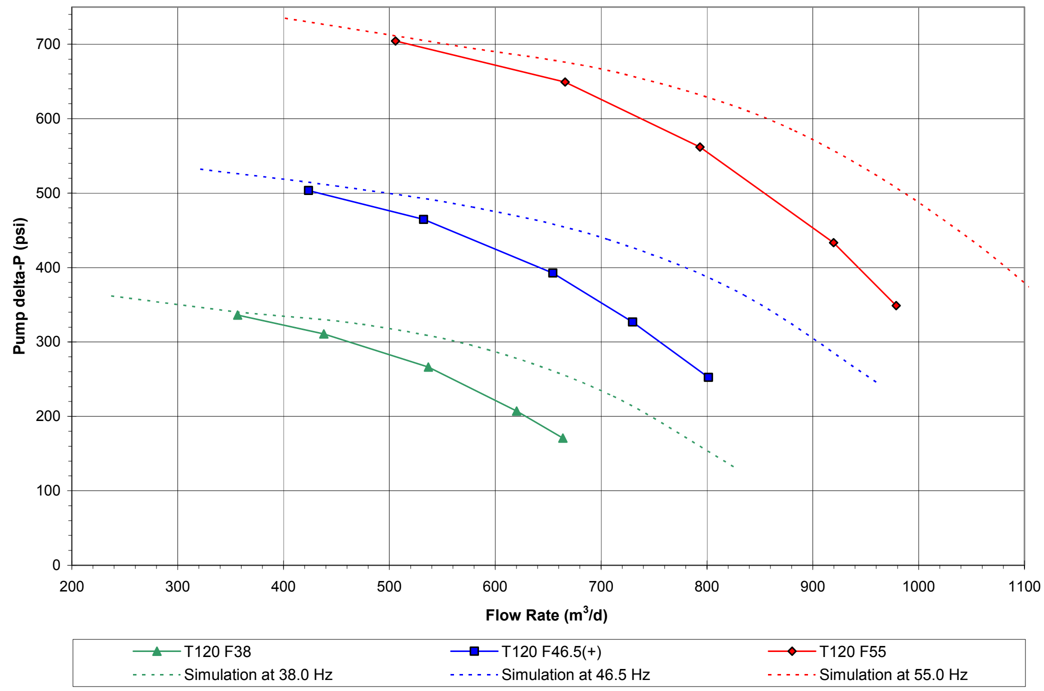


Figure 5.7 WG - Comparison of Actual Performance with 100% Oil to Simulations at 120°C

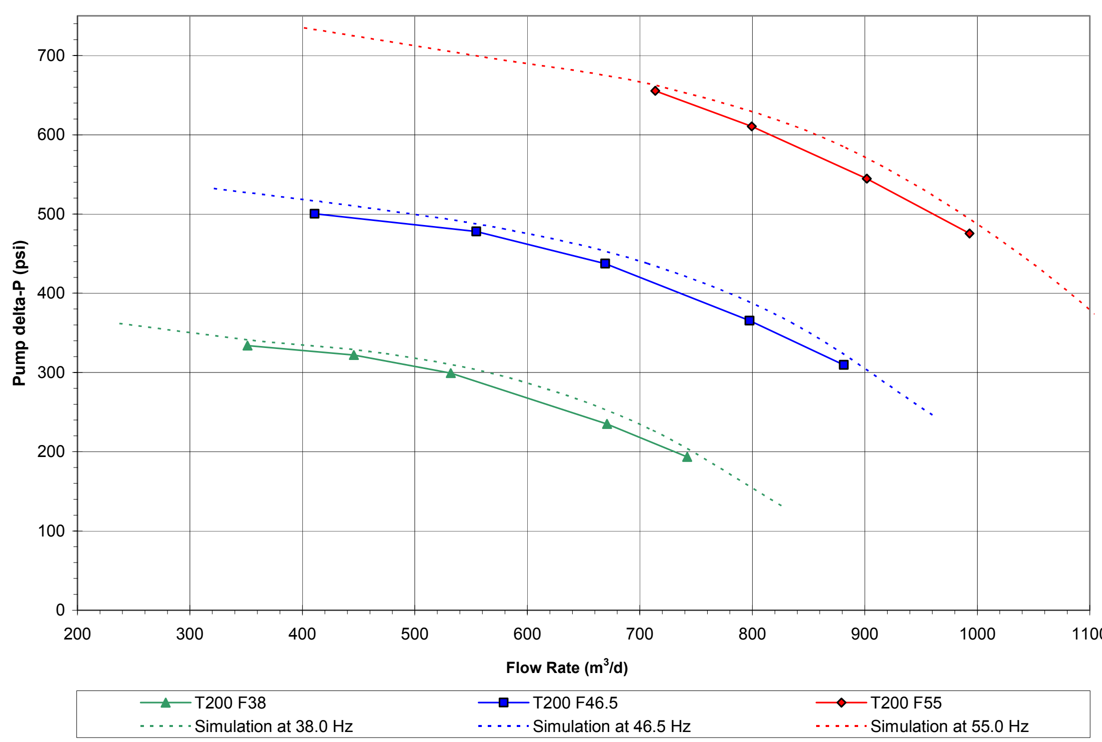


Figure 5.8 WG - Comparison of Actual Performance with 100% Oil to Simulations at 200°C

ESP System (Woodgroup)

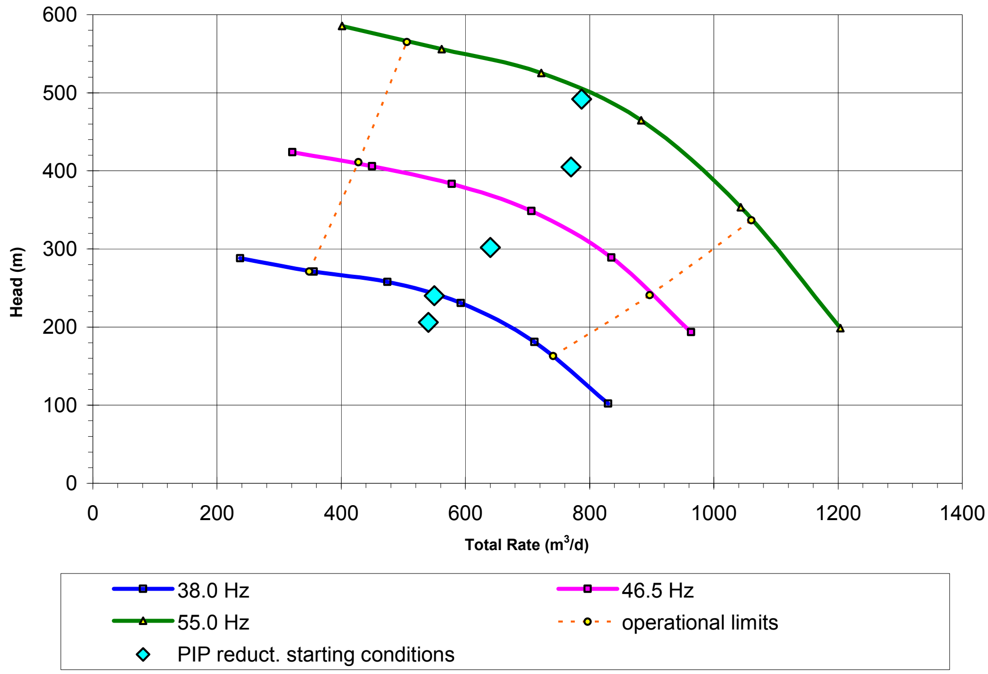


Figure 5.9 WG - Starting Conditions for PIP Reduction Tests with 100% Oil

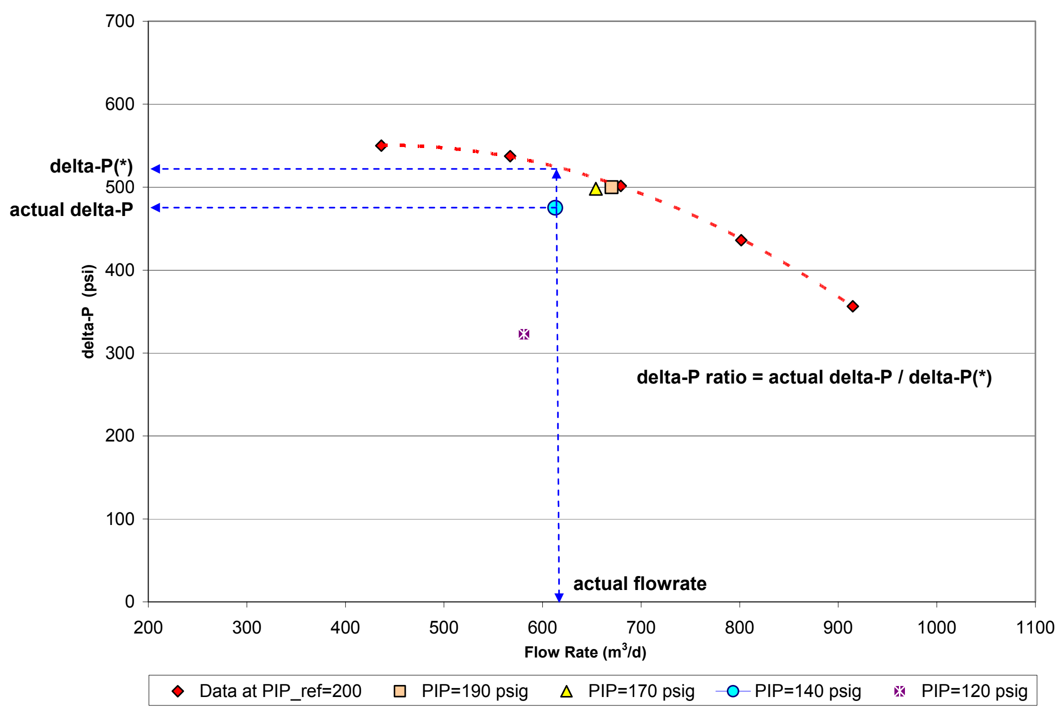


Figure 5.10 WG - Schematic Showing Calculation of “delta-P Ratio”

ESP System (Woodgroup)

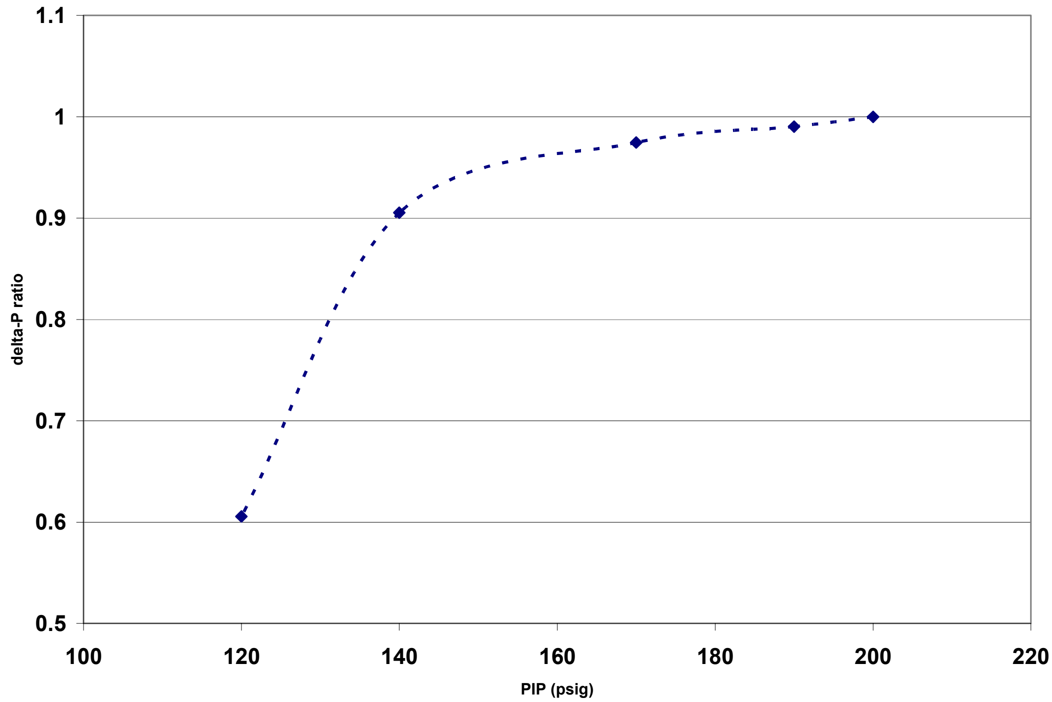


Figure 5.11 WG - Schematic of Example Result using "delta-P Ratio" Versus PIP Reduction

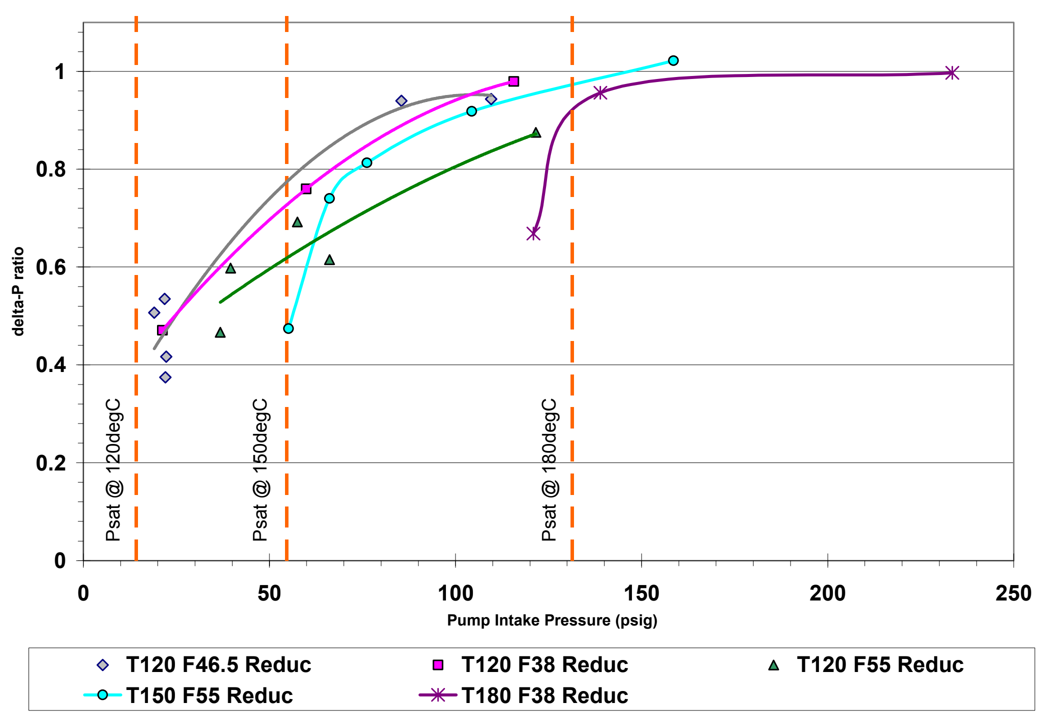


Figure 5.12 WG - PIP Reduction Test Results with 100% Oil

ESP System (Woodgroup)

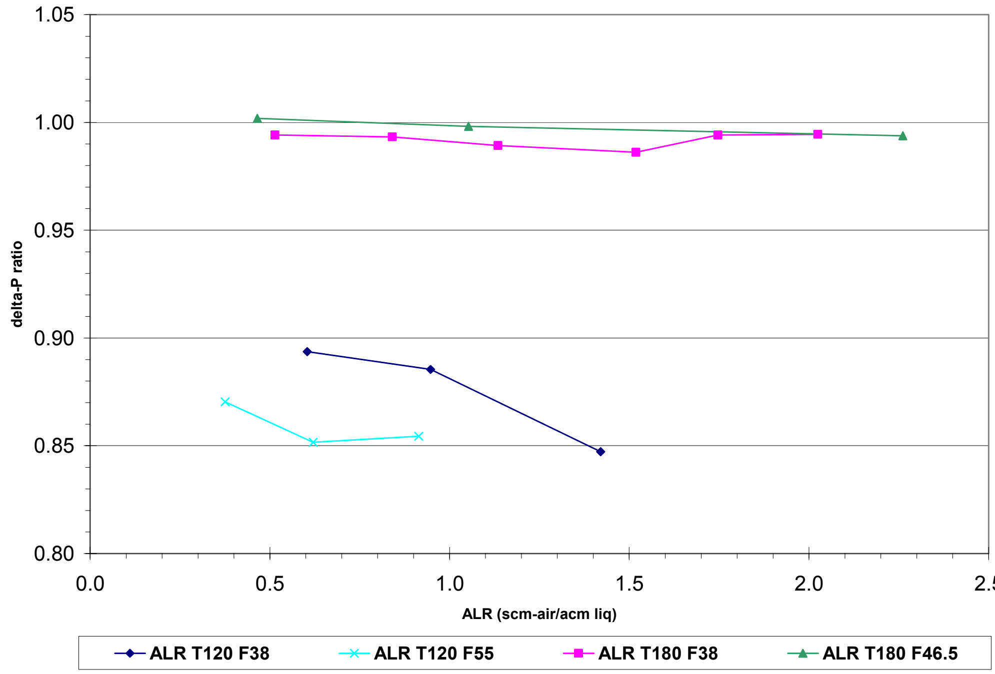


Figure 5.13 WG - Effect of Increasing ALR for 100% Oil Tests

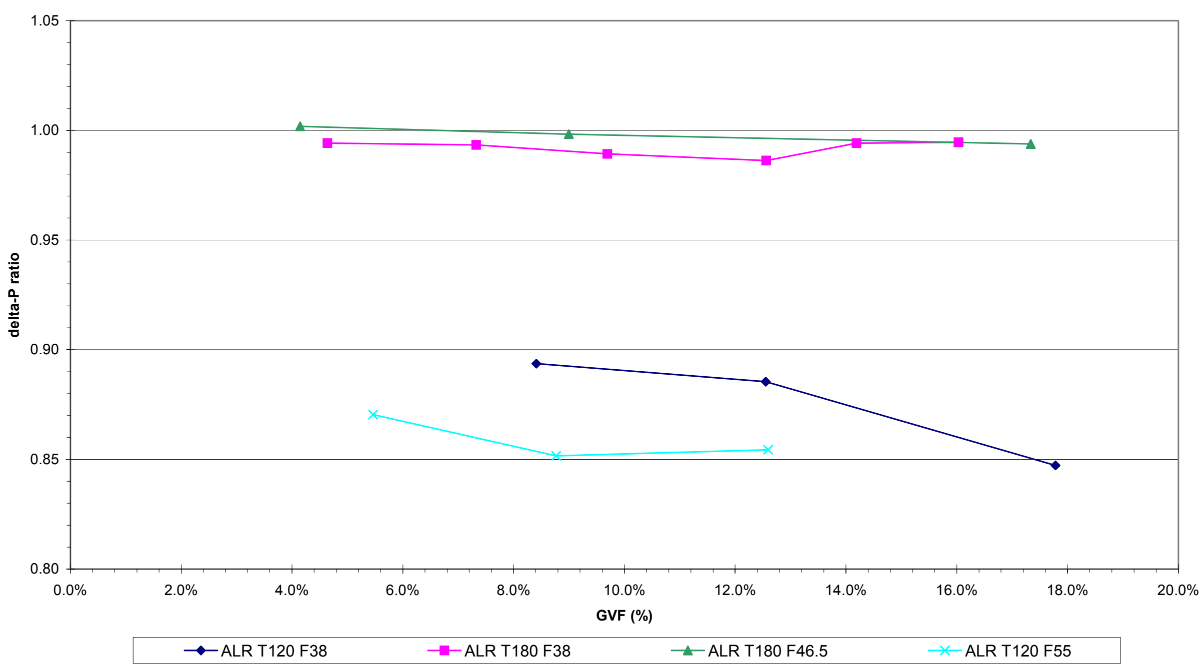


Figure 5.14 WG - Effect of Increasing ALR for 100% Oil Tests (as a function of GVF)

ESP System (Woodgroup)

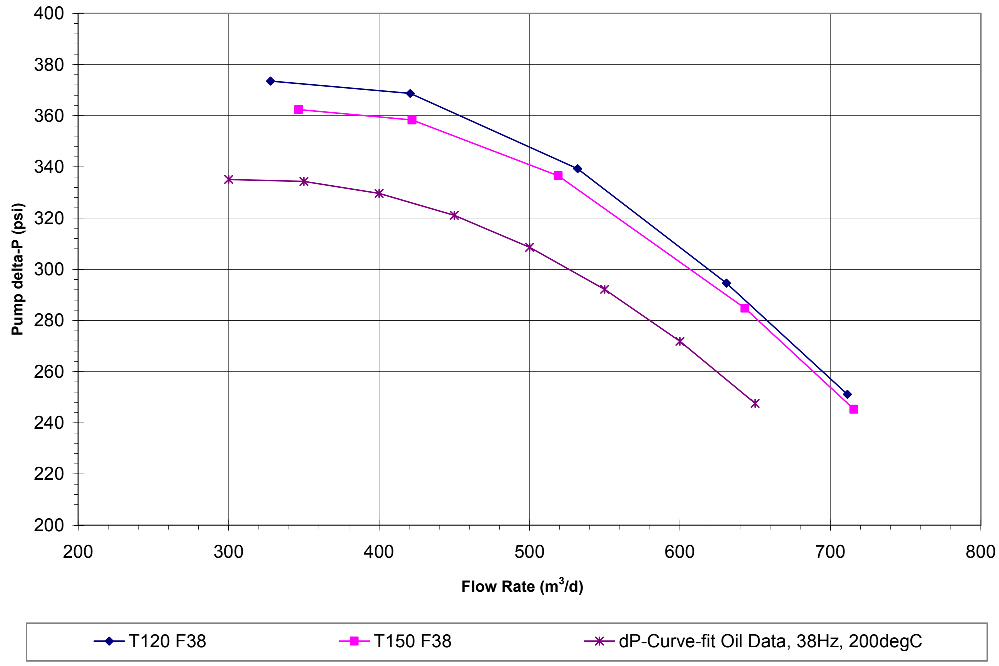


Figure 5.15 WG - Comparison of Pump Curves with Oil/Water Mixture at 120°C and 150°C (delta-P)

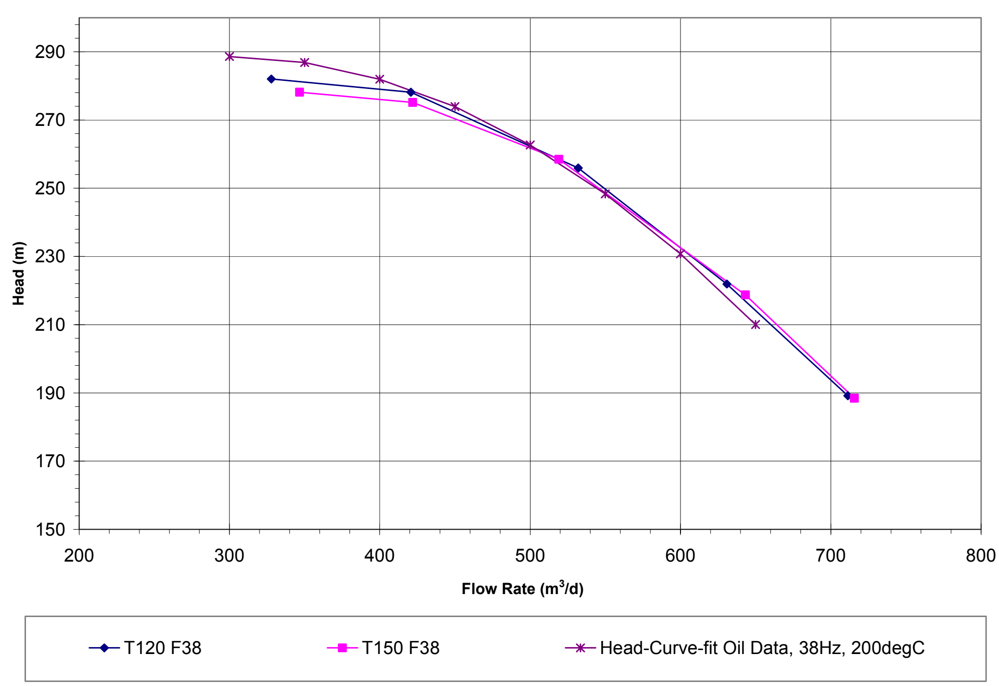


Figure 5.16 WG - Comparison of Pump Curves with Oil/Water Mixture at 120°C and 150°C (Head)

ESP System (Woodgroup)

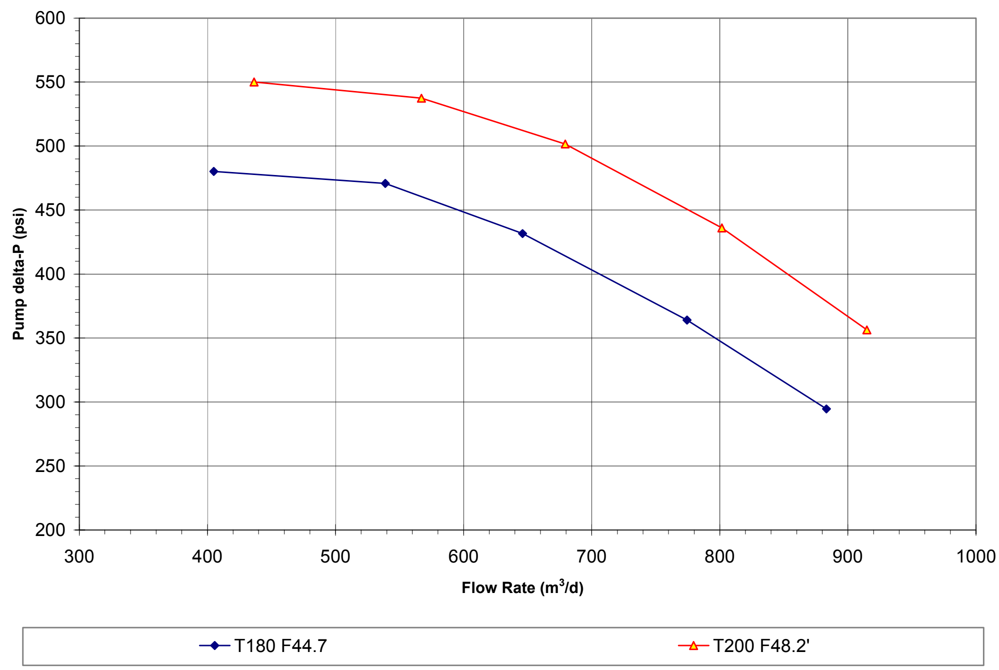


Figure 5.17 WG - Comparison of Pump Curves with Oil/Water Mixture for 180°C and 200°C (delta-P)

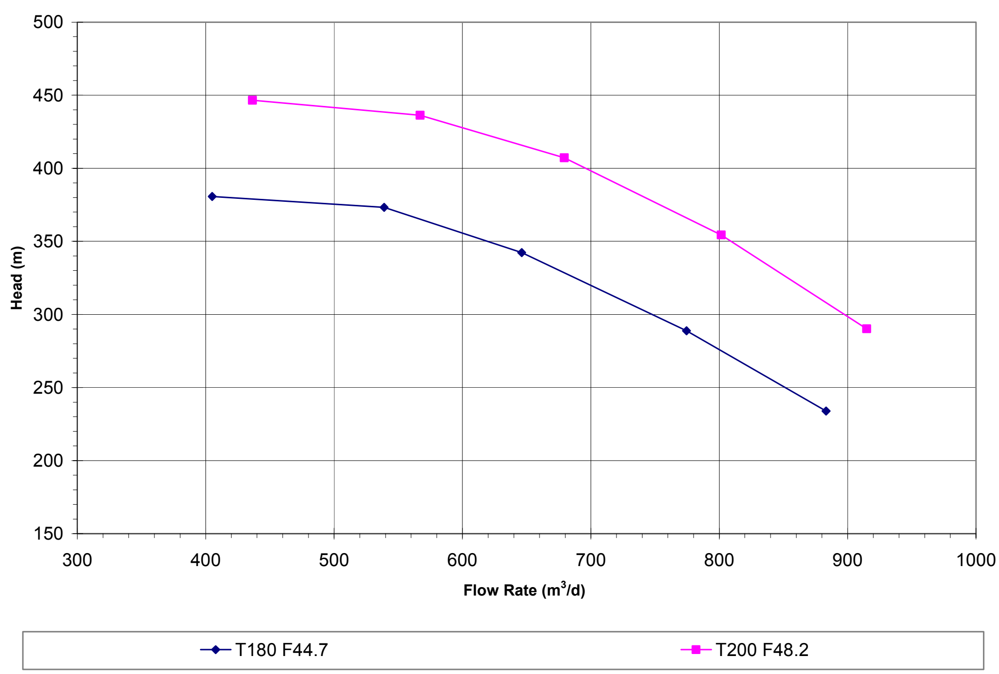


Figure 5.18 WG - Comparison of Pump Curves with Oil/Water Mixture for 180°C and 200°C (Head)

ESP System (Woodgroup)

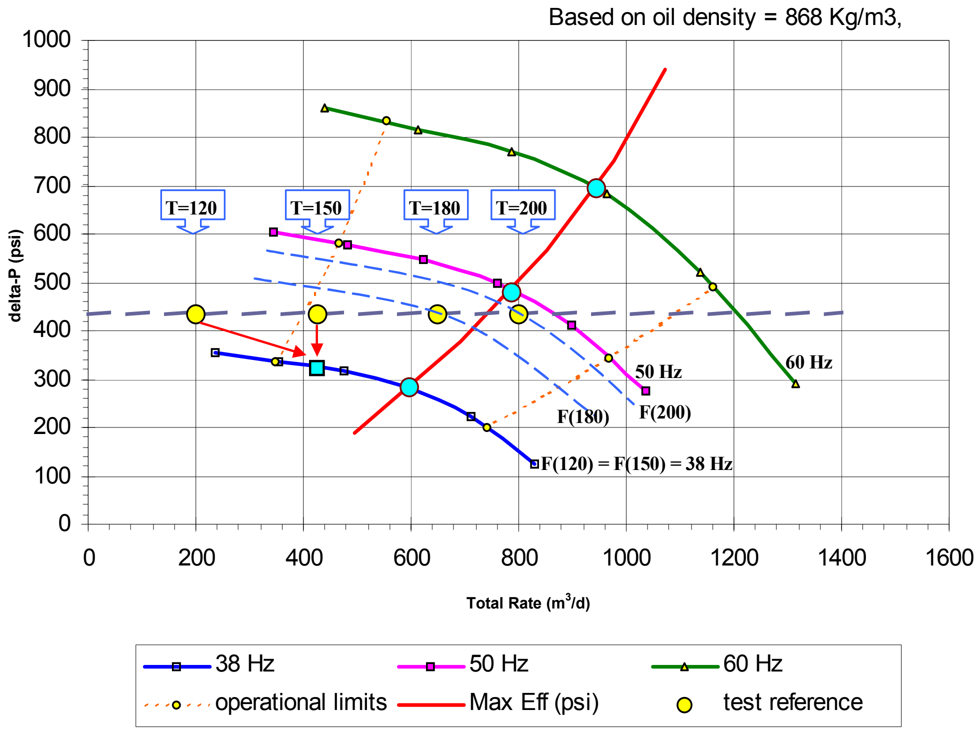


Figure 5.19 WG - Modified Reference Conditions for PIP Sensitivity Test with Oil/Water Mixture

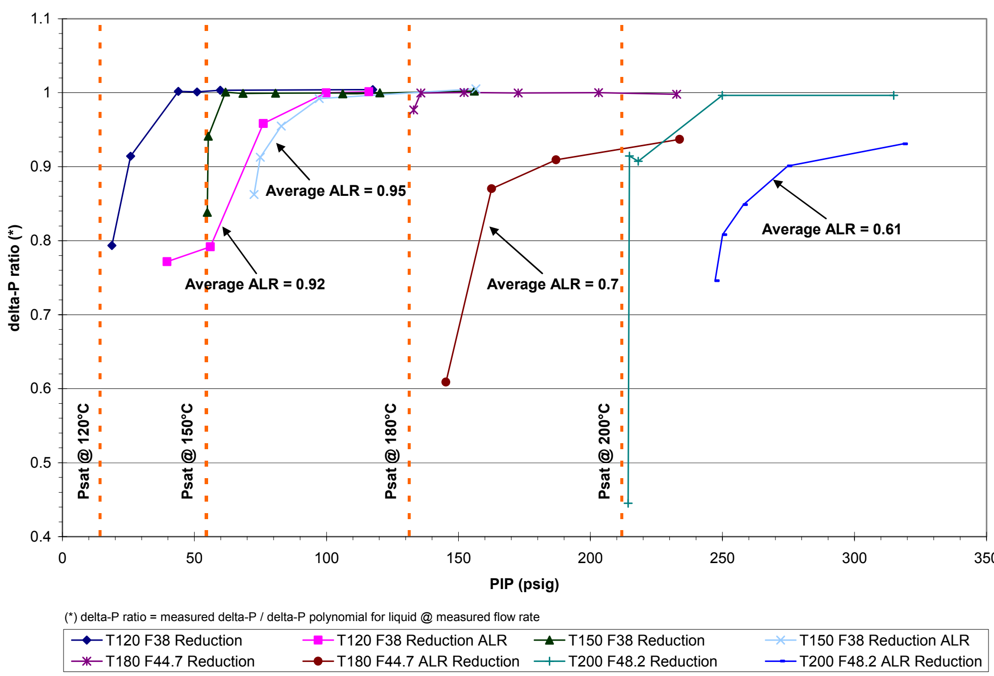


Figure 5.20 WG - PIP Reduction Performance with Oil/Water Mixture for All Temperatures

ESP System (Woodgroup)

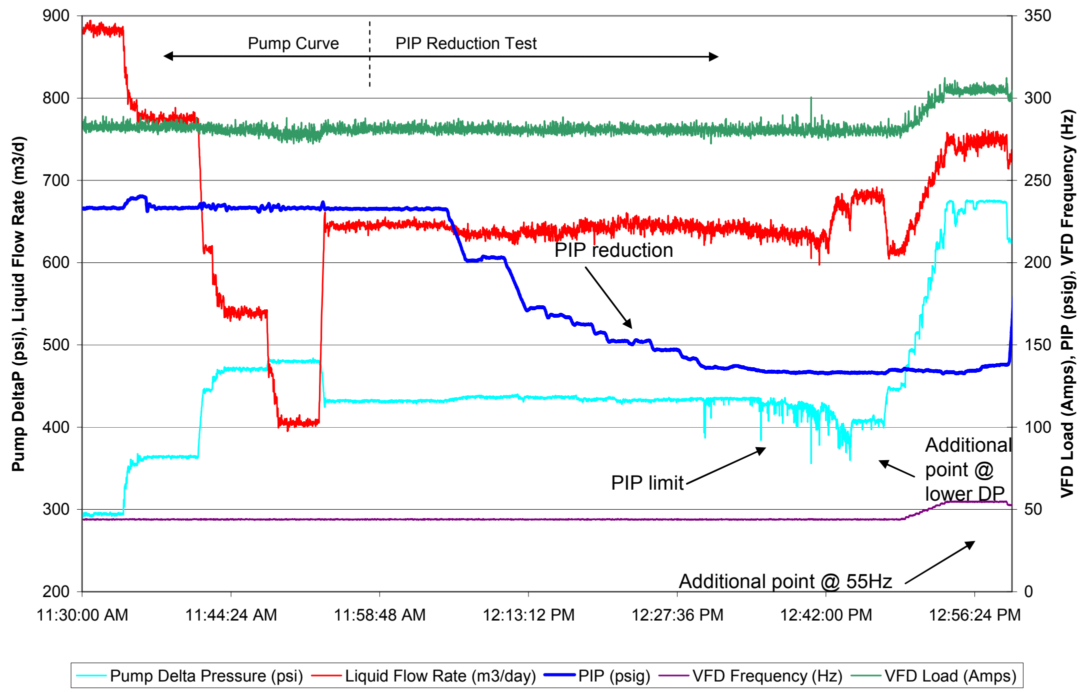


Figure 5.21 WG - Example of the Behaviour of the Variables with Oil/Water Mixture during a PIP Reduction Test

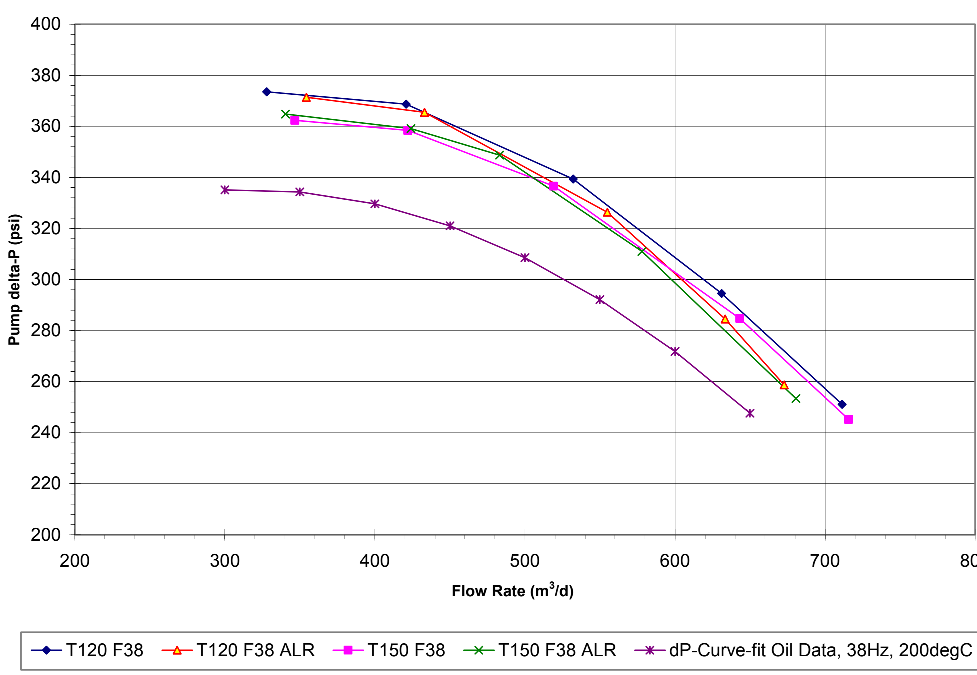


Figure 5.22 WG - Effect of Air with Oil/Water Mixture at 120ºC and 150ºC on Pump delta-P

ESP System (Woodgroup)

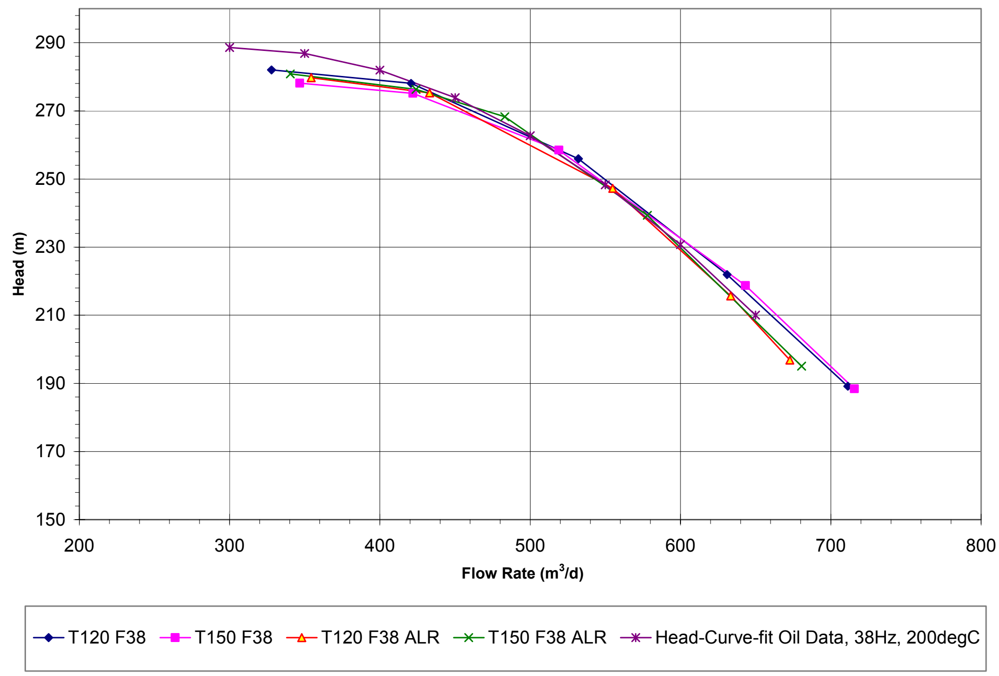


Figure 5.23 WG - Effect of Air with Oil/Water Mixture at 120°C and 150ºC on Head

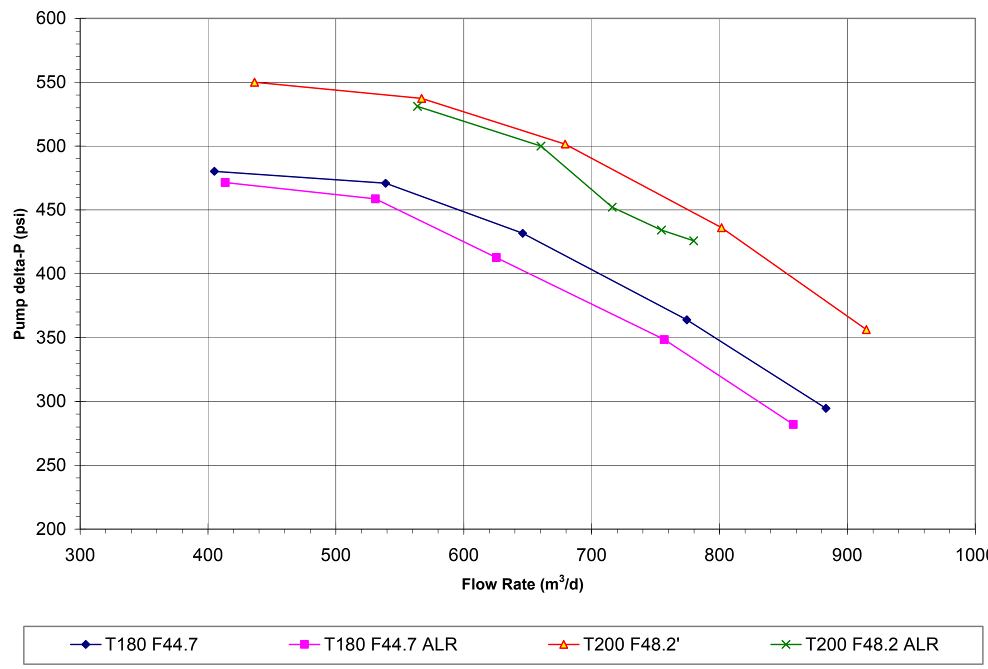


Figure 5.24 WG - Effect of Air with Oil/Water Mixture at 180ºC and 200ºC on Pump delta-P

ESP System (Woodgroup)

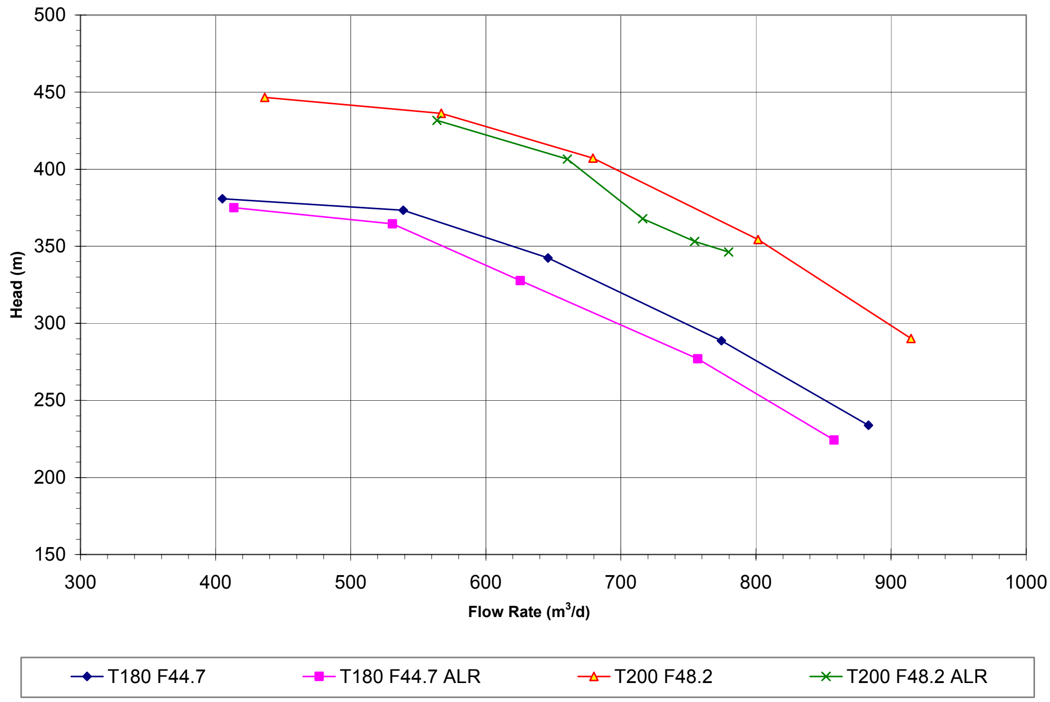


Figure 5.25 WG - Effect of Air with Oil/Water Mixture at 180ºC and 200ºC on Head

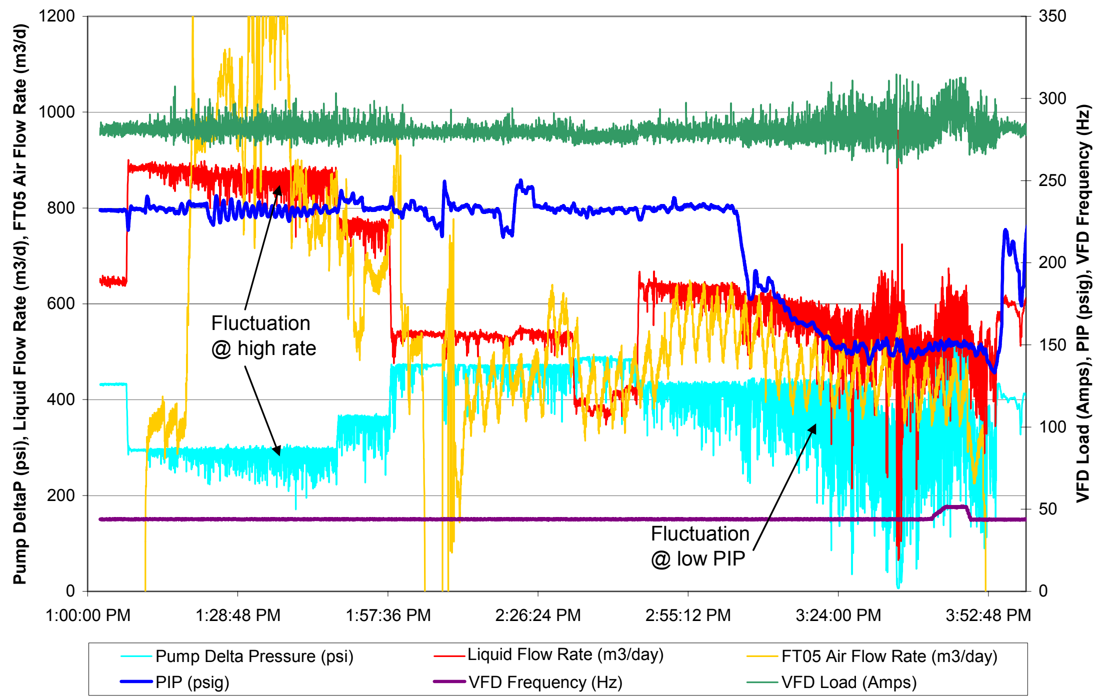


Figure 5.26 WG - Fluctuations in the Variables with Oil/Water Mixture at High Liquid Rates and Low PIP Values at 180ºC

ESP System (Woodgroup)

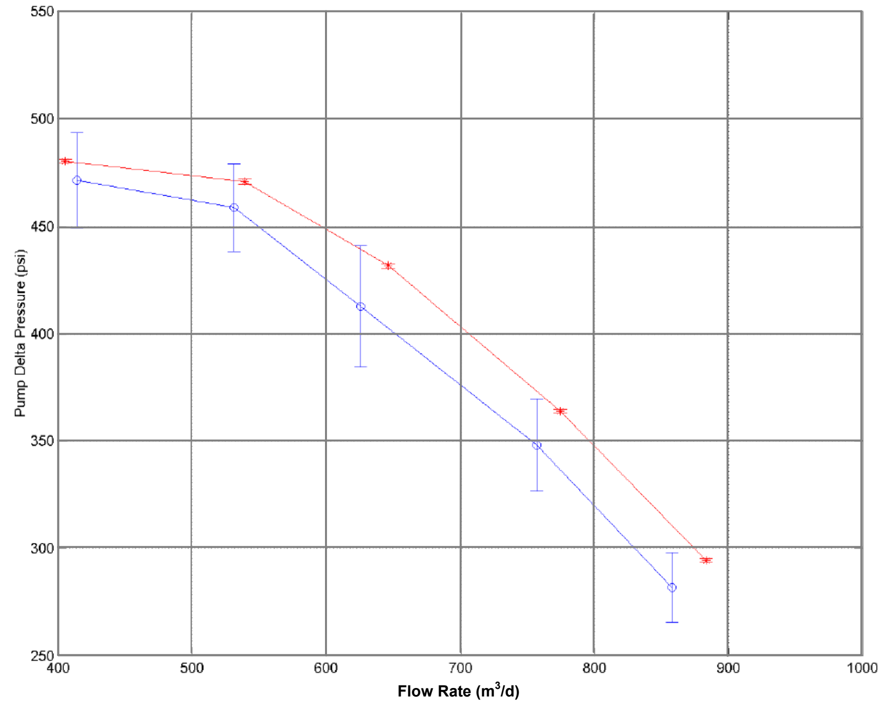


Figure 5.27 WG - Comparison of Air Versus no Air Injection with Oil/Water Mixture at 180°C

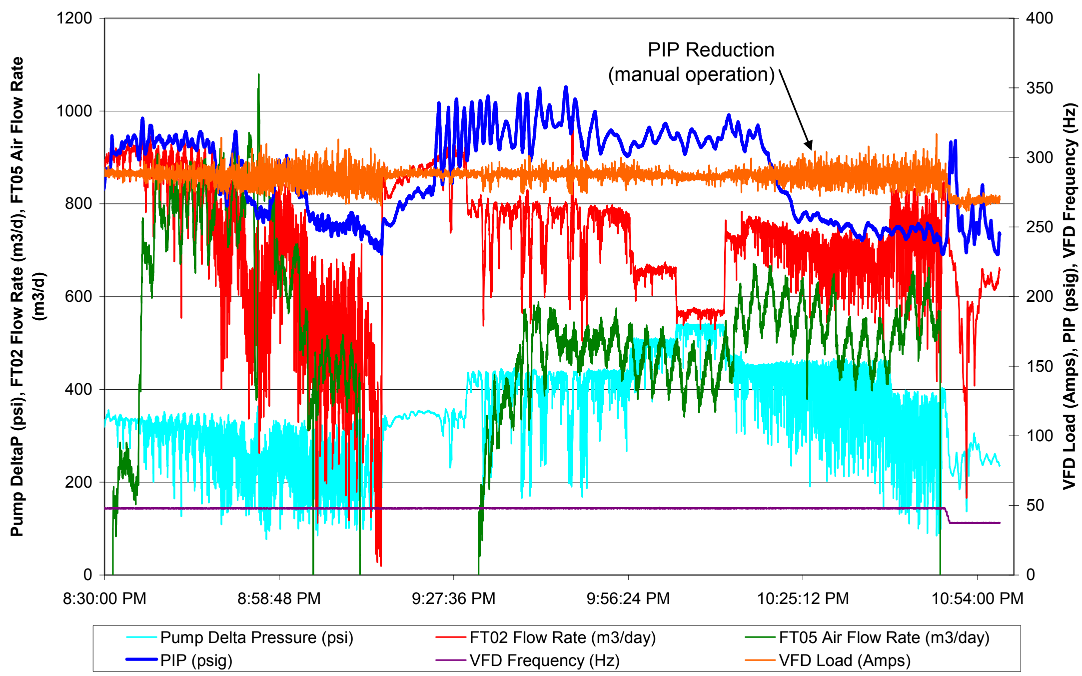


Figure 5.28 WG - Instability of the System during Air Test with Oil/Water Mixture at 200°C

ESP System (Woodgroup)

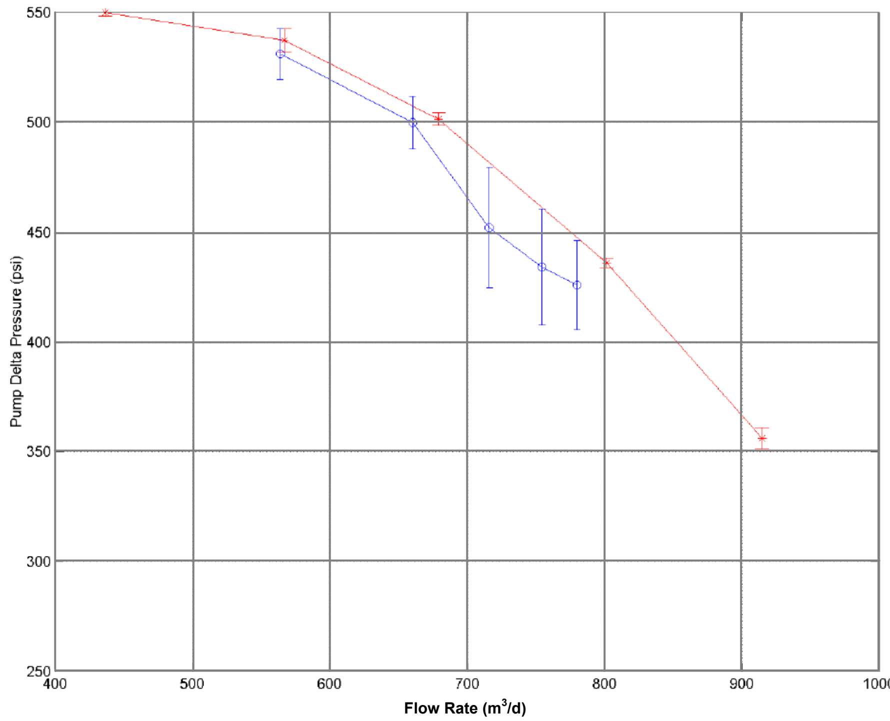


Figure 5.29 WG - Pump Performance Comparison with and without Air with Oil/Water Mixture at 200°C

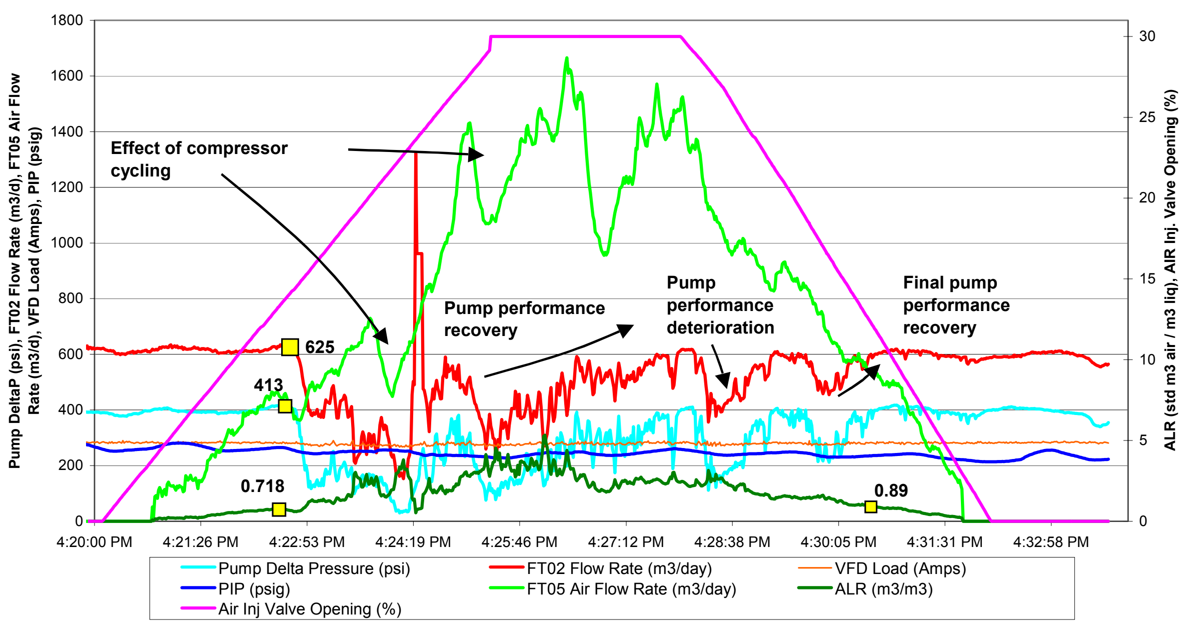


Figure 5.30 WG - History Plot of Increasing ALR Test with Oil/Water Mixture

6. PCP SYSTEM WITH METAL STATOR (KUDU)

6.1 System Description and Technical Specifications

KUDU provided the following components for testing:

- Surface Horizontal Drive Unit
    - 32 mm (1-1/4-inch) hollow shaft hydraulic motor;
    - Integral packing style stuffing box with a working pressure rating of 6,894 kPa (1,000 psi) @ 200°C;
    - Bottom flange connection: 79 mm (3-1/8 inch) x 3,000 psi flange with R-31 ring gasket.
- 550MET675 Pump Stator
    - Published pump capacity: 110 m^3/d at 100 RPM[11];
    - Maximum discharge head: 675 m of water (~960 psi);
    - Housing OD: 115 mm (4.52 inches);
    - Pump length: approximately 9 m (29.5 ft); and
    - Connections: 102 mm (4-inch) NU.
- Rotor (Part# 550MET675)
    - Connection size: 29 mm (1-1/8-inch) box;
    - Maximum speed: 350 RPM; and
    - Length: 9.0 m (29.5 ft).
- Polish Rod
    - 32 mm (1-1/4 inch) 4140 polish rod with 22 mm (7/8-inch) threaded pin connection.

6.2 Installation and Commissioning

C-FER completed installation of the pumping system into the flow loop on May 12, 2005. No major difficulties were encountered during the installation.

[11] Note that the "published" volumetric capacity for the pump was 1.10 m^3/d per RPM. However, a test of the same model of pump at KUDU's test bench showed an actual volumetric capacity of 1.1973 m^3/d per RPM. This value was used as reference for analysis of volumetric efficiency.

PCP System with Metal Stator (KUDU)

C-FER provided the hydraulic power for the drive, rod and tubing string, and drain line for the drive case drain. Encana provided the same bottom-feeder intake that was used for the Netzsch test. RGI again provided three rod centralizers for use during testing.

KUDU provided a series of actual torque measurements for the hydraulic motor, and C-FER developed a correlation to calculate the shaft torque from the delta-P (at the hydraulic motor) and the shaft speed (monitored through a magnetic pick-up).

After filling the loop with oil, an initial attempt to start the pump was made. However, the required start-up torque appeared to be extremely high, to the point that it was not possible to rotate the polished rod even with the maximum torque value specified by KUDU.

Some troubleshooting was conducted, in conjunction with KUDU, to try to find possible sources of the apparent high torque level. The wellhead drive components were removed and examined, but no misalignment or excessive friction of the components was observed. When manual torque was applied to the drive rods, there was some rotation in the rods which disappeared when torque was released, indicating that there was likely no restriction above the pump.

Subsequently, the maximum delta-P of the hydraulic power skid was increased and another attempt was made to move the rotor using the hydraulic motor. This time it was possible to rotate the pump slowly (at 40 to 70 RPM) and production was detected at the mass flow meter located at the pump discharge. According to the correlation derived from KUDU's data, the torque was still far too high, nearly 2,712 N-m (2,000 ft-lbs); therefore, this operation was maintained only for very short periods.

To aid in troubleshooting, KUDU performed a bench test on the same-model PCP (with water at room temperature) at their shop in Calgary. They observed a starting torque of between 542 to 678 N-m (400 to 500 ft-lb), which was higher than they expected, but only a fraction of that was observed by C-FER.

Published data for the hydraulic motor from the manufacturer was located by C-FER, and it was found that the torque versus delta-P curves were much lower than the values provided by KUDU. Using the data from the published charts, the start-up torque observed was very close to the values reported for KUDU's bench test. Therefore, a decision was taken (in conjunction with KUDU) to disregard the data previously provided and to use the torque versus delta-P curves from the published charts. All the values of torque recorded in the report are based on the data published by the manufacturer of the hydraulic motor.

Figure 6.1, Figure 6.2 and Figure 6.3 show the initial attempts to start the PCP. Using the published curves, the original breakout torque was about 597 N-m (440 ft-lb). As shown in Figure 6.2, there was initially a cyclic variation in the torque +/-41 N-m (+/-30 ft-lb) which did not have a direct correlation to the rotational speed of the pump. Most of the amplitude of the torque fluctuation faded away after a few minutes, being reduced to about +/- 4.1 N-m (+/-3 ft-lb) (see Figure 6.3).

PCP System with Metal Stator (KUDU)

6.3 Experimental Program

6.3.1 Test Matrix

After discussions with the SC Chairman and the Vendor, C-FER implemented some minor changes to the experimental program for KUDU, versus the test programs for Netzsch and Woodgroup, as follows:

- The minimum acceptable controllability criteria for PIP (during the generation of the data for the pump curves at reference PIP) was relaxed from +/- 7 kPa (1 psi) to +/- 20 kPa (3 psi), since previous tests showed that small variations on PIP have minimal effect on the pump performance during the tests at high PIP .

- The test matrix for 100% oil was changed somewhat, mainly to allow more time to be spent in testing with the oil/water mixture:

  - Obtain test data at 60, 150 and 200°C only (eliminate 120 and 180°C).

  - During the flow loop heating process, keep the PCP turned on, while maintaining the reference delta-P (3,000 kPa), to allow for some characterization of the slippage as a function of temperature and viscosity.

  - Limit testing to only 2 RPMs at 60 and 150°C, and 3 RPMs at 200°C.

  - An additional PIP reduction test was included for the oil test with ALR = 0.905 (only at 150°C) to allow for comparison to the same test with the oil/water mixture.

- For the oil/water mixture tests, the reference flow rate range established for testing (i.e. from 200 m^3/d at 120°C to 800 m^3/d at 200°C) could only be met at 120°C due to the RPM limitations for the KUDU pump. At all higher temperatures, the rate was limited by the maximum speed (350 RPM). Therefore, it was decided to perform **all** of the oil/water mixture tests at the same speed of 350 RPM.

KUDU also specified additional operational constraints during testing:

- Minimum speed: 200 RPM;

- Maximum speed: 350 RPM; and

- Minimum flow rate: 2 m^3/hour (48 m^3/d).

PCP System with Metal Stator (KUDU)

Table 6.1 summarizes the experimental matrix for this system.

	OIL		OIL/WATER	
T (°C)	NO AIR	WITH AIR	NO AIR	WITH AIR
60	• Pump curve and PIP reduction at 2 RPM's	• N/A	• N/A	• N/A
120	• N/A	• N/A	• Pump curve and PIP reduction at 350 RPM	• Pump curve and PIP reduction at 350 RPM
150	• Pump curve and PIP reduction at 2 RPM's • Increase RPM at low PIP	• 1 RPM ALR Sensitivity • 1 RPM reducing PIP	• Pump curve and PIP reduction at 350 RPM	• Pump curve and PIP reduction at 350 RPM
180	• N/A	• N/A	• Pump curve and PIP reduction at 350 RPM	• Pump curve and PIP reduction at 350 RPM • ALR Sensitivity
200	• Pump curve and PIP reduction at 3 RPM's	• N/A	• Pump curve and PIP reduction at 350 RPM	• Pump curve and PIP reduction at 350 RPM

(*) Instructions from the SC chairman were to minimize the time spent on the RPM sensitivity tests

Table 6.1 Summary of Test Matrix for KUDU

6.3.2 Test Program Summary

The test program with 100% oil was conducted as per the above test matrix, with the following exceptions:

- Due to difficulties in obtaining PIP reduction data at temperatures above 100°C (see Section 6.4.2 below), an additional PIP reduction test was performed at ~93°C. During this test, some additional pump performance data was also generated, which is included in the performance curve plots[12].

- For the PIP reduction step at 200 RPM and 200°C, the volumetric efficiency was very low at the reference delta-P (3,000 kPa), so a decision was made to lower the delta-P to approximately 1,380 kPa (200 psi).

[12] Note that the test points used to build these additional performance curves do not strictly fulfill the stability criteria established for the test program; however, they are still considered to be a reasonable approximation of the performance of the PCP under stable conditions.

PCP System with Metal Stator (KUDU)

The following table summarizes the tests performed with 100% oil.

<table>
<tr><th>T°C</th><th>Pump speed (RPM)</th><th>Pump performance curve</th><th>PIP reduction with 100% oil</th><th>ALR sensitivity</th></tr>
<tr><td rowspan="2">60</td><td>200</td><td>4 pts + 1 at the end</td><td>Full</td><td></td></tr>
<tr><td>350</td><td>4 pts</td><td>Full</td><td></td></tr>
<tr><td rowspan="2">93</td><td>200</td><td>3 pts(*)</td><td>Partial(*)</td><td></td></tr>
<tr><td>350</td><td>3 pts(*)</td><td>Partial(*)</td><td></td></tr>
<tr><td rowspan="2">150</td><td>200</td><td>Full</td><td>Full</td><td>ALR increase up to ~15 std m^3/m^3</td></tr>
<tr><td>350</td><td>Full</td><td>Full</td><td>ALR increase up to ~2.3 std m^3/m^3, PIP reduction at ALR=~0.88 std m^3/m^3</td></tr>
<tr><td rowspan="3">200</td><td>200</td><td>Full</td><td>Full</td><td></td></tr>
<tr><td>275</td><td>Full</td><td>Full</td><td></td></tr>
<tr><td>350</td><td>Full</td><td>Full</td><td></td></tr>
</table>

(*) Additional test points, not with some variability in T and delta-P

Table 6.2 Summary of Tests with Oil Carried out for KUDU System

The oil/water mixture tests were executed as per the test matrix, with the following exceptions:

- While performing the PIP reduction test at 150°C, excessive pump slippage was observed at the reference delta-P (3,000 kPa); therefore, a decision was made to perform the PIP reduction tests at 150, 180 and 200°C at a lower value of delta-P (690 kPa, 100 psi).

- During the PIP reduction tests with air injection it was not possible, in some cases, to maintain a stable temperature during flashing conditions (i.e. the sum of the heater capacity plus the energy provided by the PCP was less than the sum of heat losses plus the energy lost by the flashed steam and air mixture). In those cases, the PIP was reduced, but the temperature was slightly lower than the reference test temperature.

- In order to investigate possible changes in volumetric efficiency with pump run-time, additional test data was obtained at 120°C at the very end of the experimental program (i.e. after testing at 200°C).

6.4 Results and Analysis

6.4.1 Pump Curves with 100% Oil

Figure 6.4 and Figure 6.5 show the pump performance curves at different temperatures at 200 RPM and 350 RPM, respectively. In both cases, at the lowest temperature (60°C) the slope was relatively flat (indicating the positive effect of viscosity on reducing the slippage); however, the rates were somewhat lower than expected. For instance, in Figure 6.5, the projection of the plot corresponding to 60°C intercepts the y-axis below 370 m^3/d, which is substantially lower than the theoretical rate of 419 m^3/d for 350 RPM. As temperature increased, the rate at minimum delta-P improved but the slope of the curve increased.

Although pump curve tests were not repeated when cooling the system back to room temperature, some additional data was obtained at 150°C, after the tests at 200°C were completed. (Most of these points were obtained during the PIP reduction and air injection tests; however, one stable point with no air injection at high PIP was also obtained.) This data was also plotted in Figure 6.4 and Figure 6.5. It shows an apparent decrease in flow rate versus the data points originally obtained at 150°C. C-FER looked for any indication of a material change in oil properties to account for this deterioration in pump performance, but none was found. This data seems to indicate that a physical change in the pump occurred between these two tests. It is important to take this into consideration during the interpretation of the other test results.

Figure 6.6 shows the theoretical volumetric efficiency of the pump for different temperatures and speeds. The reported volumetric efficiency is based on the volumetric capacity of the pump provided by KUDU (1.1973 m^3/d per RPM)[13]. The fact that the volumetric efficiency is affected by both the fluid temperature (i.e. fluid viscosity) and pump speed makes the interpretation of the results difficult for this type of plot.

Another way to represent the results is to show the slippage rate as a function of the pump delta-P. Based on the assumption that the volumetric efficiency is affected only by the slippage, "theoretical slippage" may be defined in terms of the difference between the theoretical flow rate and the actual flow rate:

Theoretical Slippage = RPM * (Pump Theoretical Capacity) – Actual Pump Rate.

Figure 6.7 shows a summary of the results for all of the oil tests using this parameter. Note that at 60°C (maximum viscosity) the slope of the curve of slippage rate versus delta-P is very flat (as expected). At higher temperatures (lower viscosities) the slopes of the curves are more pronounced. Again, it is evident that the rates at low delta-P for 60°C are below theoretical rates. With this plot it is easier to compare the pump performance at the two speeds. For example, note how the slippage for 60°C at 350 RPM is considerably higher than for 200 RPM. This effect is also observed at 93 and 150°C but to a lesser degree. This seems to indicate a negative effect of viscosity in the performance of the PCP at low delta-P values, which is more pronounced at higher pump speed. A possible explanation for this behaviour could be an incomplete filling of the first cavity due to viscous effects.

Another way to analyze the data is to define the slippage in terms of the extrapolated rate at zero delta-P. This is equivalent to the practice of setting the volumetric efficiency at 100% at zero delta-P for each curve. The plot corresponding to this approach is shown in Figure 6.8. This

[13] Note that the "published" volumetric capacity for the pump was 1.10 m^3/d per RPM. However, a test of the same model of pump at KUDU's test bench showed an actual volumetric capacity of 1.1973 m^3/d per RPM. This value was used as reference for analysis of volumetric efficiency.

type of plot is more illustrative in showing the changes in slippage as a function of the pump delta-P. Since the slippage resulting from delta-P is more a function of the viscosity (temperature) than of the pump speed, it can be observed how the points corresponding to different speeds tend to collapse in a single cluster for a given temperature.

Figure 6.9 shows the torque versus delta-P plot for all of the oil tests. Note how most of the plots lay quite close to each other, suggesting that the torque was mainly affected by the delta-P and just slightly by the pump speed. Only for the case of maximum viscosity (at 60°C) was the torque substantially larger.

6.4.2 PIP Reduction and ALR Sensitivity Tests with 100% Oil

As mentioned above, the test matrix was changed so that all of the PIP reduction tests were completed after the pump performance tests, with the expectation that all traces of water in the loop would be flashed after heating the loop to 200°C. However, even with this modified procedure it was difficult to achieve intake pressures much below saturation pressure at temperatures above 100°C. It appears that a very small amount of water was still being flashed below water saturation pressures, which caused problems in controlling temperature, pressure and maintaining submergence.

In order to obtain data to characterize the NPSH performance of the PCP at very low pressures, PIP reduction tests were also conducted at two different temperatures below 100°C (60 and 93°C), corresponding to two different viscosities. Table 6.3 summarizes the intake pressures achieved, compared to the saturation pressure at each temperature.

T	P_{sat}	Minimum PIP Achieved
(°C)	kPa (psig)	kPa (psig)
60	81.4 (-11.8)	6.9 (1)
93	-22 (-3.2)	3.5 (0.5)
150	376 (54.6)	331 (48)
200	1,460 (211.8)	1,344 (195)

Table 6.3 Minimum Intake Pressure Achieved for Each Temperature

Figure 6.10 to Figure 6.13 show the pump flow rate (as well as the controlled variable, delta-P) as a function of the PIP. At 150 and 200°C the change in flow rate was almost imperceptible (note that the minimum PIP achieved was limited to saturation pressures). However, at 60 and 93°C, the reduction in volumetric efficiency was noticeable.

These results are consistent with the “viscous effect” discussed for Figure 6.7 (higher PIP at 60°C), in that they were more pronounced at higher values of viscosity and pump speed. Figure 6.14 presents the results for all the PIP reduction tests with oil at different temperatures, in terms of volumetric efficiency (normalized using the theoretical displacement of the pump). Note that in this figure, the most important parameter is the change in volumetric efficiency with changing

PIP, rather than the absolute value of the volumetric efficiency (especially considering that not all of the tests were performed at the same reference delta-P).

For the air injection test at 150°C, there was little effect on pump performance at 200 RPM, which suggests that close to 100% of the air was separated in the casing. This is consistent with what was observed at this speed with the Netzsch PCP. At this speed, more than 1,980 std m^3/day of air was injected, corresponding to an ALR of 14.7 sm^3/m^3 and a GVF of approximately 65%. At 350 RPM, it was more difficult to control the annulus level. Nevertheless, up to 670 sm^3/d of air was injected, corresponding to an ALR of ~2.3 sm^3/m^3 (GVF ~ 30%). The data points corresponding to these tests are shown in Figure 6.15 and Figure 6.16.

A PIP reduction test with air injection was performed at 150°C and 350 RPM, maintaining an ALR close to 0.9 sm^3/m^3. It was possible to get very close to the saturation pressure, but at this point it was not possible to maintain the intake temperature. It seems that the combined effect of the injected air and the low pressure promoted some flashing, causing a decrease in the temperature. It has been observed that any time steam is flashed, there is a noticeable decrease in the energy of the system, which affects the temperature.

6.4.3 Additional Tests with 100% Oil

After the test at 200°C, data was continuously recorded as the temperature was reduced to 150°C under the following conditions: pump speed of 350 RPM, delta-P of 3,000 kPa (435 psi) and a PIP value above the PIP reference (Psat + 700 kPa). The purpose of this test was to evaluate the effect of fluid viscosity on pump slippage during continuous operation. Figure 6.17 shows that during the cooling process, the flow rate increased from 285 m^3/d to 302 m^3/d, corresponding to an increase in volumetric efficiency from 68 to 72%. Note that this final value was lower than originally measured at these conditions (see Figure 6.3).

6.4.4 Pump Curves with Oil/Water Mixture

Figure 6.18 summarizes the pump performance plots for all the tests with the oil/water mixture (without air) at different temperatures. The curve corresponding to oil at 200°C was included in the plot for comparative purposes. Several relevant observations may be noticed in this figure:

- The oil curve at 200°C illustrates that the "effective" viscosity of the mixture (at least from the slippage stand point) was always lower than the minimum viscosity obtained during the oil tests.

- The flow rate was the highest at 120°C and the lowest at 200°C (as expected based on the effect of temperature on viscosity and slippage), but the relative position of the plots at 150 and 180°C are opposed to this expected trend. This may be explained due to a change in water cut between the two tests (as discussed below).

PCP System with Metal Stator (KUDU)

- The shape of the curves (curving up) is different from what is normal for elastomeric PCPs (curving down) or for a "loose" pump (straight line). A careful review of the data confirmed that this trend appears to be real and not related to any problem in obtaining the data.
- The additional test data taken at 120^{o}C at the end of the test program shows an apparent additional decrease in volumetric efficiency of the pump during the oil/water mixture test program. Note that these additional data points at 120^{o}C correspond roughly to previous oil/water mixture testing at 180°C (considerably below the original plot at 120°C).

As mentioned in Section 3, the target was to keep the average water cut of the oil/water mixture in the vicinity of 70 to 80%, and this was largely achieved. Based on the operations performed between tests and the density readings from the Coriolis flow meters, it was confirmed that the water cut during the tests at 180 and 200°C was approximately 5 to 10% lower than during the tests at 150°C, which has some effect on the relative pump efficiencies between different temperatures.

Figure 6.19 shows the estimate of the water cut as a function of the mixture density. This estimation was based on density readings obtained during the oil test with this pump[14]. According to this estimation, the water cut values for the pump performance tests ranged from a minimum of about 75% (at 200°C) to a maximum of ~87% (at 150°C). Additional points have been included on the plot to show the density of the mixture while heating after the PIP reduction test at 180°C and also the density for the final test 120°C.

An oil sample was also sent to Norwest for analysis after the test program was complete. The results showed that both the viscosity and the density were higher than the values obtained before testing. Using the new oil density, the water cuts were re-estimated. Figure 6.20 illustrates the effect of the new density on the water cut estimation, which in the most extreme case (at 200°C) represented an increase of ~7% on the estimated water cut.

Figure 6.21 shows the values of viscosity for several oil analyses. While the project initially called for no measurement of emulsion viscosity, the issue of quantifying this parameter was later discussed in one of the SC Meetings, and C-FER attempted to retrofit the flow loop with a "viscosity measurement" section after the first test. For this purpose, a 25 mm OD x 4.6 m (1-inch OD x 15 ft) straight bypass instrumented with a delta-P transducer was installed. The strategy was to divert the flow to this line at the end of each set of tests (at each temperature) and later estimate the viscosity based on the frictional pressure losses.

[14] It was determined that the most accurate way to obtain density values for the water and oil was by using the actual readings from the Coriolis meter obtained during testing and commissioning, rather than using densities obtained from external labs. This eliminates error that may be introduced by small differences between the calibration of the Coriolis meter and the instruments used by external labs. Actual readings were compared with data obtained from external labs for quality control purposes, with good results.

PCP System with Metal Stator (KUDU)

While this line was retrofitted into the loop and different DPT ranges tried, this approach unfortunately was unsuccessful due to the following reasons:

- For the oil/mixture tests, most of the flow rate ranges produced with the pumping system caused a turbulent flow regime; therefore, the pressure drop was not a good estimator of the viscosity.
- The low rate circulation pump was used to operate at lower flow rates (and therefore to stay in laminar flow regime), but at such low rates it appears that the overall characteristics of the mixture were different from the ones observed during the actual test at higher flow rates. This was likely due to phase separation occurring at such low flow rates as well as to the location of the viscosity line (on top of the flow line).

Subsequently, some time was spent trying to establish a correlation between the pressure drop through the control valve at the discharge of the pump and the viscosity, but the turbulent nature of the flow at the valve port made the pressure drop insensitive to the viscosity (as expected). Some time was also spent trying to correlate the pressure drop in other sections of the flow loop to flow rate and temperature, but the results were inconclusive. Therefore, using the calculated water cut to estimate the mixture viscosity apparently remains the most accurate method of quantifying the "effective viscosity".

While the water cut variability provides some explanation of the efficiency changes between tests at different temperatures, the apparent change in pump condition may also have caused performance changes. Figure 6.22 shows the state of the rotor after the test program was complete. As shown, there was some degree of rotor wear. This may account for some of the noticeable change in efficiency observed between the 100% oil and the oil/water mixture tests and in fact throughout the test program. (Remember that there was some indication of pump efficiency deterioration over time even with the 100% oil test.)

Figure 6.23 shows a summary of the torque versus delta-P data for all oil/water mixture tests without air. The torque curve for 200°C with oil was included for comparative purposes. Note how the points collapse very closely to a single trend on the plot, denoting almost no effect of temperature or pump speed on the pump torque.

Figure 6.24 shows the "theoretical" slippage:

Theoretical Slippage = RPM * (Pump Theoretical Capacity) – Actual Pump Rate.

The results are very similar to those observed for the flow rate versus delta-P plot, basically because all the tests with oil/water mixture were performed at the same speed.

In Figure 6.25, the set of slippage curves is presented based on setting the volumetric efficiency to 100% at zero delta-P. (This extrapolation is shown in Figure 6.18.) It is interesting that, although the flow rates were different for these cases, the increase in slippage rate as a function of delta-P (i.e. $dQ/d[\Delta P]$) was practically the same for the three temperatures above 120^{o}C.

Figure 6.26 shows the curves for the air injection tests. The curves for oil at 200°C, and oil/water mixture (without air) at 120 and 200°C have been plotted as reference. Note how the case most affected by the air injection was that corresponding to 120°C, while the higher temperature cases were less affected. The average ALR during these tests was 0.85sm^3/m^3, with a variation between 0.7 and 1.1 sm^3/m^3.

6.4.5 PIP Reduction and ALR Sensitivity Tests with Oil/Water Mixture

Figure 6.27 summarizes all the PIP reduction test results with the oil/water mixture, with and without air injection. The vertical lines correspond to the saturation pressure at each testing temperature. Note that the main reason the flow rates at 120°C are so low compared to the others is that the reference delta-P in this case was 3,000 kPa (435 psig), while in all other cases the reference value was reduced to 690 kPa (100 psi) because the flow rate was so low at the original reference delta-P.

During the execution of some of the PIP reduction tests, it was difficult to maintain a constant delta-P. Even for the lower reference delta-P (100 psi), the sensitivity of flow rate to delta-P sometimes made it difficult to monitor the actual effect of the PIP on the flow rate. However, in general, very low values of PIP could be achieved with this pumping system, and the operation was relatively smooth, as shown in Figure 6.28 (for 200°C).

In some cases there was a slight increase in flow rate as PIP was lowered, which was counter-intuitive to the expected behaviour. Since pump flow rate was sensitive to delta-P, and delta-P was also changing slightly, this data was analyzed. As shown in Figure 6.29 (for 120^{o}C), the delta-P values ranged from approximately 2,895 to 3,102 kPa (420 to 450 psi). However, this figure shows that even after considering the effect of the delta-P, there is still a slight trend of increased flow rate as the PIP was reduced (until very low PIP was achieved). This was also seen for PIP tests at other temperatures.

6.4.6 Post-test Observations

After testing, the KUDU pumping system was pulled from the loop and the following observations were noted:

- The rotor could be manually turned using a pipe wrench.
- As mentioned above, there was some evidence of wear on the rotor. Note that only the top (roughly 2 m) of the rotor was examined, so the condition of the entire rotor is unknown. KUDU is presently performing an inspection of the pump and reported that they will provide information on the pump condition to the JIP.
- The centralizers provided by RGI did not perform well during the KUDU test. While they were apparently identical to those provided for the Netzsch test (which performed relatively well), the material on the centralizers was completely removed during the course of the test. A portion of the material was found in the discharge strainer. One major change between the

two test programs was that centralizers operated at a maximum speed of 350 RPM during the KUDU test, compared to 200 RPM for Netzsch. The other differences between the two tests include longer test duration with the oil/water mixture and longer test duration at 200°C with the KUDU tests. RGI has retrieved some of the centralizer material and indicated that they will perform a failure analysis.

- Even with the loss of the rod centralization during the test program, the drive system stuffing box performed well, with very little evidence of leakage.

6.5 Conclusions

- The test program was successfully completed with the 100% oil and the oil/water mixture, with changes to the test matrix as outlined.

- The pump initially showed "high" starting torque at low temperature (more than 400 ft-lb), which closely matched bench test results (with water) conducted by KUDU on a similar pump. The torque was reduced considerably as the test was carried out and the temperature of the fluid was increased.

- The volumetric efficiency of the pump with 100% oil decreased noticeably at 200°C compared to initial tests at 60 and 150°C. This was illustrated by an increase in "theoretical slippage" rates which were as high as 120 m^3/d (at 200°C and 600 psi delta-P).

- For the oil/water mixture tests, the theoretical slippage was considerably higher than for the 100% oil tests, up to 250 m^3/d (for delta-Ps ranging from 400 to 500 psi, depending on temperature).

- Additional data points taken at 150°C near the end of the 100% oil test and at 120°C at the end of the oil/water mixture test (not included in the original test matrix) suggest that the pump performance may have decreased during the test program, irrespective of fluid properties or temperature.

- Visual inspection of the top few stages of the rotor after the test program showed evidence of rotor wear.

- The effect of air injection in the pump performance was mild, suggesting that close to 100% of the injected air was separated in the casing annulus.

- The NPSH of the pump (with 100% oil) was determined to be very low. When the PIP was reduced, a gradual effect on volumetric efficiency was observed and was proportional to pump speed. The reduction of volumetric efficiency due to this effect was in the order of 25% for the worst case at minimum pressure (close to atmospheric).

- This system allowed operation at very low PIPs with the oil/water mixture, showing only a mild effect of this variable on the pump flow rate.

PCP System with Metal Stator (KUDU)

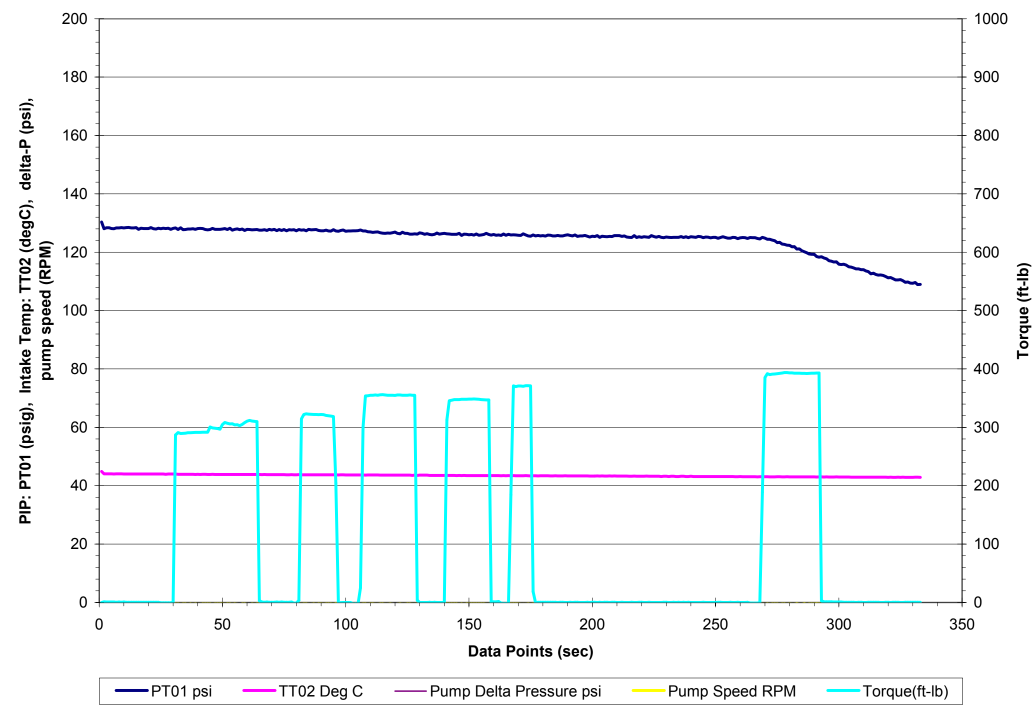


Figure 6.1 KUDU - Unsuccessful Attempts to Start the Pump

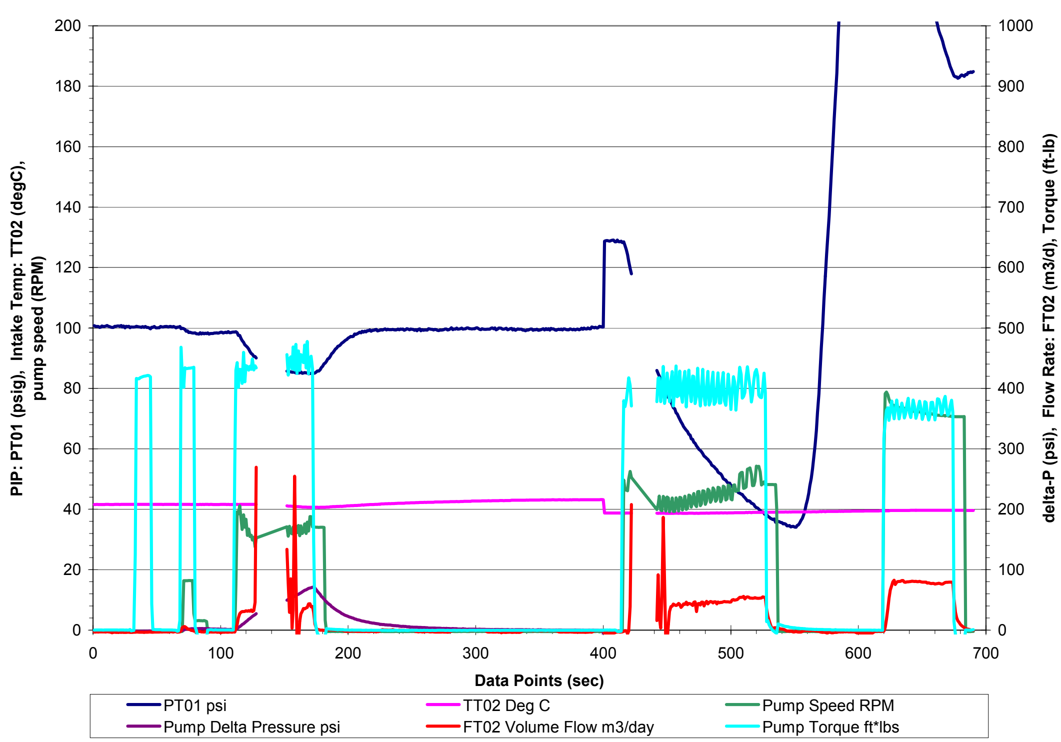


Figure 6.2 KUDU - Initial Start-up Torque

PCP System with Metal Stator (KUDU)

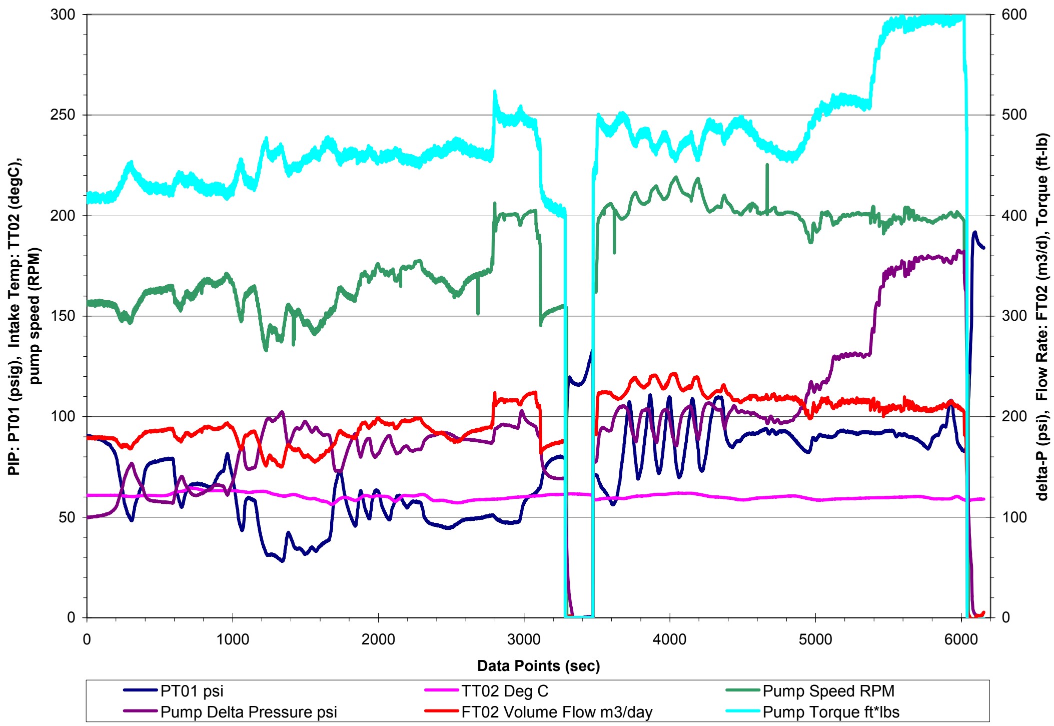


Figure 6.3 KUDU - Stabilization of Pump Torque

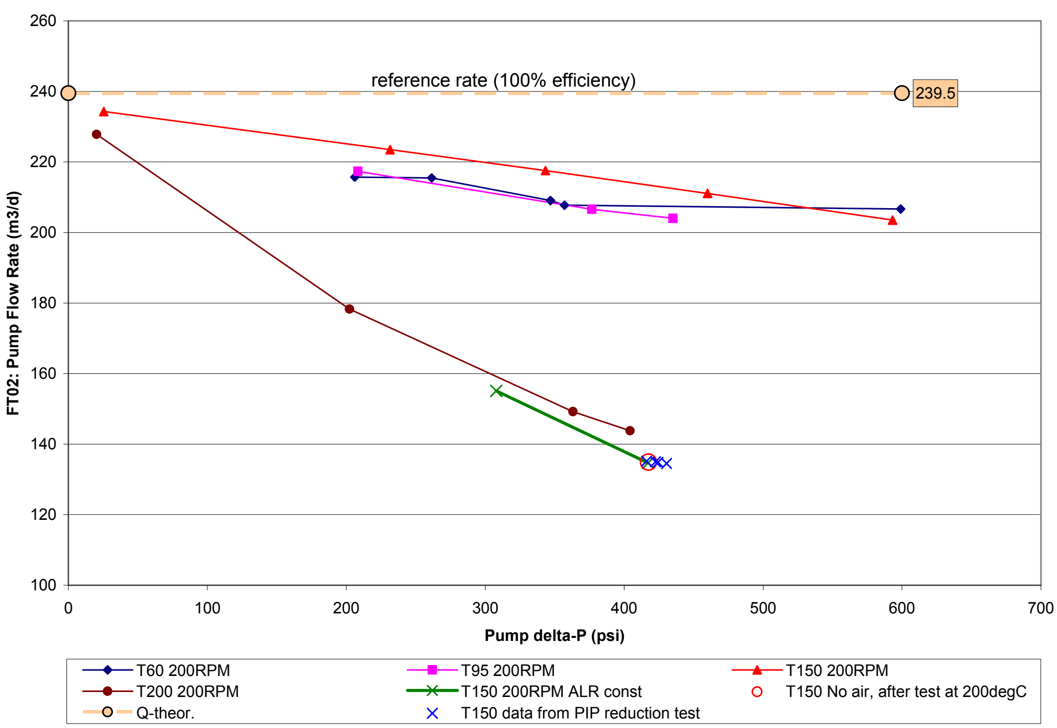


Figure 6.4 KUDU - Q Versus delta-P at 200 RPM for 100% Oil

PCP System with Metal Stator (KUDU)

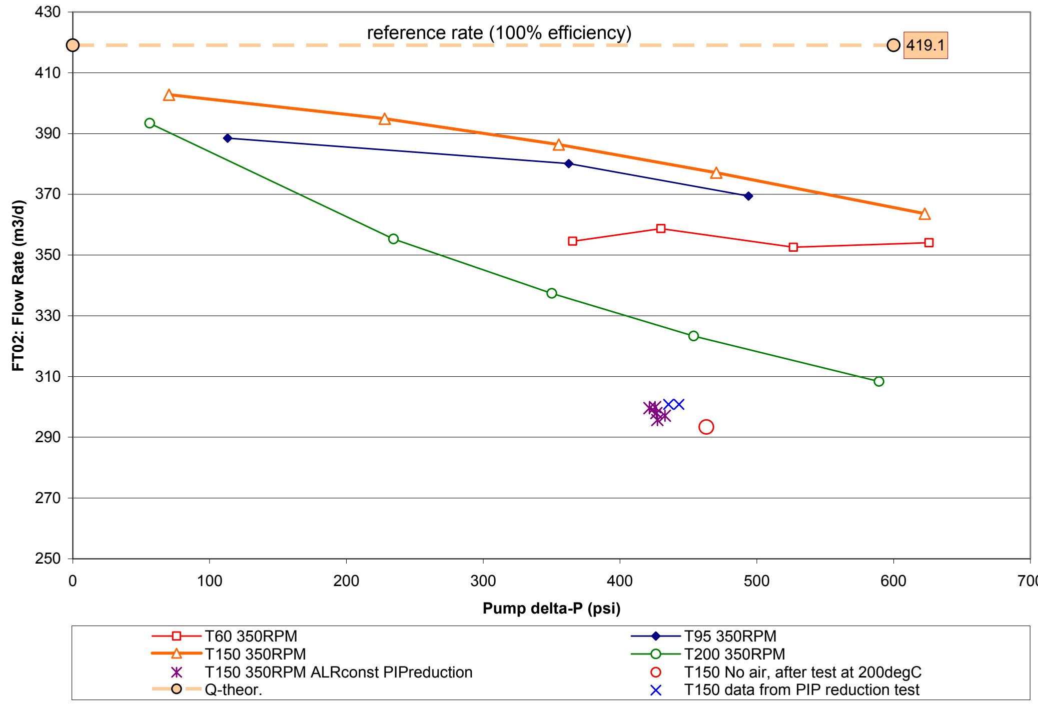


Figure 6.5 KUDU - Q Versus delta-P at 350 RPM for 100% Oil

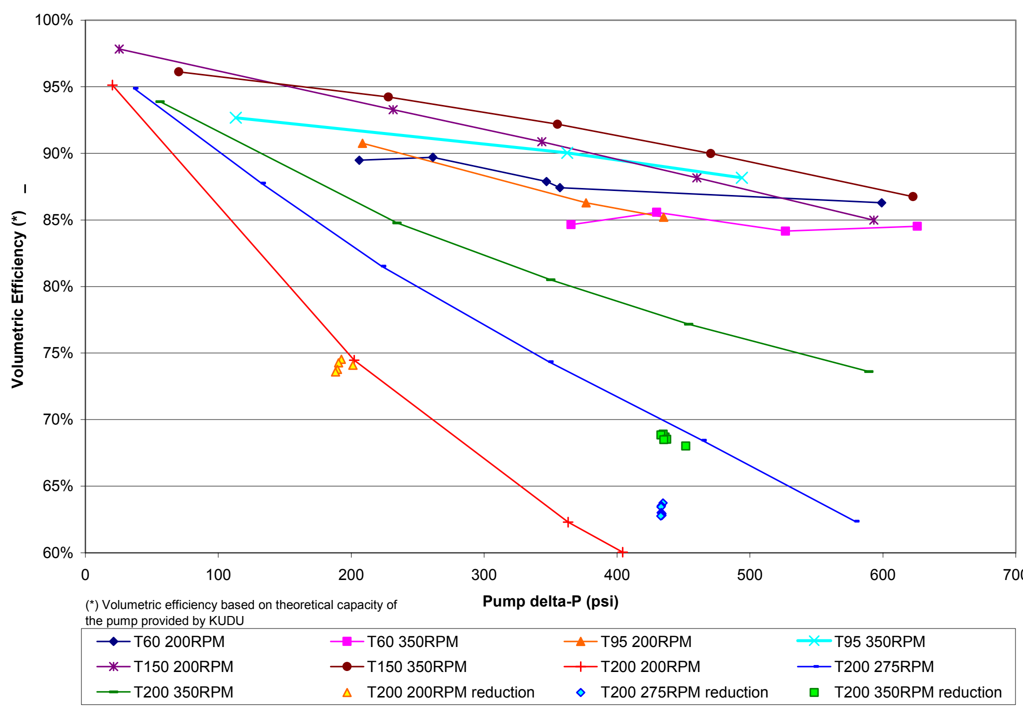


Figure 6.6 KUDU - Theoretical Volumetric Efficiency for 100% Oil

PCP System with Metal Stator (KUDU)

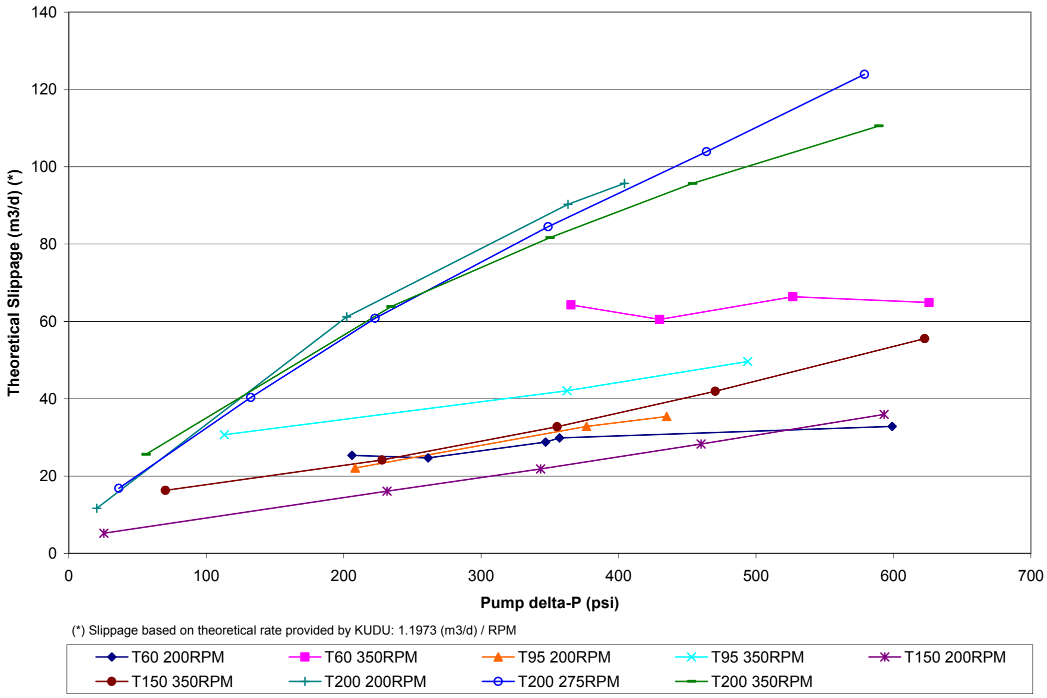


Figure 6.7 KUDU - Theoretical Slippage for 100% Oil

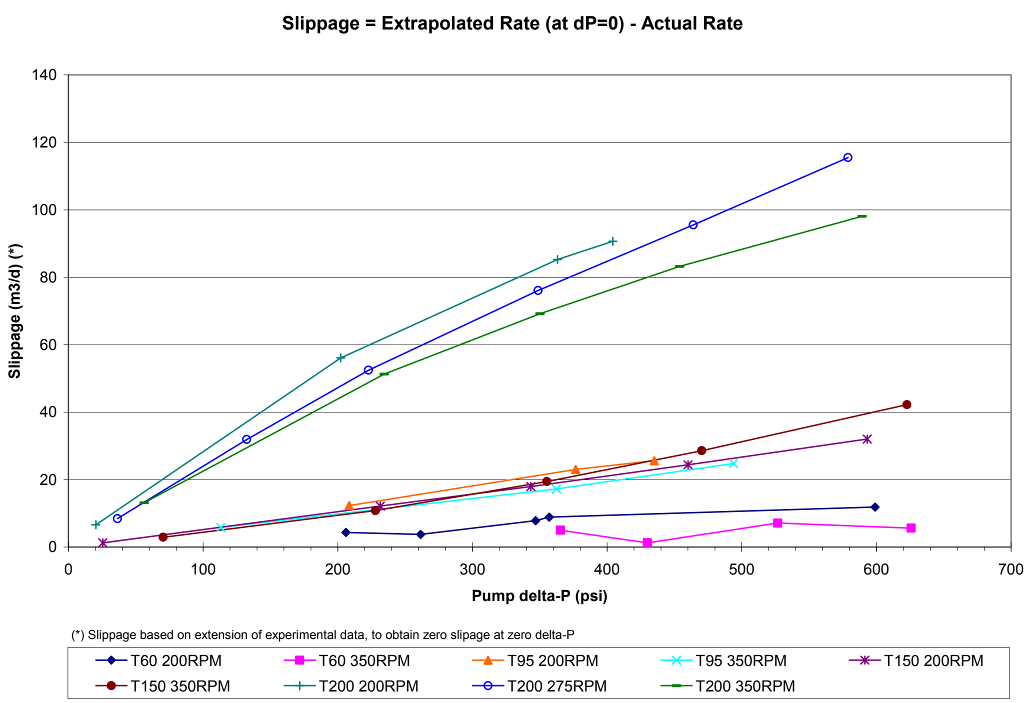


Figure 6.8 KUDU - Normalized Slippage for 100% Oil

PCP System with Metal Stator (KUDU)

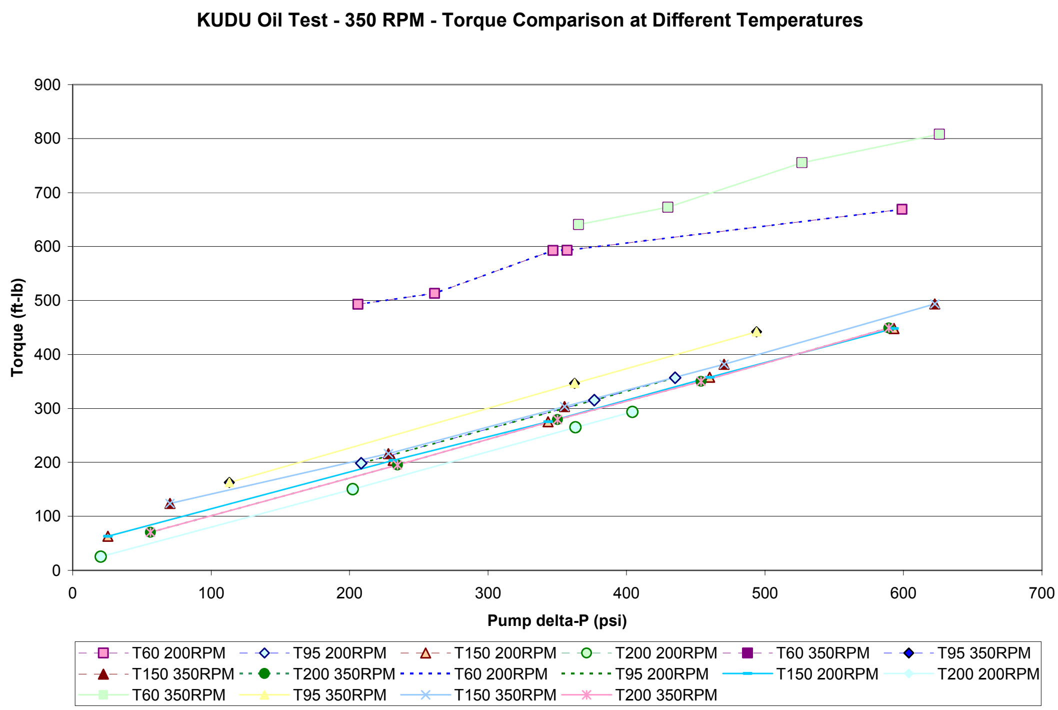


Figure 6.9 KUDU - Torque at Different Temperatures with 100% Oil

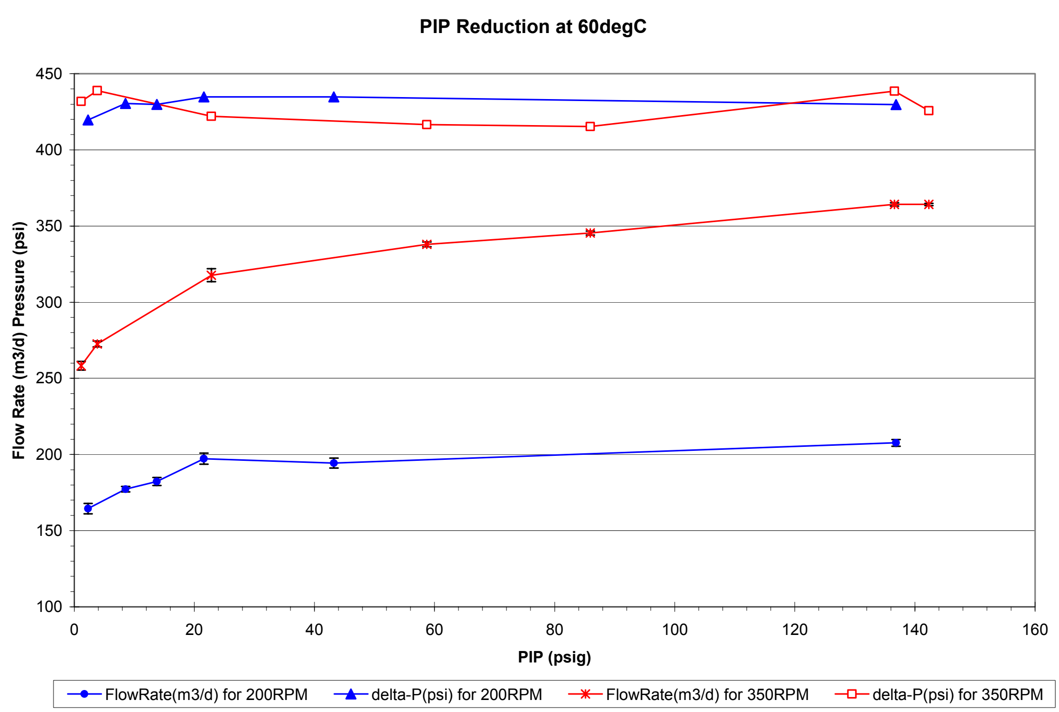


Figure 6.10 KUDU - Effect of PIP Reduction on Pump Performance with 100% Oil at 60°C

PCP System with Metal Stator (KUDU)

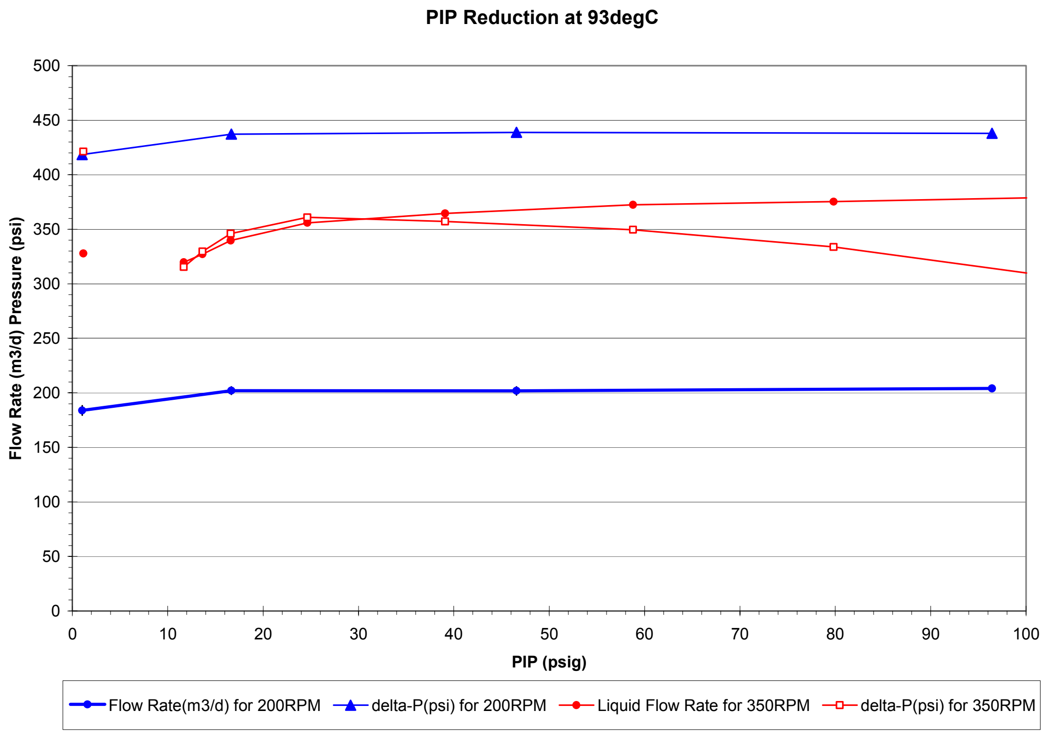


Figure 6.11 KUDU - Effect of PIP Reduction on Pump Performance with 100% Oil at 93°C

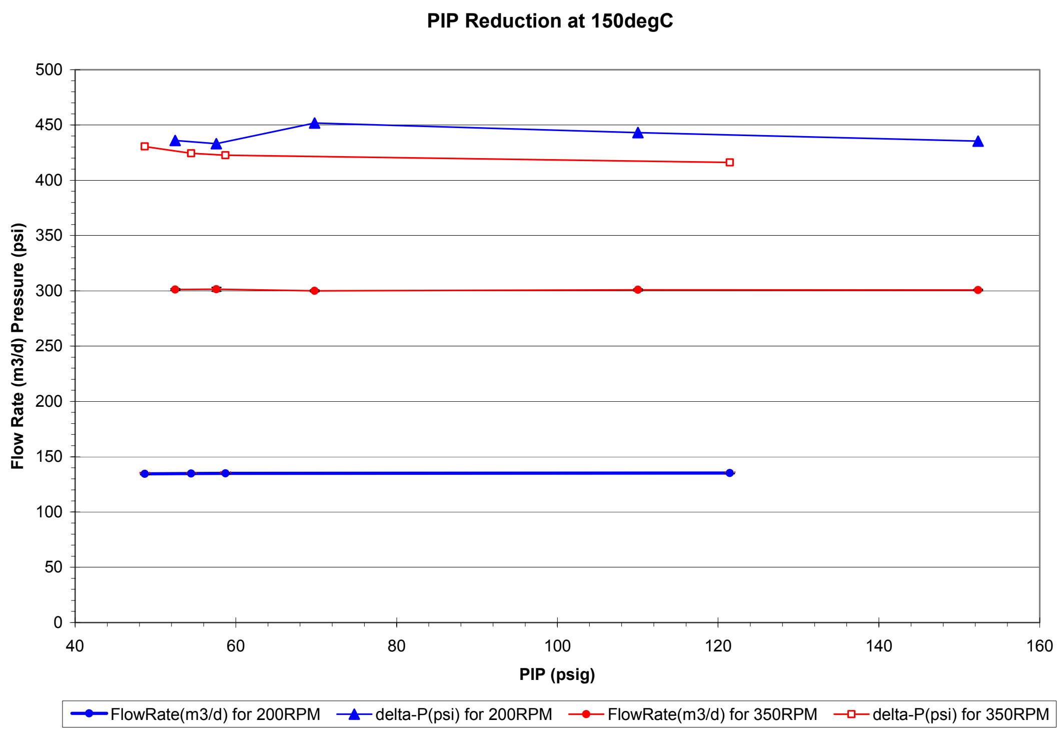


Figure 6.12 KUDU - Effect of PIP Reduction on Pump Performance with 100% Oil at 150°C

PCP System with Metal Stator (KUDU)

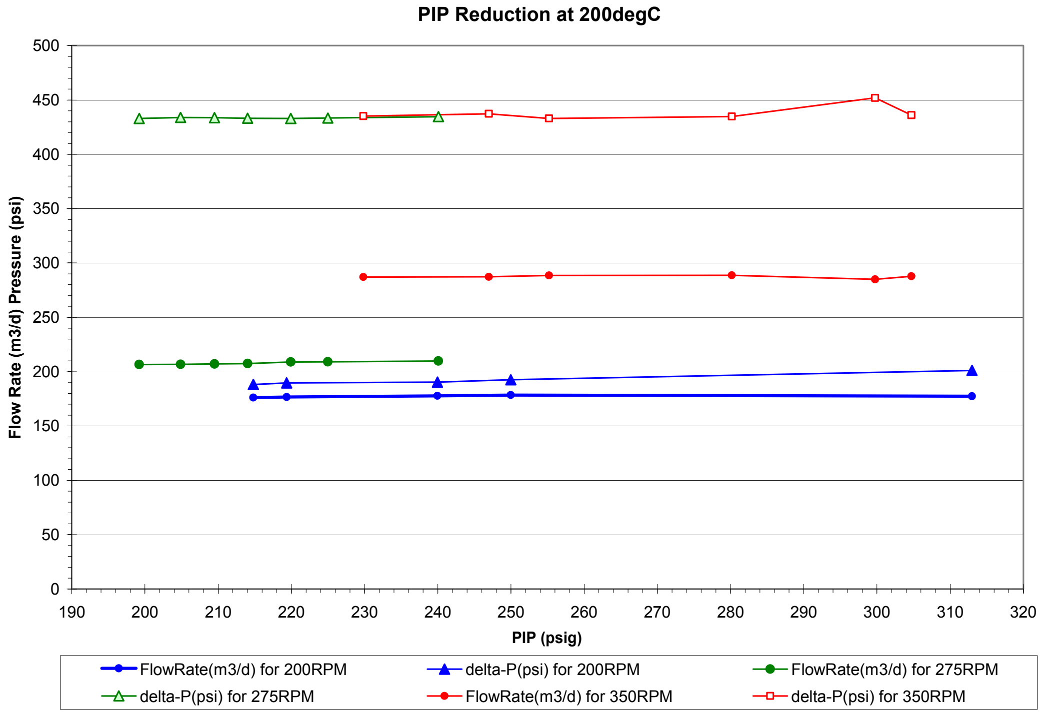


Figure 6.13 KUDU - Effect of PIP Reduction on Pump Performance with 100% Oil at 200°C

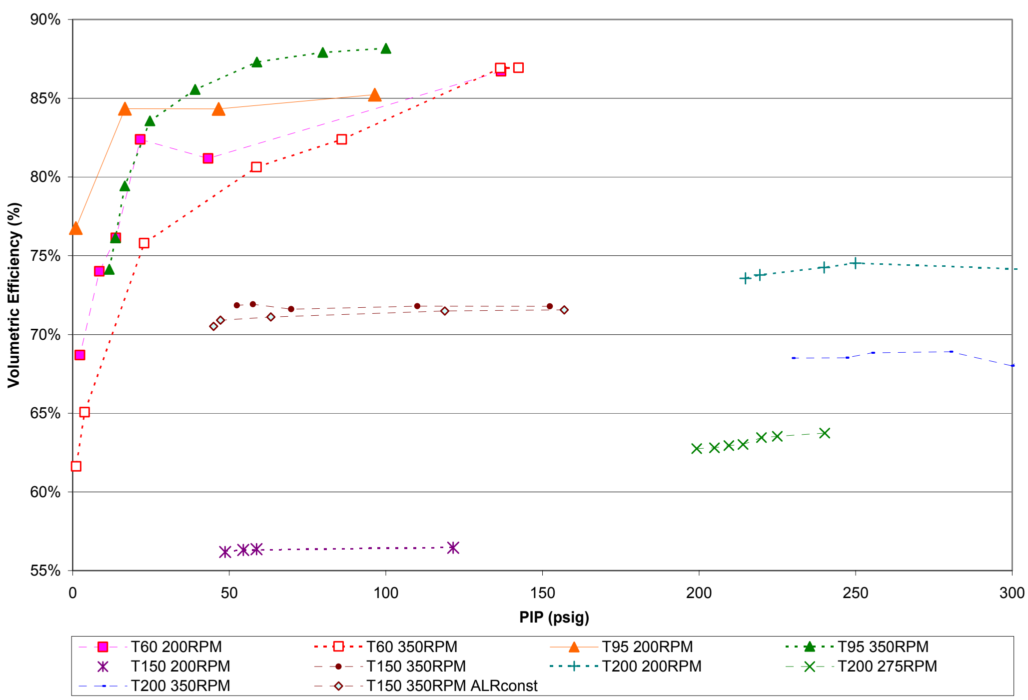


Figure 6.14 KUDU - Effect of PIP Reduction on Volumetric Efficiency with 100% Oil

PCP System with Metal Stator (KUDU)

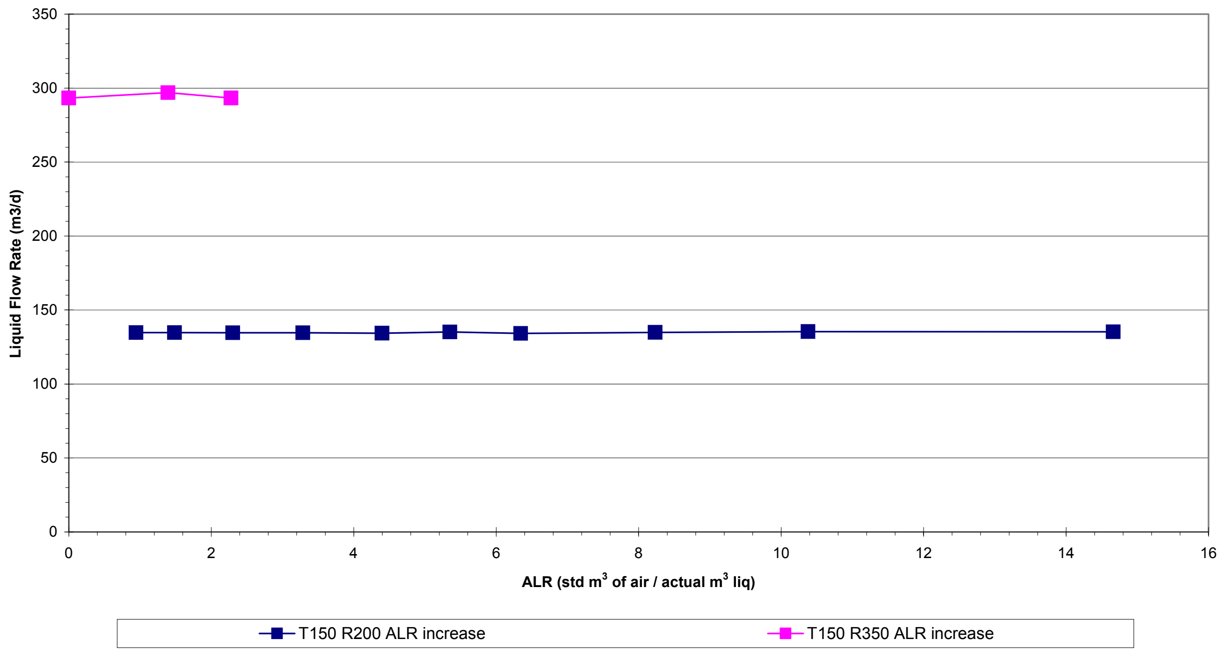


Figure 6.15 KUDU - Effect of ALR Increase on Pump Performance with 100% Oil

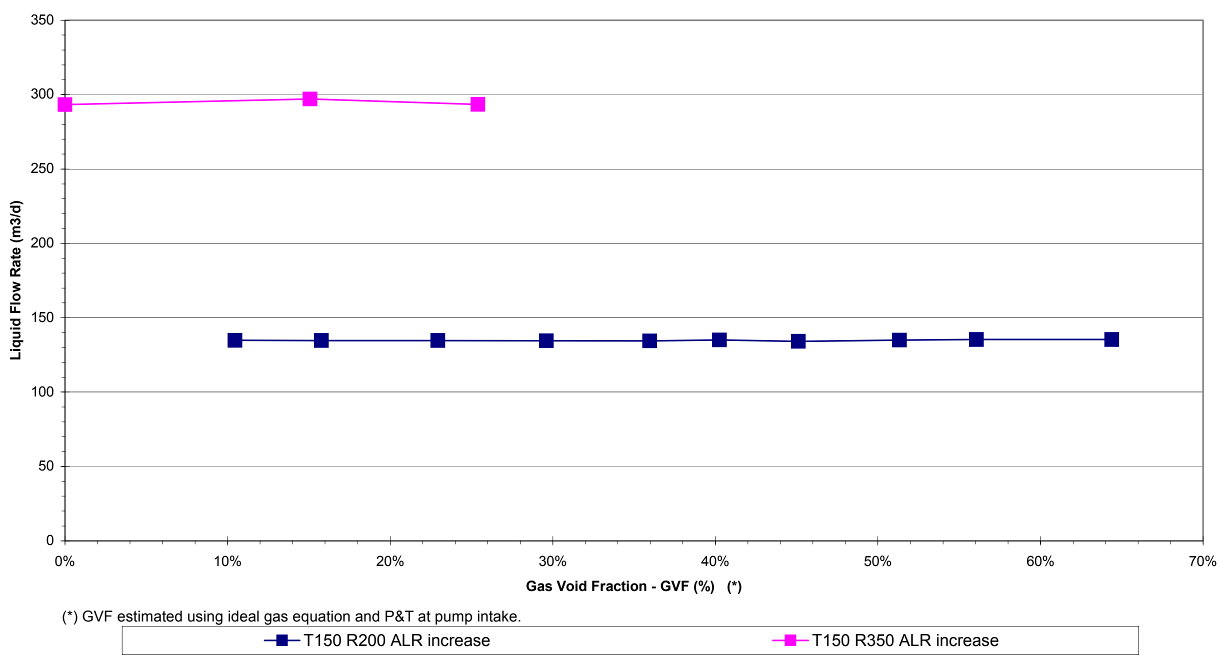


Figure 6.16 KUDU - Effect of GVF Increase on Pump Performance with 100% Oil

PCP System with Metal Stator (KUDU)

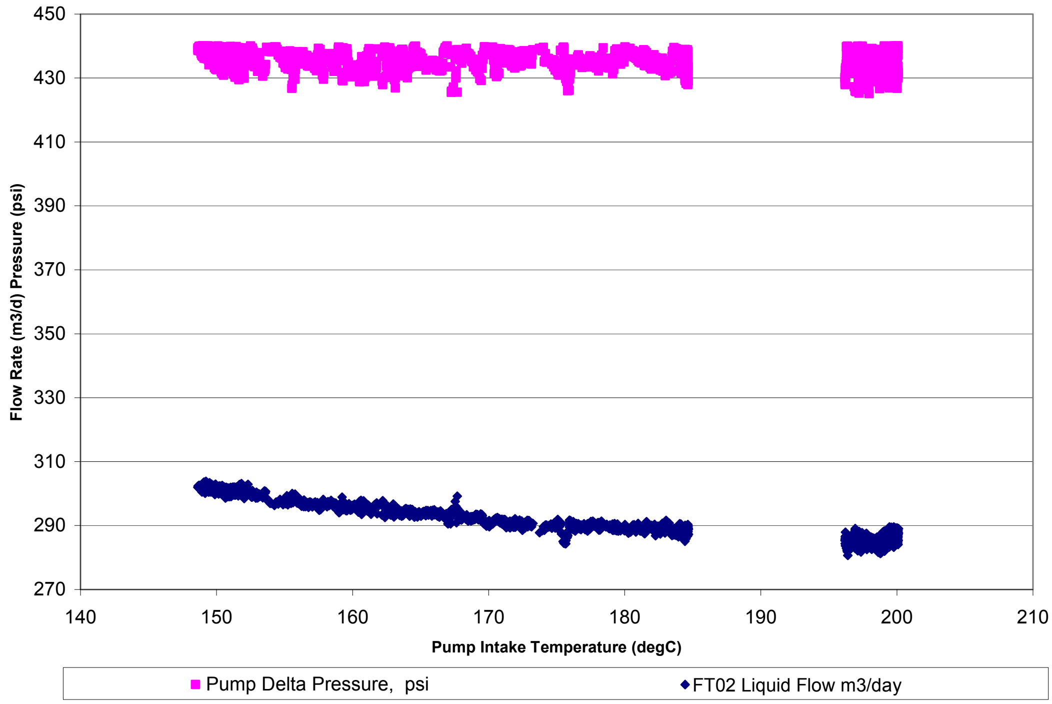


Figure 6.17 KUDU - Effect of Temperature Reduction on Pump Performance with 100% Oil

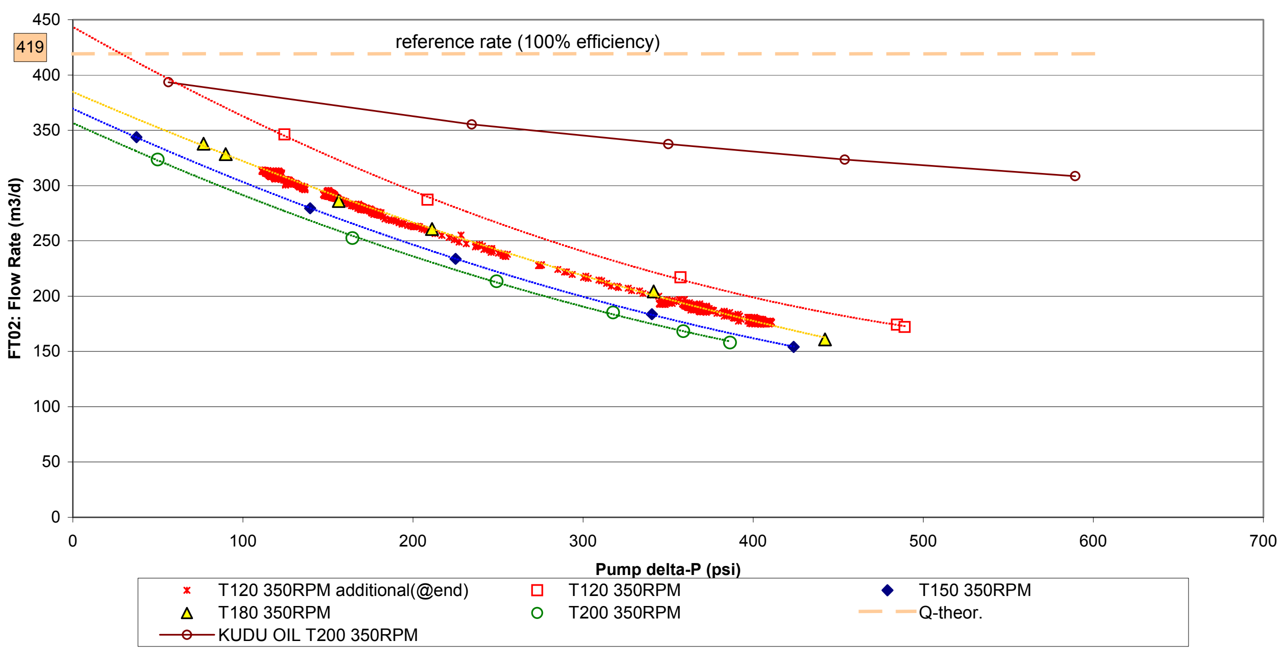


Figure 6.18 KUDU - Q Versus delta-P for Oil/Water Mixture

PCP System with Metal Stator (KUDU)

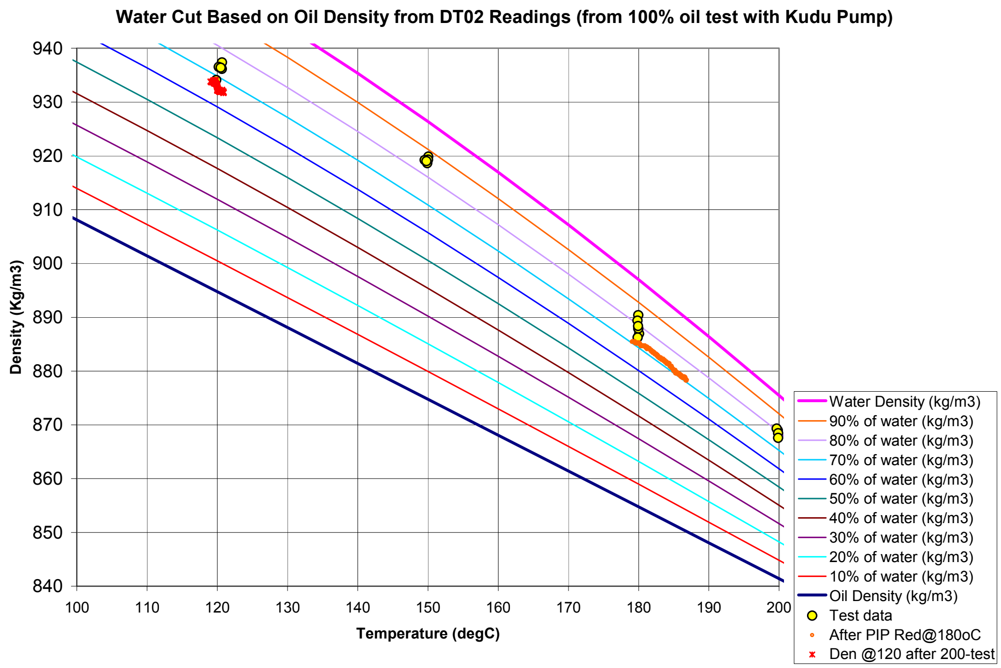


Figure 6.19 KUDU - Estimation of Water Cut Based on Oil Density Readings from Coriolis Meter

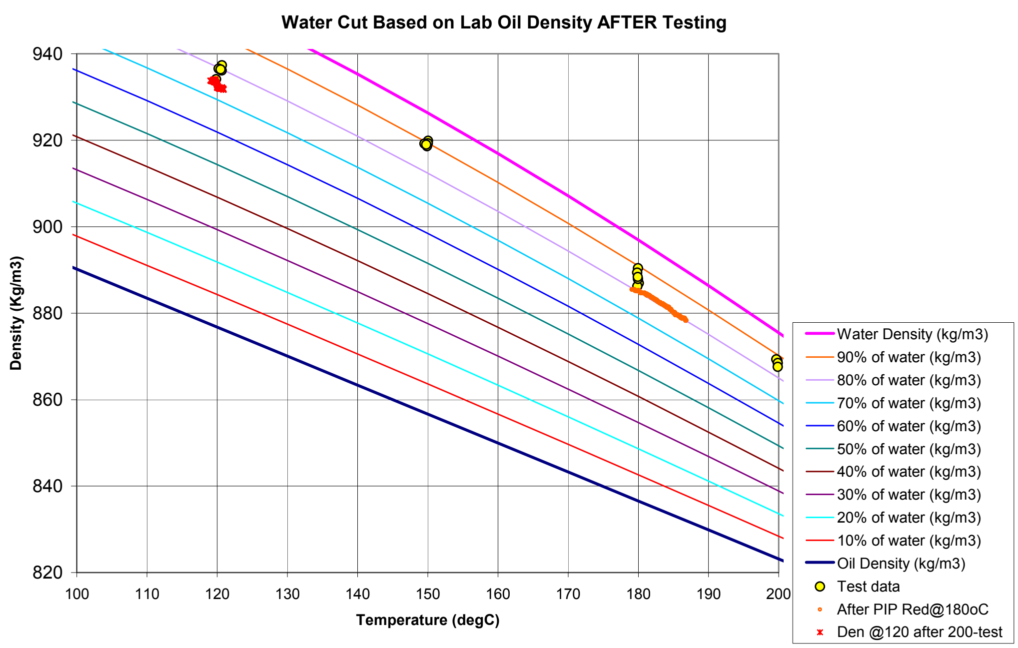


Figure 6.20 KUDU - Estimation of Water Cut Based on Oil Density Obtained from External Lab Testing after Pump Test

PCP System with Metal Stator (KUDU)

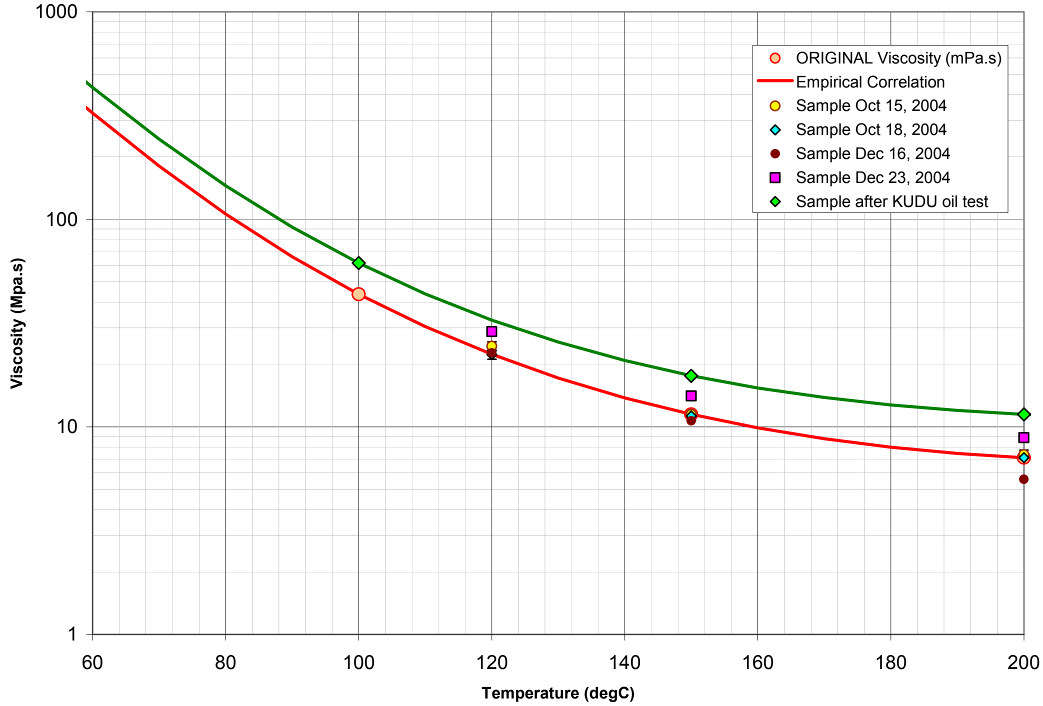


Figure 6.21 KUDU - Oil Viscosity Before and After Pump Test

Figure 6.22 KUDU - Images or Rotor Condition at the Discharge End

PCP System with Metal Stator (KUDU)

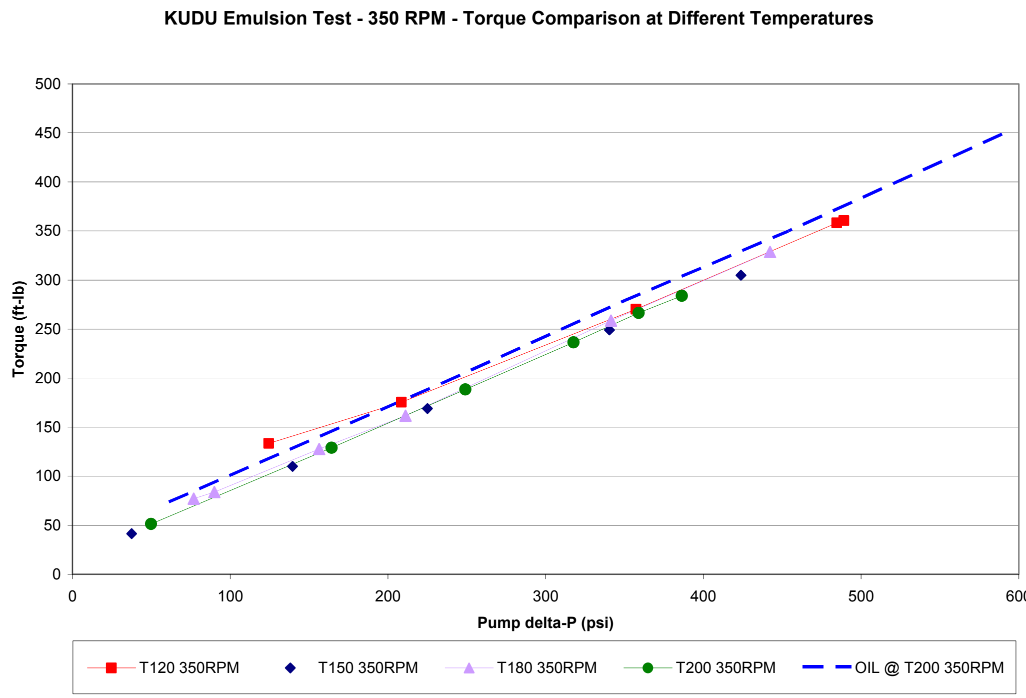


Figure 6.23 KUDU - Torque for Oil/Water Mixture

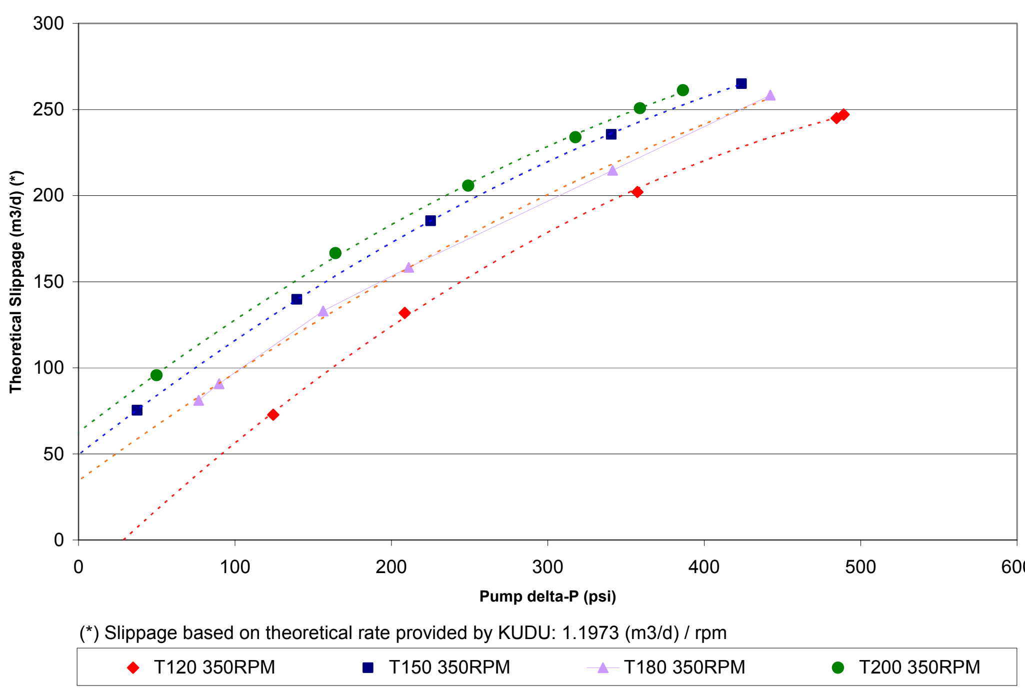


Figure 6.24 KUDU - Theoretical Slippage for Oil/Water Mixture

PCP System with Metal Stator (KUDU)

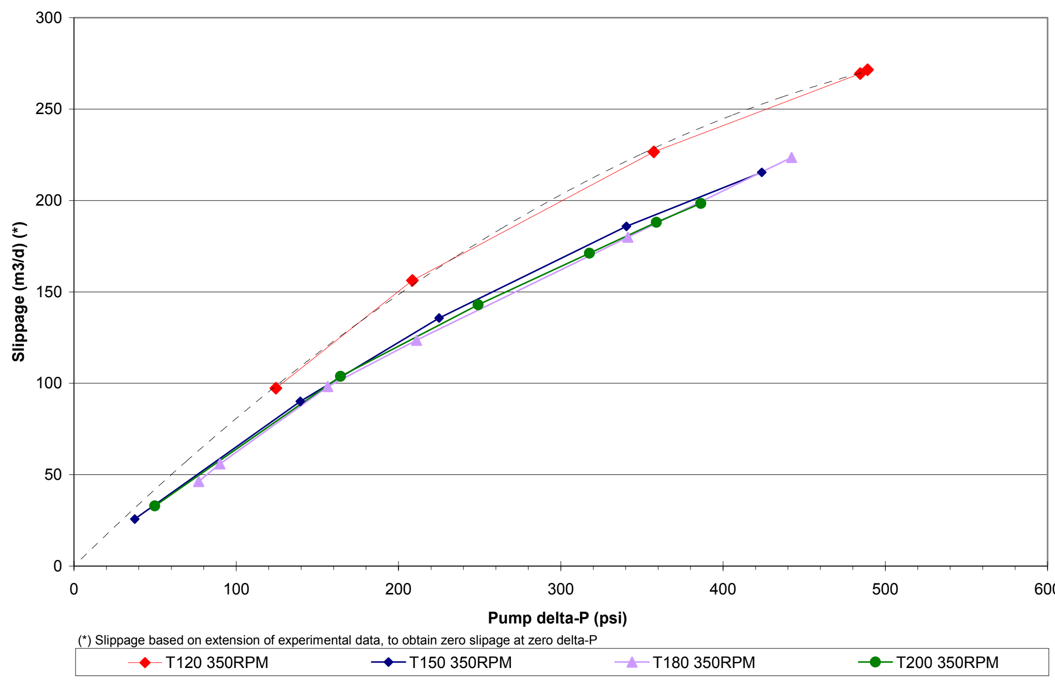


Figure 6.25 KUDU - Normalized Slippage for Oil/Water Mixture

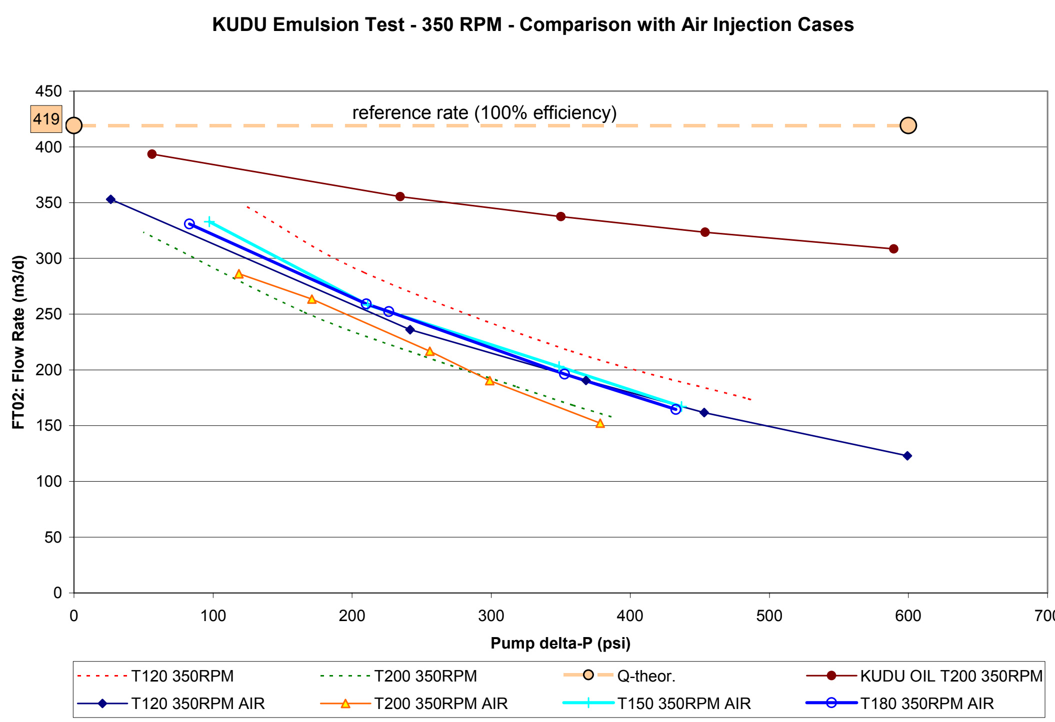


Figure 6.26 KUDU - Effect of Constant ALR on Pump Performance for Oil/Water Mixture

PCP System with Metal Stator (KUDU)

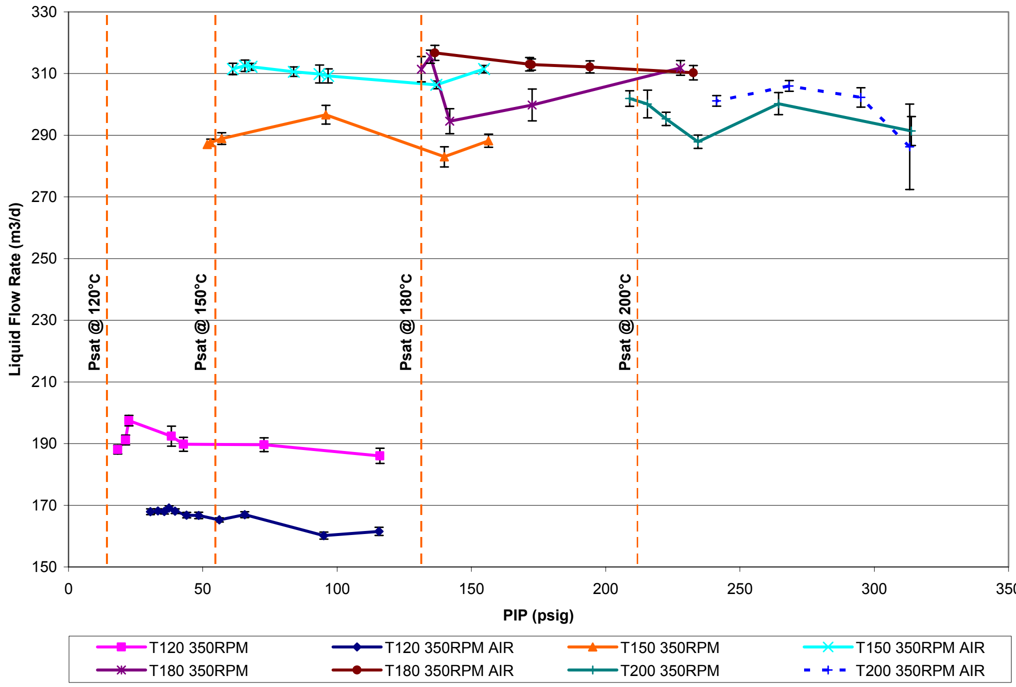


Figure 6.27 KUDU - Effect of PIP Reduction on Pump Performance for Oil/Water Mixture

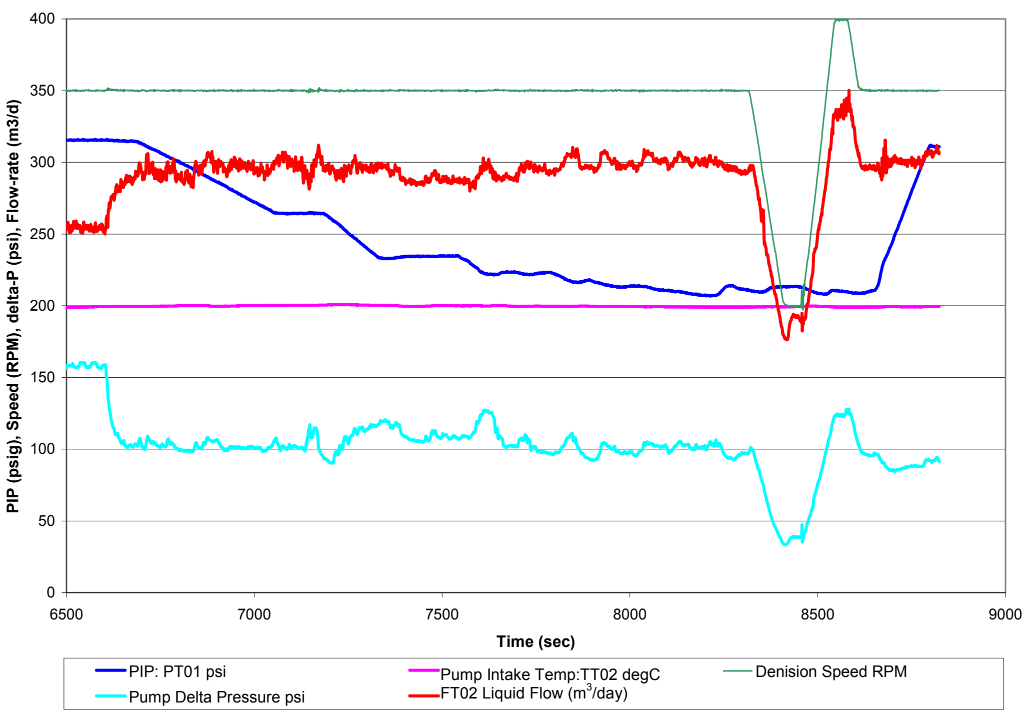


Figure 6.28 KUDU - Example of Stability during PIP Reduction Tests for Oil/Water Mixture

PCP System with Metal Stator (KUDU)

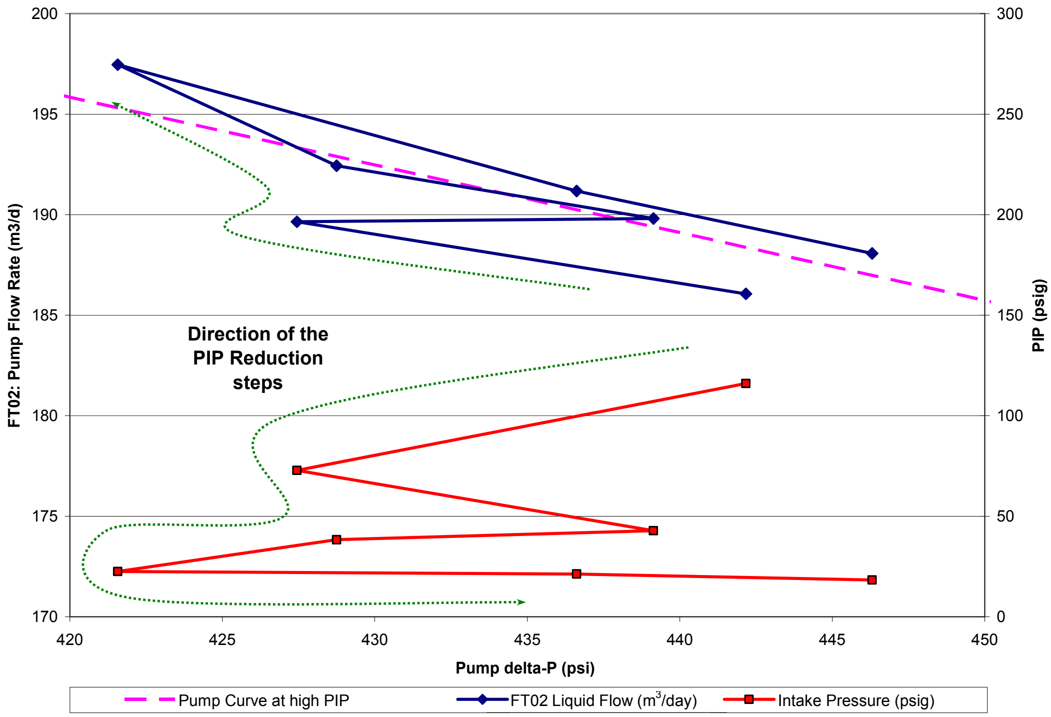


Figure 6.29 KUDU - Effect of Variations in delta-P during PIP Reduction Test for Oil/Water Mixture

APPENDIX A

PHASE I FINAL REPORT (CAN-K TWIN SCREW PUMPING SYSTEM TEST)

C-FER Technologies

Tel 780.450.3300 | Fax 780.450.3700
www.cfertech.com
200 Karl Clark R
Edmonton, Albe
Canada T6N 1H

August 11, 2004

C-FER File: P061

Laboratory Testing of Artificial Lift Systems
for LP-SAGD Applications - Joint Industry Project

Attention: Steering Committee Members

Dear Participant:

Re: Can-K Test – Update on Status and Preliminary Results

Background

The proposed test program for the Can-K pumping system, incorporating the decisions made during the SCM #2, was sent to the Participants by e-mail on June 22.

This report provides you with an update on the status, and the preliminary results obtained during testing between June 17 and July 15, 2004.

Summary

The Can-K pumping system was first started in the afternoon of June 17 and it operated for about one hour. This time was used to tune up some of the control systems, mainly those that depended on the pump being in operation (such as those for the hydraulic motor speed and the downhole pump delta-P) and therefore could not be fully checked during the initial commissioning of the experimental loop. After one hour of operation a failure of the Can-K stuffing box produced a spill of oil and the loop had to be shut down.

Can-K made modifications to the stuffing box to make it more suitable for horizontal operation. C-FER also made some modifications to the test set-up, adding a second centralizer and a tighter support at the thrust bearing, in an attempt to provide additional radial support and prevent any excessive radial load on the stuffing box.

After the stuffing box was repaired, testing resumed on July 5. Some data was collected during the next 3 days, while a portion of the time was again spent tuning up the various control systems (pump intake pressure, temperature, rpm and pump differential pressure). In the evening of July 8, the torque started to increase without any obvious reason, so the test was stopped. The system was restarted but after a few minutes the torque increased again, so the decision was made to stop the test to assess the situation.

The Can-K stuffing box was removed and inspected and, according to Can-K, it was in good shape. The hydraulic motor was tested at 800 rpm without load, and the torque reading was very low and stable. The pumping system was pulled out of the loop, and rod string and the centralizers were inspected with no evidence of excessive wear found.

After consulting with ConocoPhillips (and Sandeep Solanki on behalf of the SC) a decision was made to restart the system but using a different stuffing box from R&M (which had been purchased as a contingency item). The system was re-installed but after start-up a similar increase in torque was observed. The downhole pump system was then retrieved and shipped back to Can-K.

A summary of the partial results gathered during the tests is presented below, along with a discussion of key observations made during the time the pumping system was in operation.

June 17, 2004

The equipment was started around 4:40 p.m. and operated for about one hour, with the stuffing box failing at about 5:40 p.m. Figure 1 shows a summary of the behaviour of the main operating parameters until the moment the test was suspended due to the stuffing box incident. Key observations are discussed below.

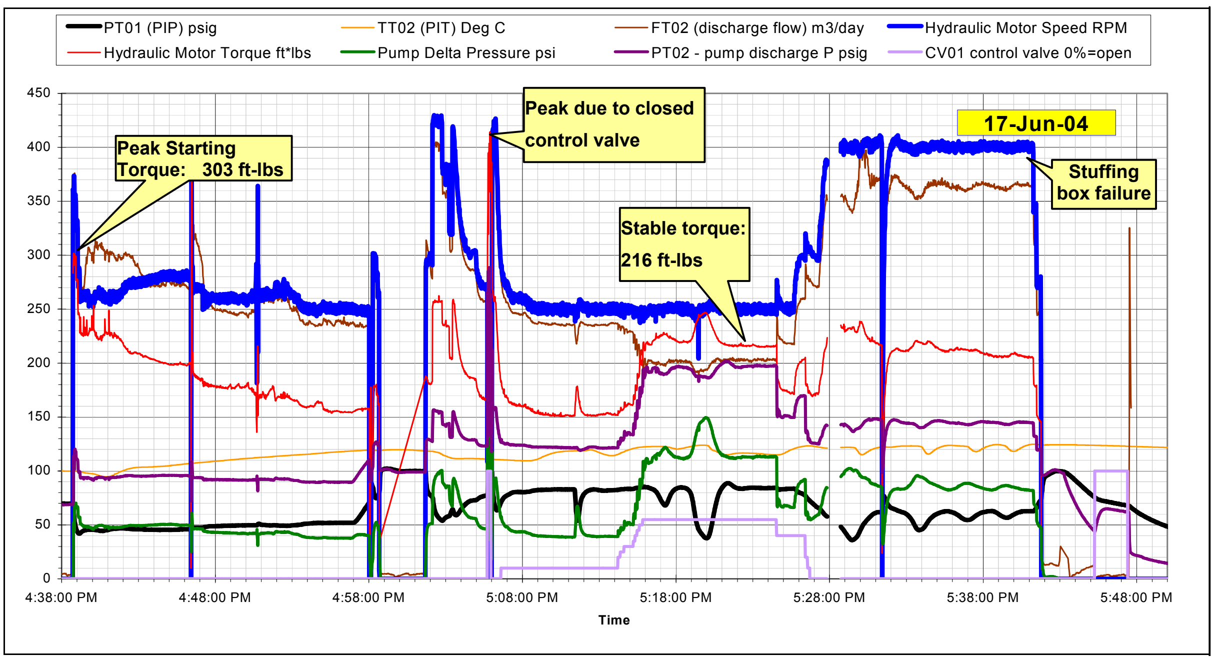


Figure 1

As requested by the SC, a stand-alone high-speed data acquisition system (HS-DAS) was set-up in order to gather torque data during the pump start-up. The measured data is shown in the figure below. Note that the measured peak torque (303 ft-lb) matched the one obtained from the main DAS.

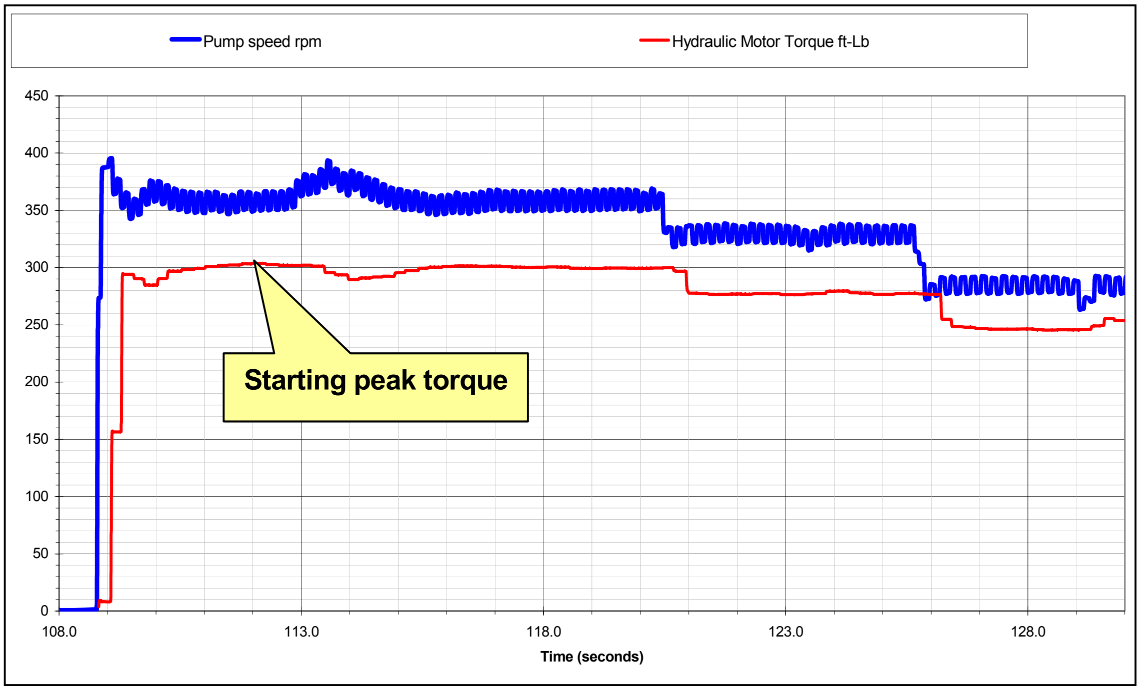


Figure 2

The ripple in the rpm signal was investigated, and it is believed to be caused by the set-up used to measure the rpm (two magnetic marks on the shaft and one magnetic pick-up transducer) rather than by any actual variation of the shaft speed.[1]

During the one hour of operation, the main operational parameters varied as follows: Pump Intake Pressure (PT01): 42 to 100 psig; Temperature (TT02): 95° to 125°C; Pump speed: 250 to 430 RPM; Hydraulic Motor Torque: 150 to 414 ft-lbf ; Flow Rate: 200 to 400 m^3/d; and Pump DP: 80 to 192 psi.

Clearly, there were several periods of stable operation, such as the one around 5:22 PM, further illustrated in the Figure 3 below. During this two-minute period, the average values of the main operating parameters are shown in Table 1:

PT01 (PIP) (psig)	TT02 (PIT) (° C)	Hydraulic Motor Speed (RPM)	Hydraulic Motor Torque (ft*lbf)	Pump Delta Pressure (psi)	FT02 (discharge flow) (m^3/day)
84.0	116.2	249.8	215.9	113	202.9

Table 1

[1] Adjustments were made to the DAS the following day to remedy this ripple

According to Can-K, the values measured for torque and flow rate at this speed and differential pressure were as expected.

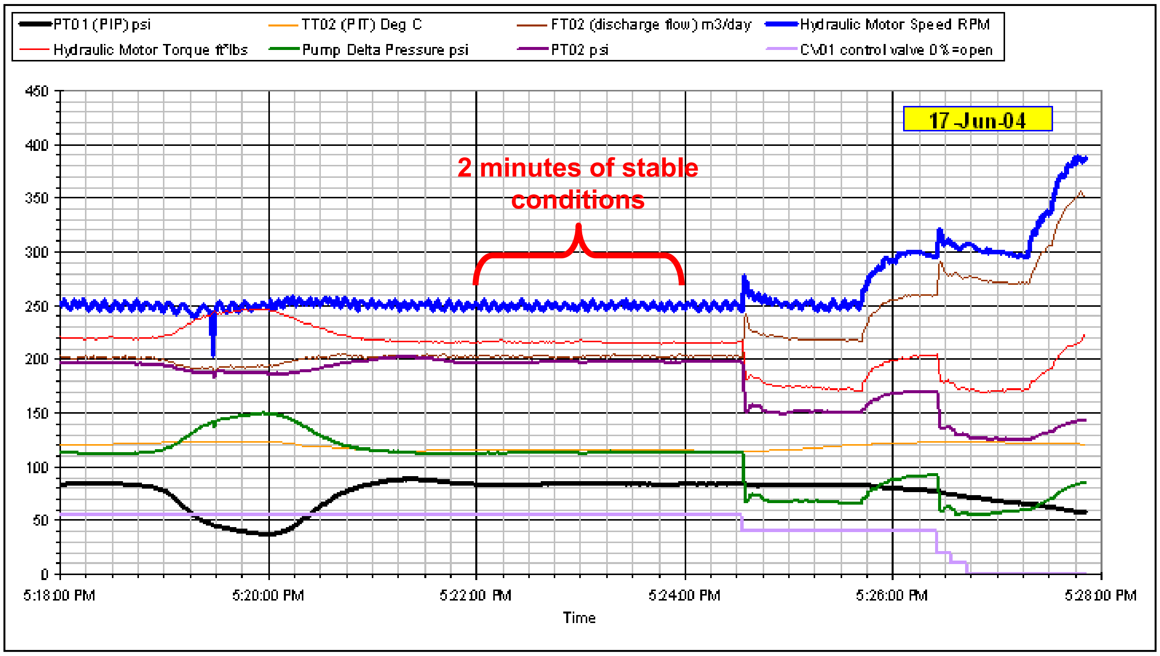


Figure 3

As indicated in Figure 1, there was a short period of time around 5:06 PM when the control valve used to adjust discharge pressure remained closed (for about 13 seconds), due to a configuration problem in the automatic control system[2]. As the torque increased, the motor shaft speed went to zero. As seen in Figure 4, while the valve was closed, the control system tried to restart the pump six or seven times, but every time the torque increased again and the shaft speed returned to zero. The pump finally successfully restarted after the valve was open.

[2] Additional protections have been included in the LabView application and in the operational procedures to prevent the same situation from occurring in the future.

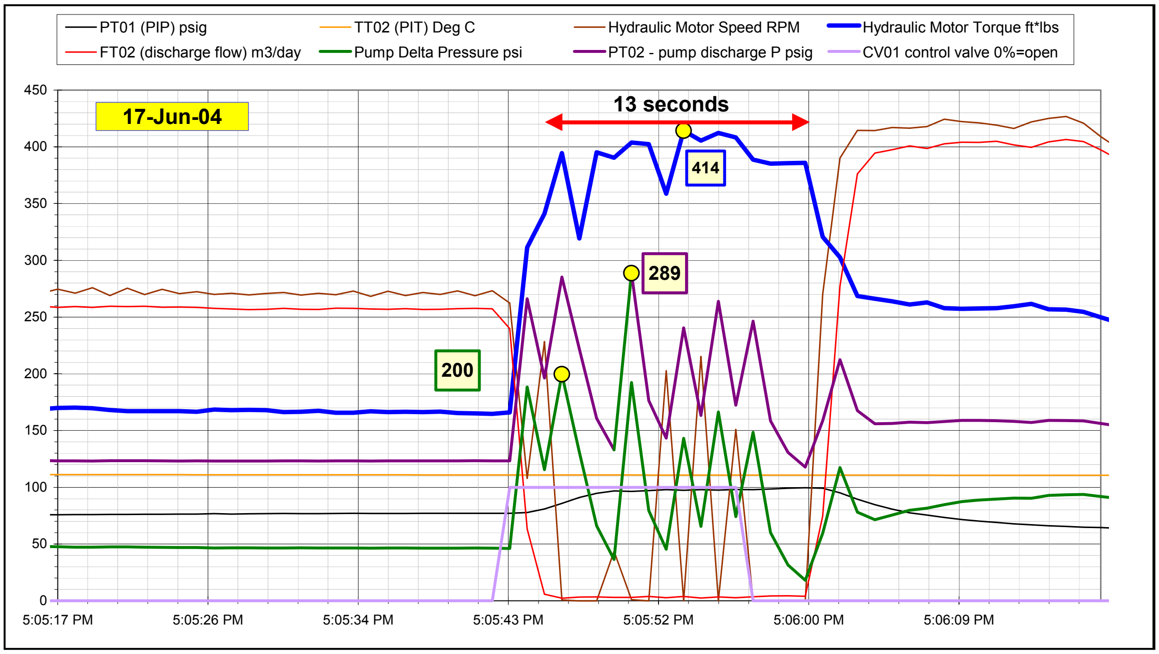


Figure 4

It is important to note that due to the limit imposed by the hydraulic motor capacity, the maximum torque applied to the system during this period was limited to 414 ft-lb, and the maximum differential pressure was just 200 psi.

While several periods of stable operation were achieved, there was some trouble trying to maintain a constant pump speed. In our set-up, the hydraulic motor speed is controlled through a control valve in the hydraulic power loop, as detailed in Figure 5 below.

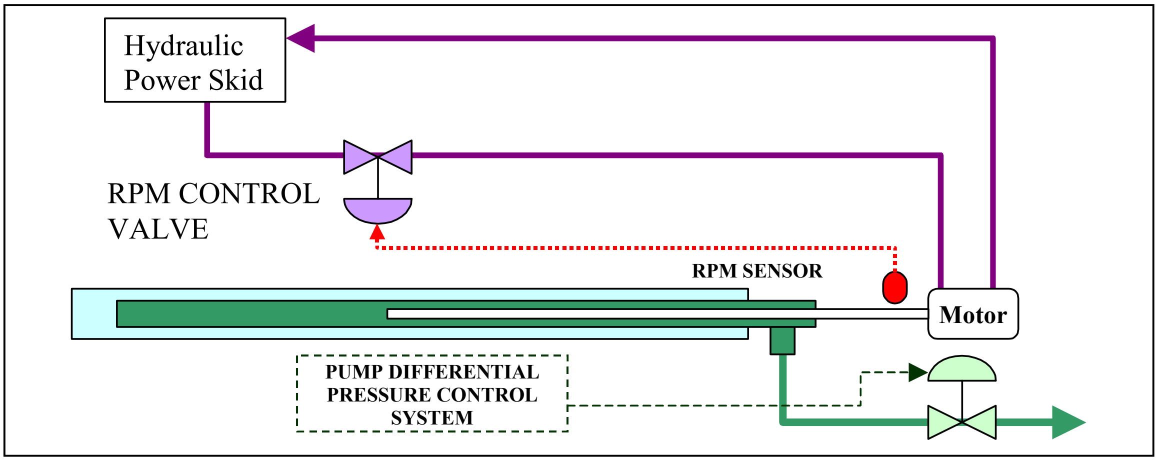


Figure 5

For a constant torque at the motor, closing the valve decreases the hydraulic fluid flow rate and therefore the motor speed. The decrease in motor speed causes a decrease in the system flow rate. Therefore, if the pump differential pressure control is not active, and the pump differential control valve opening is not changing, a decrease in the pump delta-p and in the torque will be observed. This normal behaviour is illustrated in Figure 6 below.

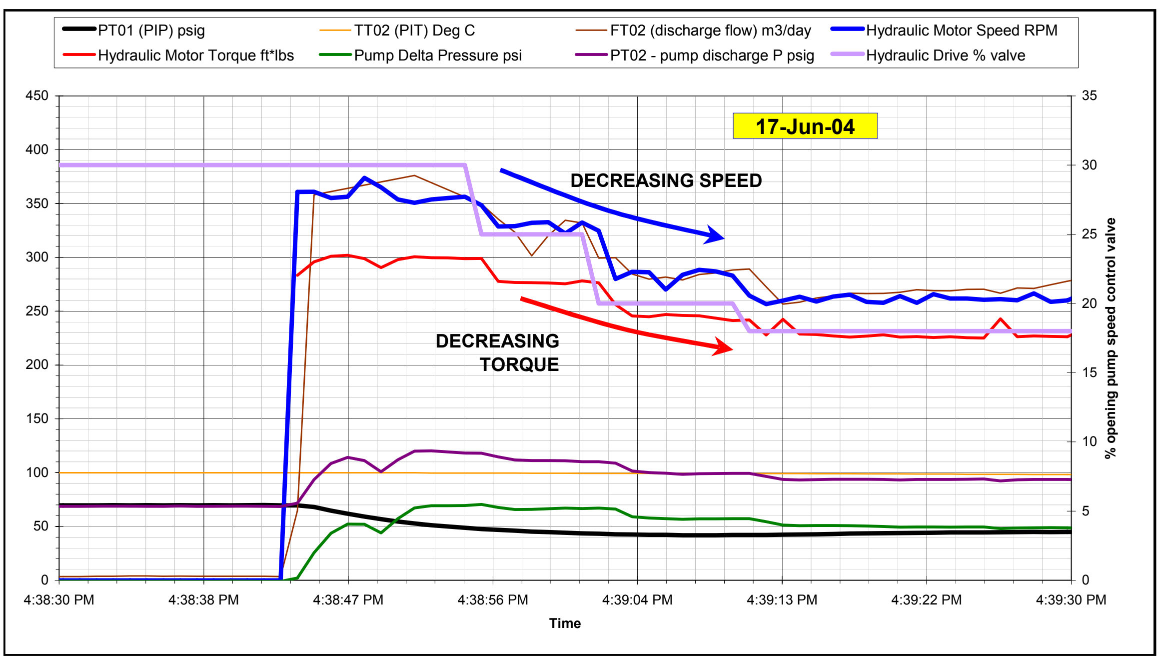


Figure 6

If the pump differential pressure control valve is (partially) closed, and both the pump delta-p and the torque go up, the hydraulic fluid flow rate will tend to decrease (because the hydraulic power system has a constant power), and so will the motor speed. However, if the motor speed control is active, the control valve in the hydraulic power loop will open to re-establish the desired motor speed.

Proper setting of the PID constants is required to keep the system stable. Therefore, when the test started to have trouble trying to maintain a constant pump speed, it was first thought that the problem was being caused by improper PID constants. However, further examination of the data indicated that some of the observed fluctuations were being trigged by unexpected changes in the pumping system torque, as illustrated in Figure 7.

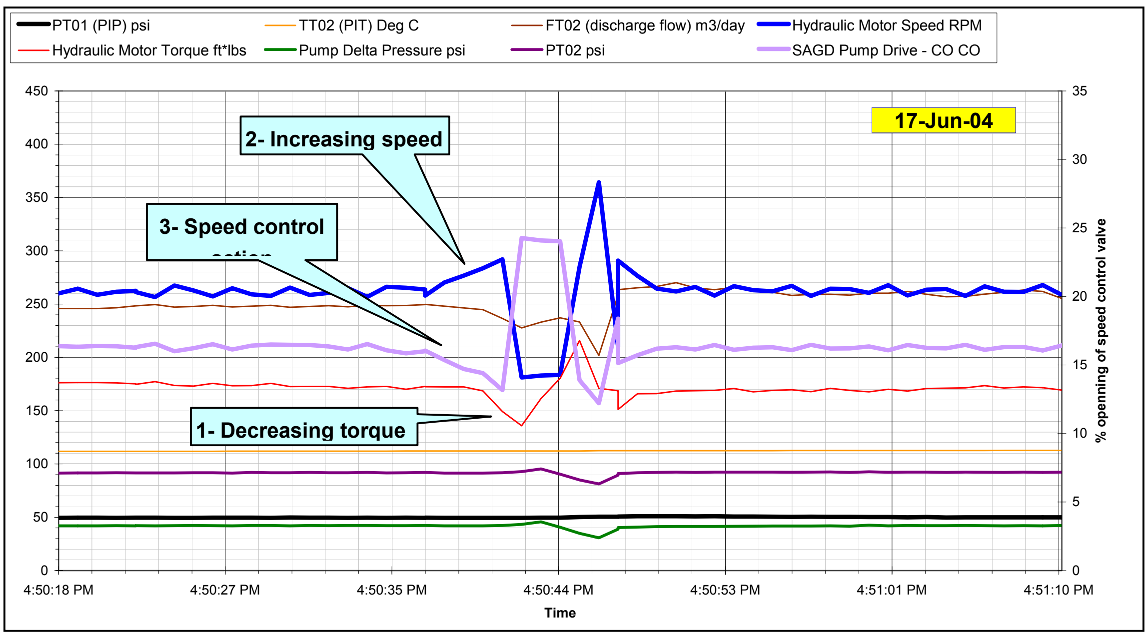


Figure 7

The torque starts going down for no apparent reason. As expected, the motor speed initially rises (because the hydraulic power system has a constant power). However, the motor speed control system orders the control valve in the hydraulic control loop to close to try to re-establish the desired motor speed. The variables fluctuate up and down until a new stable plateau is achieved.[3]

The decrease in motor speed cannot be attributed to any change to the parameters being controlled. An increase in motor speed, for instance, would result in an increase in torque (as discussed above), not a decrease in torque (as observed).

---

[3] The recorded channels have "moving average" filters which causes a relative delay between the signals recorded from the channel; this explains why the change in torque seems to happen after the change in motor speed.

Figure 8 illustrates a period in which the pump differential pressure control valve was fully open (not shown) and the opening of the motor speed control valve was constant. Nevertheless, the torque experienced variations of about 8% of its average value.

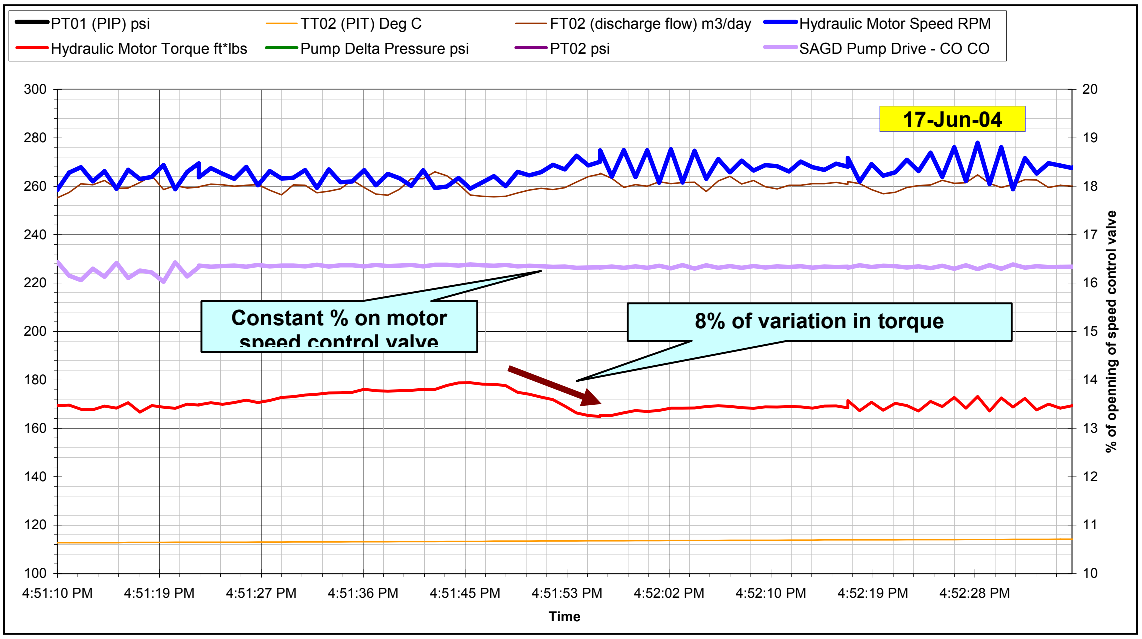


Figure 8

It is important to note that these unexpected variations in torque were being observed even before the short duration where the differential pressure control valve was closed (which occurred at 5:06 PM).

July 05, 2004

After Can-K repaired the stuffing box, the test program resumed and C-FER attempted to build the pump curve for oil at 120°C and 250 rpm. As shown in Figure 9 below, for the first two values of delta-p (40 and 100 psig) the operation was quite stable. However, for higher values of delta-p, there were problems in obtaining a period of stable operation.

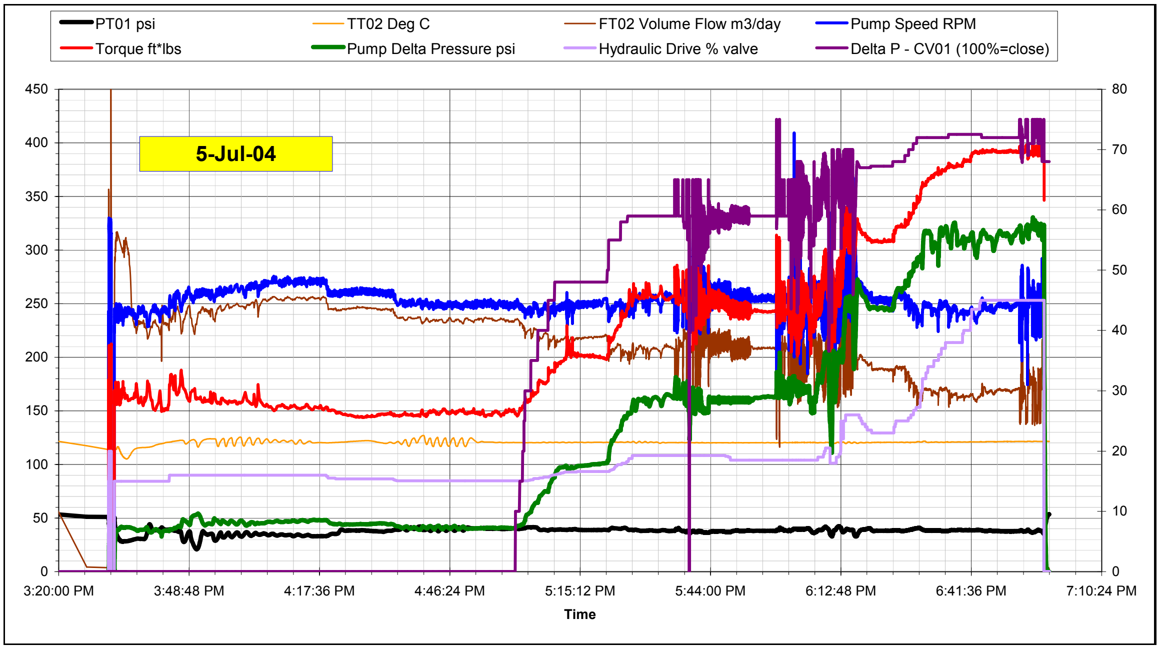


Figure 9

Nevertheless, at all levels of differential pressures, there were brief periods (of two minutes of more) of stable operation, which we could use to build the pump performance curve, as illustrated in the Figure 10. The average values of the main parameters over these periods are shown in Table 2 below:

PT01- PIP (psig)	TT02 - PIT (deg C)	Pump Speed (rpm)	Pump Delta Pressure	FT02 Flow rate (m3/d)	Torque (ft-lbf)
40.0	120.6	249.6	40.9	235.1	162.1
38.9	120.7	250.1	100.5	219.0	211.8
38.0	120.2	255.0	163.0	208.5	251.4
38.2	120.6	253.1	245.4	188.7	312.9
37.6	121.3	248.1	314.3	169.3	391.7

Table 2

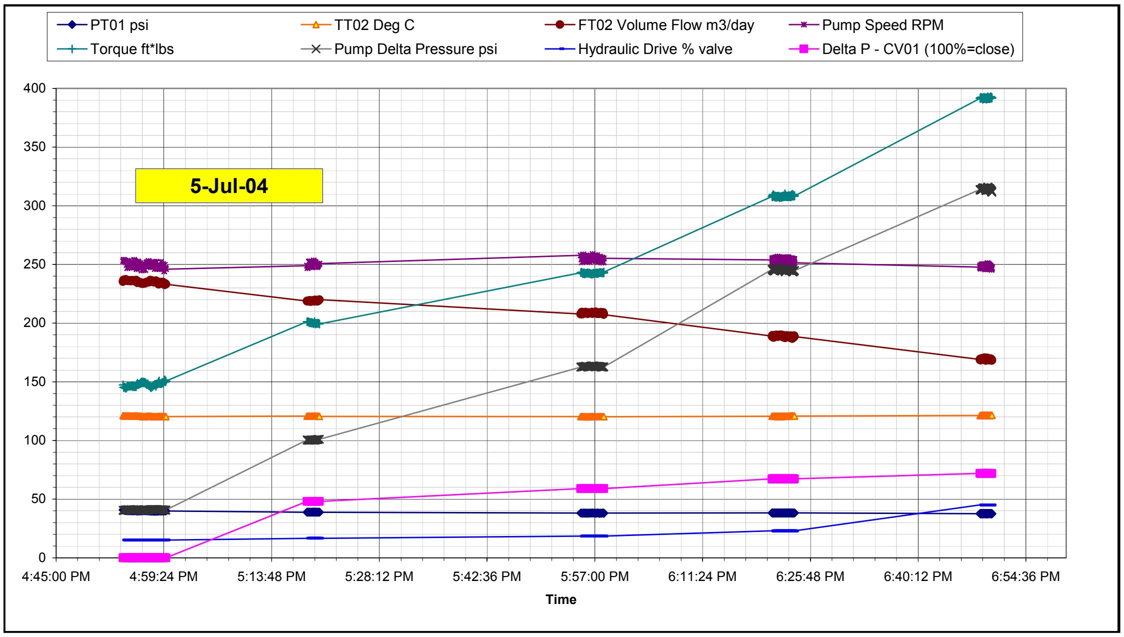


Figure 10

Figure 11 shows the pump curve, at 120°C and 250 rpm, built with these average values.

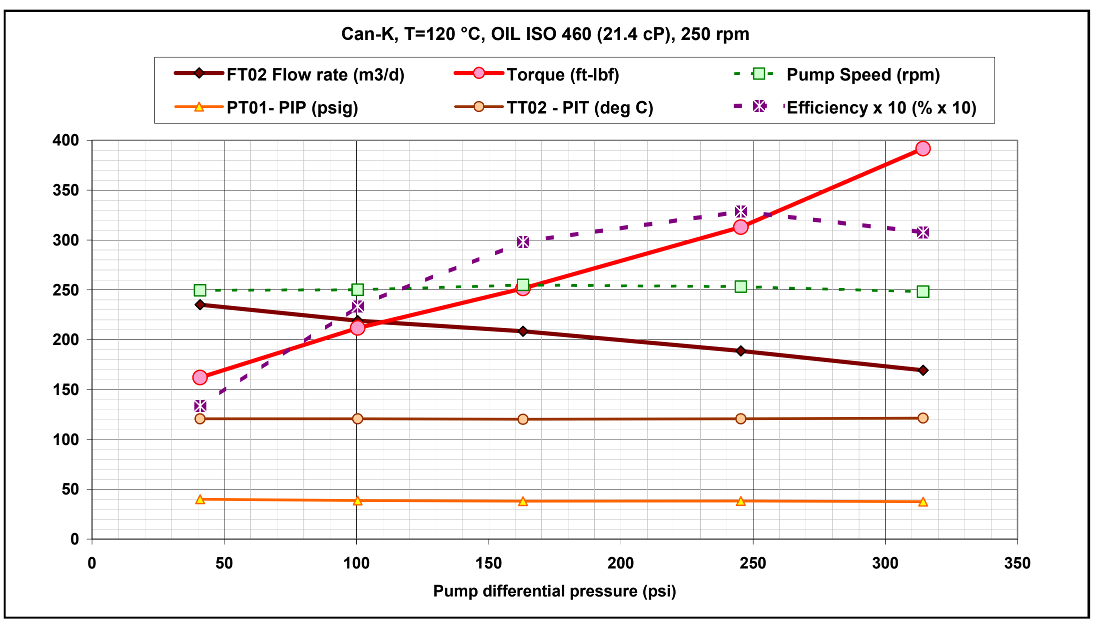


Figure 11

When the data acquired that day was examined more carefully, abnormal variations in torque in the order of 5% to 10% were observed again, as illustrated in Figure 12.

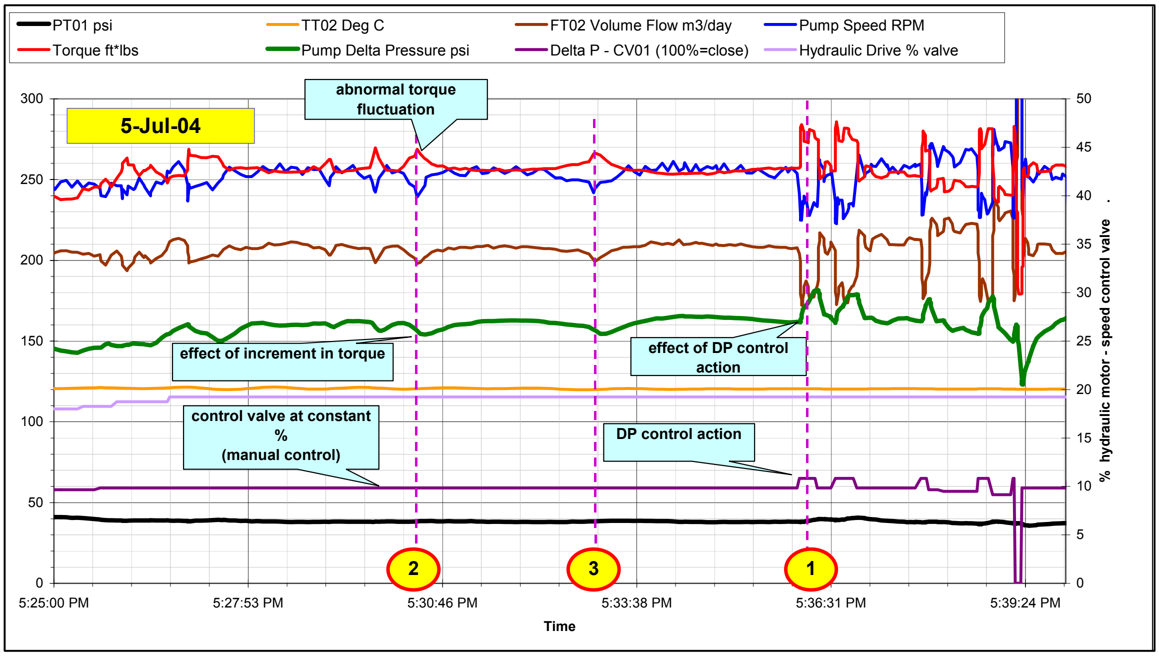


Figure 12

At the time identified as “1”, the action of the differential pressure control valve resulted in an increase in the differential pressure, an increase in torque, and a decrease in the pump speed, which corresponds to a normal system behaviour.

At the times identified as “2” and “3”, both the differential pressure and the motor speed control systems were inactive, yet there was an increase in the torque, followed by a reduction in the motor speed, the flow rate and the pump differential pressure. Again, the increase in torque cannot be attributed to changes in the controlled parameters. A reduction in the motor speed or in the pump differential pressure should result in a decrease in torque, not an increase. This suggests that something else was affecting the value of the torque required by the pumping system.

Another way to examine this effect is by estimating and plotting the theoretical values of the output (hydraulic) power delivered by the pump and the input (mechanical) power delivered by the motor:

$$HP\ (pump) = delta\text{-}p\ (psi) \times Q\ (m^3/d) / 9344$$

$$HP\ (motor) = Torque\ (in\text{-}lb) \times RPM / 63025$$

The ratio of these two values is the pumping system overall efficiency[4]:

E = HP (pump) / HP (motor)

Figure 13 illustrates that, in general, the pump and the motor power followed each other. It also shows that the overall pumping system efficiency varied between 12% and 34%.

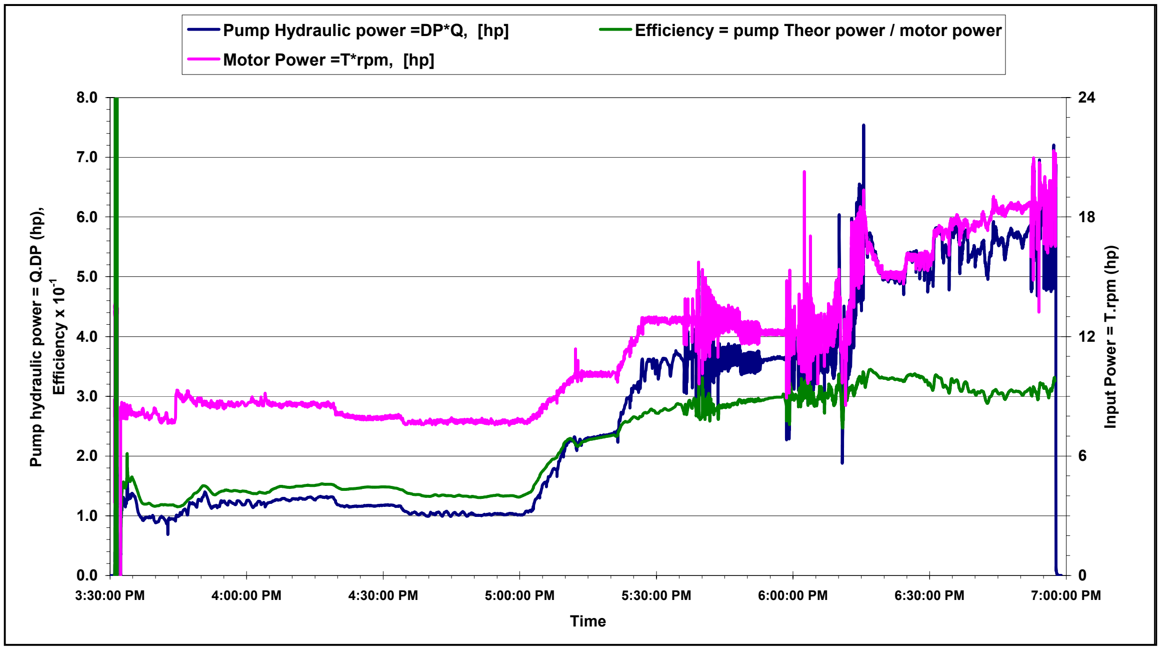


Figure 13

The close relationship between HP (motor) and HP (pump) can be better observed in a different scale, as illustrated in Figure 14[5].

---

[4] This definition of efficiency includes both the pump volumetric efficiency and the pumping system mechanical efficiency. Efficiency is lower at low delta-p, because most of the energy provided by the motor is used to overcome friction within the downhole components and at the stuffing box.

[5] The time variable was changed from actual time to seconds, in order to allow the plot to reflect changes occurring in fractions of a second.

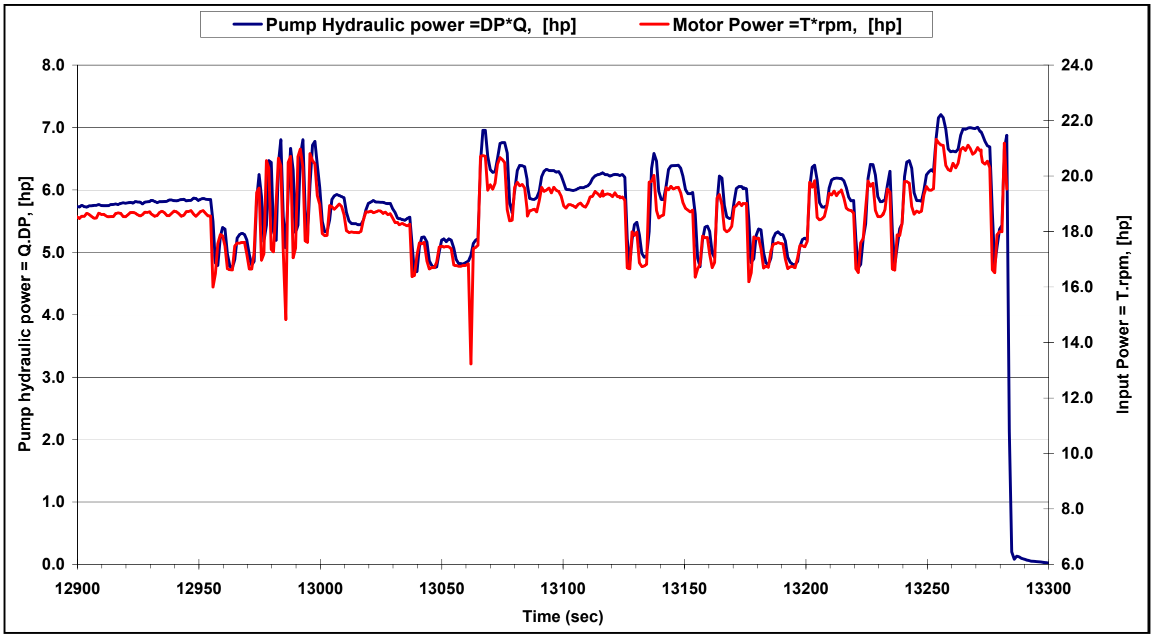


Figure 14

The above behaviour is the "normal" behaviour of the pumping system.

When the same plot was generated around the times where abnormal variations in torque were observed, a sudden increase in motor power, not corresponding to an increase in the pump power, could be seen, as illustrated in Figure 15. Again, this suggests that something else was affecting the value of the torque required by the pumping system.

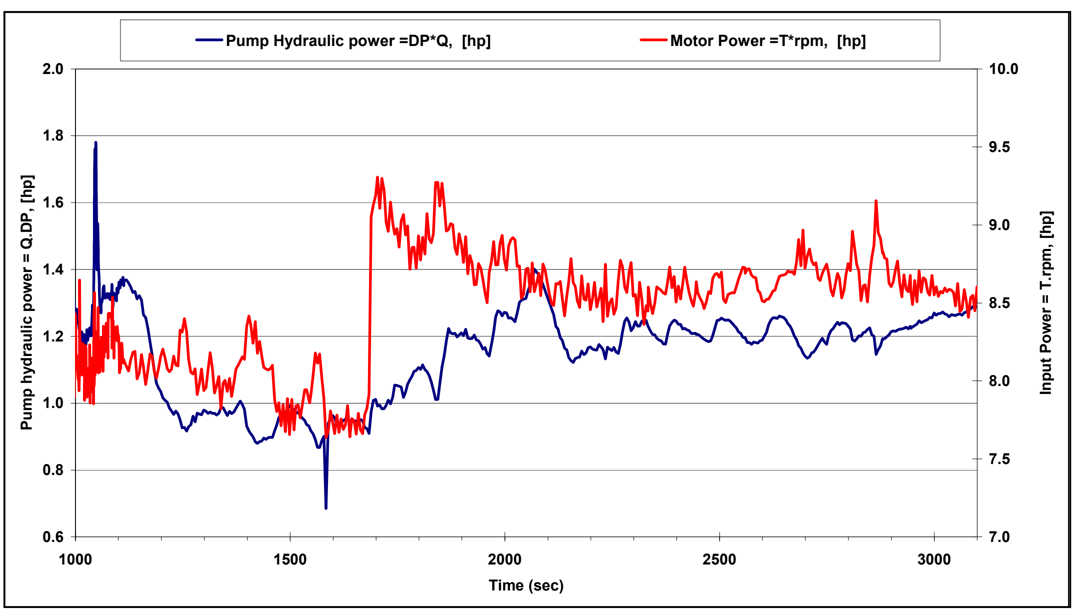


Figure 15

July 08, 2004

Between July 5 and July 8, the Can-K pumping system remained shut down while C-FER performed modifications to the experimental loop control systems. Testing resumed on July 8, with the goal of building the pump curve for oil at 120°C and 375 rpm.

That day problems were again experienced in obtaining periods of stable operation and the system was intentionally stopped at about 7:25 p.m. to check some of the instrumentation. The system was restarted after 30 minutes, at about 7:55 p.m. C-FER was in the process of stabilizing the temperature when the torque started to ramp up without any apparent reason. It finally reached the maximum value available at the hydraulic motor and the system had to be stopped. A system restart was attemped, but after 2 minutes the system had to be stopped due to high torque. Figure 16 shows a summary of the system behaviour during this time.

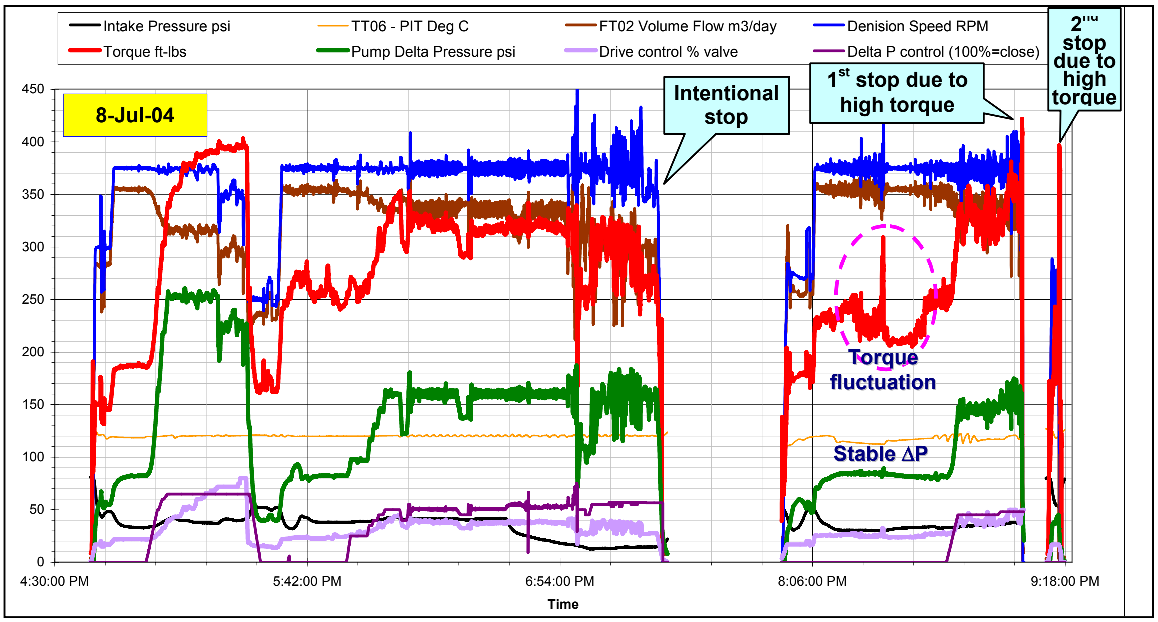


Figure 16

As a result of previous discussions with Can-K, ramp up and ramp down steps were incorporated into the procedures. With this, the start up torque was lower than the observed before (190 vs. 210 ft-lb). Note that the peak torque occurred before the system started to rotate, as shown in the Figure 17.

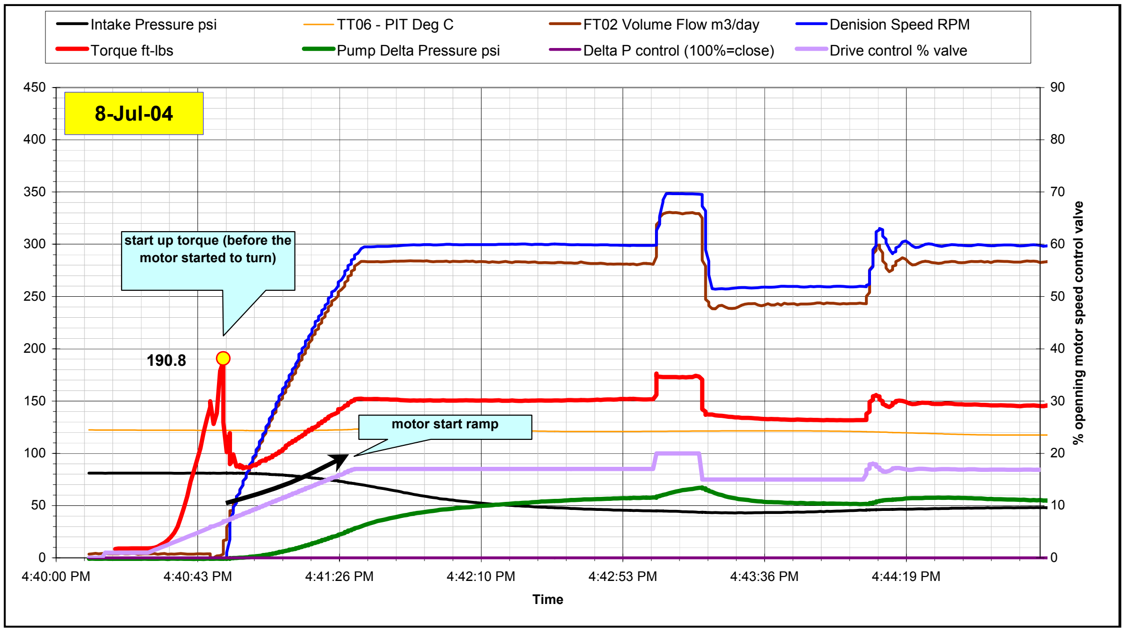


Figure 17

Further analysis of the data showed that when trying to establish the maximum differential pressure achievable with the hydraulic motor (at around 5:00 p.m.) there was an important increase in torque (about 11%) which was not related to any increase in differential pressure, as shown in Figure 18:

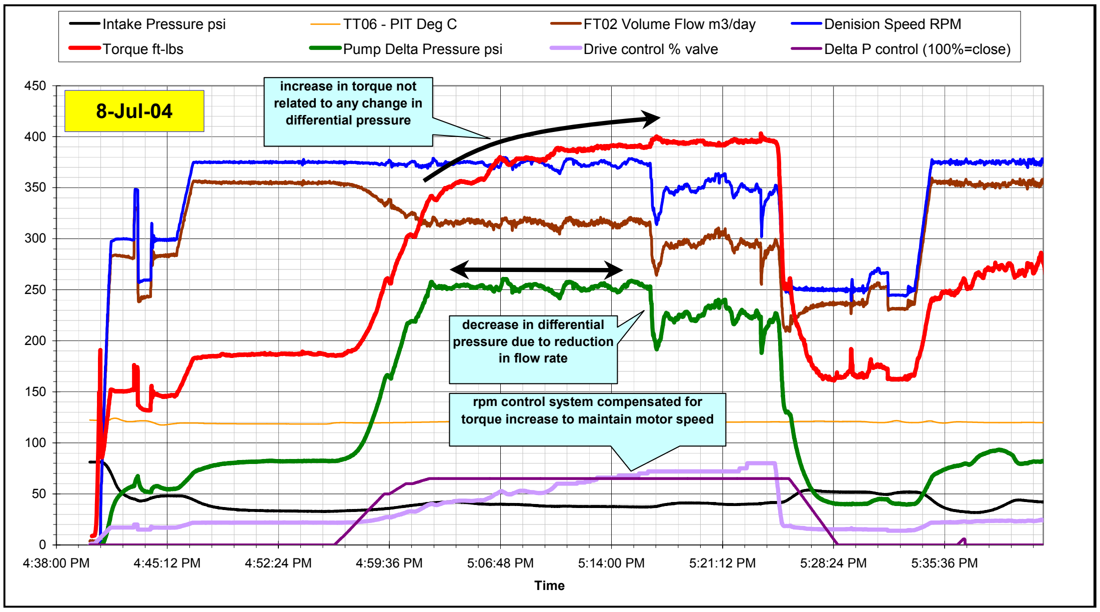


Figure 18

The fluctuations in the torque were more pronounced after the intentional stop. The period immediately before the torque reached the maximum torque available at the motor is illustrated in the Figure 19.

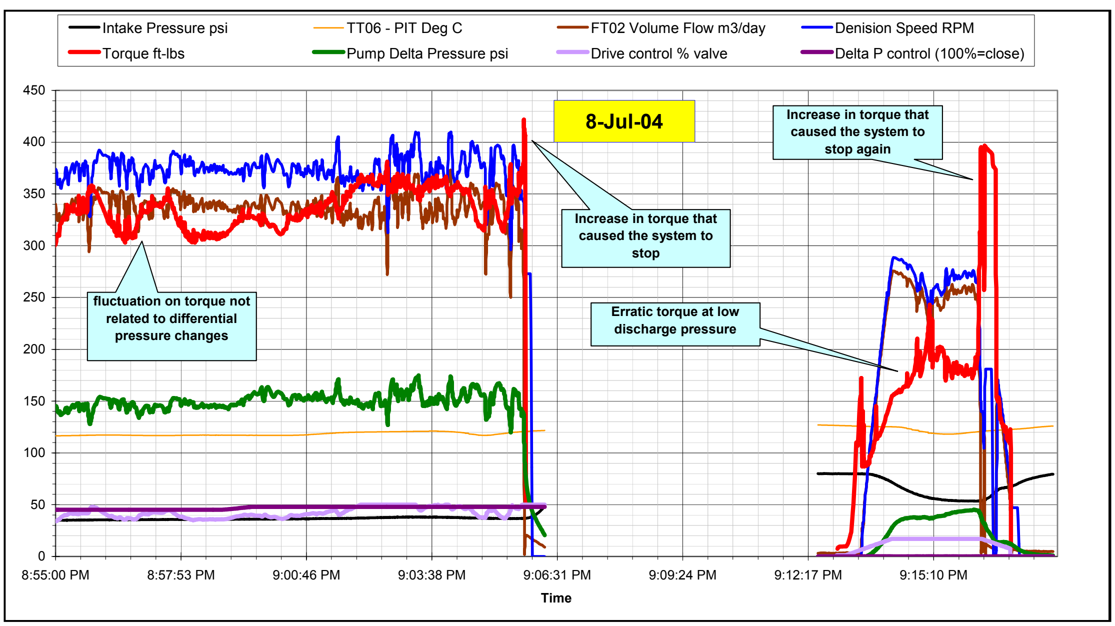


Figure 19

Once again, despite the problems encountered in achieving periods of stable operation, it was still possible to identify four short periods (95-110 seconds) of relative stable operation that were then used to build a pump performance curve. These periods are illustrated in Figure 20. Note that, except for a couple of points, the torque was not steady but rather varying during the period.

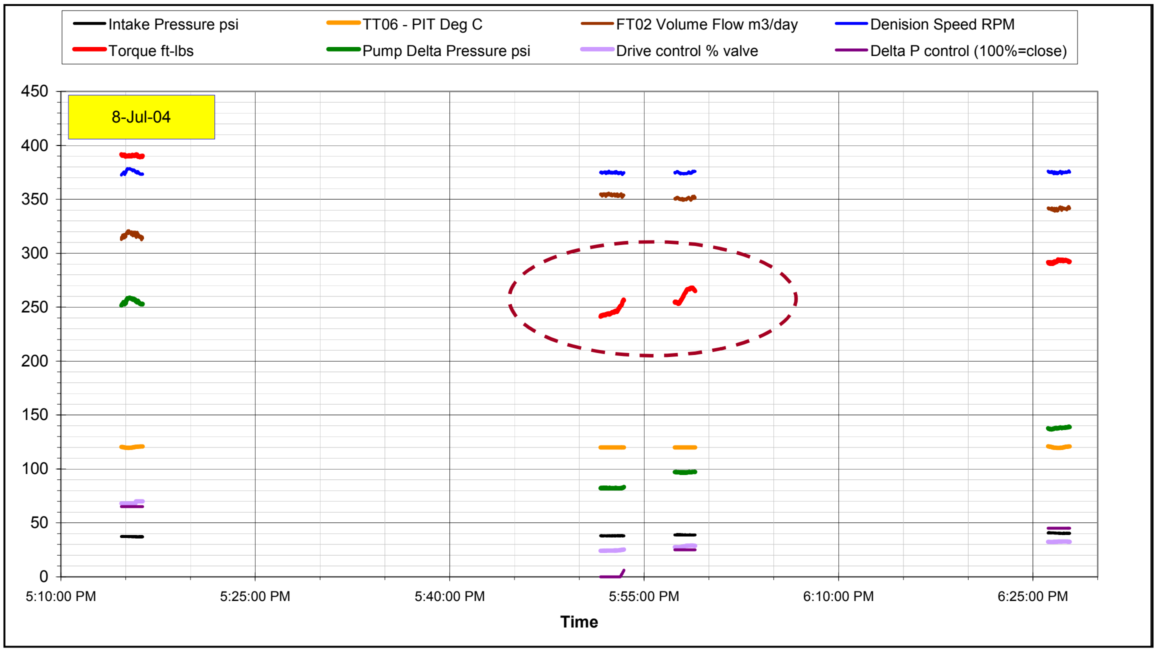


Figure 20

The average values of the main parameters over these periods are shown in Table 3 below:

Pump Delta Pressure (psi)	FT02 Flow rate (m3/d)	Torque (ft-lbf)	Pump Speed (rpm)	PT01- PIP (psig)	TT02 – PIT (deg C)
82.3	354.1	246.2	374.7	38.0	120.0
96.9	350.7	261.4	374.6	38.9	120.0
137.9	341.2	292.4	375.0	40.5	120.1
255.6	317.0	390.4	375.6	37.2	120.0

Table 3

Figure 21 shows the pump curve, at 120°C and 375 rpm, built with these average values. Note that the torque at 375 rpm is larger than at 250 rpm, for the same differential pressure. This may potentially be explained by the existence of a viscous frictional torque at the downhole gear box, which would be expected to be proportional to the rotational speed. Although the overall efficiency is more strongly affected by the differential pressure, it is also affected by the speed. However, no conclusion can be made since the mechanical condition that was causing the erratic torque (which would be expected to get worse with time), might have also affected the overall efficiency of the pump.

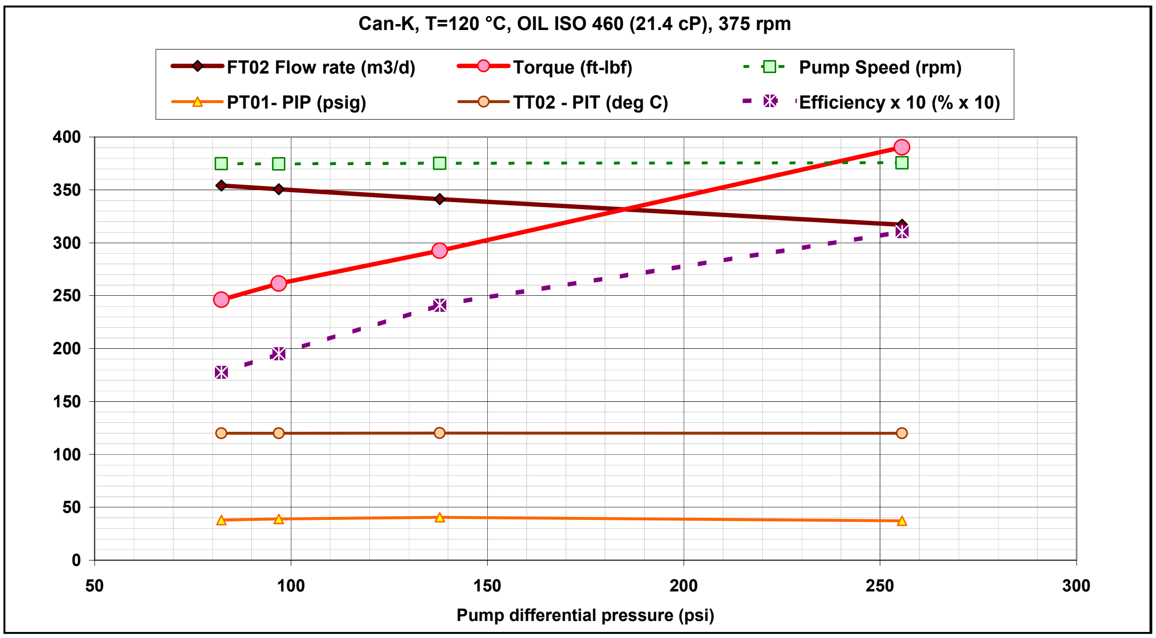


Figure 21

During that day, the first attempt to determine the NPSH limit for this pump was also made, as illustrated in Figure 22.

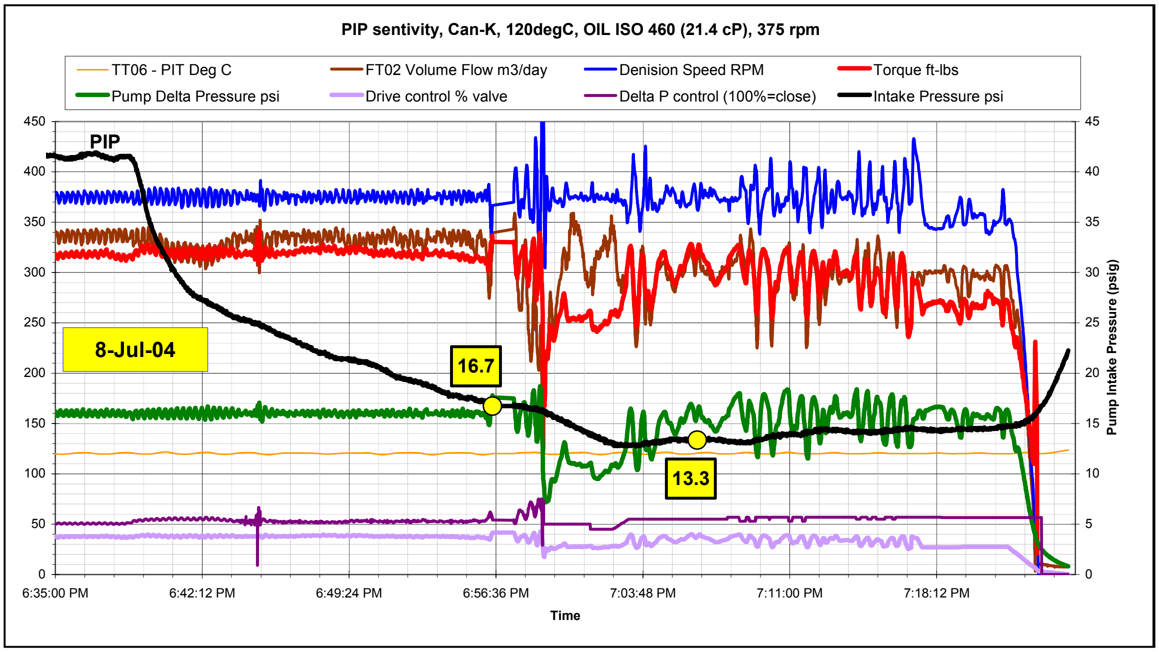


Figure 22

With a stable delta-p of approximately 160 psi, the intake pressure (PIP) was progressively reduced. As shown in the figure, stable operating conditions were maintained until reaching a PIP of about 16.7 psig. Around this value, the flow rate started to oscillate, and there were problems maintaining a constant pump speed, mainly due to the interdependency between flow rate, pump delta-P, motor torque and motor speed, as explained before. At 13.3 psig, fairly stable readings were again achieved. However, while the average values for motor speed and pump differential pressure were still the same as before, the average value for flow rate was significantly less (300 m^3/day versus 340 m^3/day). Based on this data, it was concluded that at 375 rpm and 120°C the NPSH limit for this pump is between 13.3 and 16.7 psig.

July 15, 2004

As described before, after consulting with ConocoPhillips (and Sandeep Solanki on behalf of the SC) a decision was made to try to restart the system, but using a different stuffing box, from R&M (which had been purchased as a contingency item).

Following Can-K's suggestion, the pump was started at a lower temperature (75°C). At this temperature, however, C-FER was unable to achieve the minimum speed recommended by Can-K (250 rpm). When the speed reached 190 RPM, the torque had already reached 390 ft-lb, therefore it had already approached the maximum value allowed at the motor. The decision was made to stop and continue heating the fluid. It was also decided to increase the hydraulic skid limit a bit (about 5%) in order to have more room to apply torque to the pumping system.

At about 90°C, another attempt to start the system was made. This time, 270 rpm was achieved.

The torque stayed around 310 ft-lb for approximately two minutes. It started to ramp up again reaching a value of 440 ft-lb and the system had to be stopped.

At approximately 110°C, six other attempts to start the system were made, as illustrated in Figure 23. In the first attempt, using a 60-second ramp up, the start up torque was 127 ft-lb, and stable operation at 270 rpm was achieved for approximately two minutes, with a torque of 204 ft-lb. The torque then increased rapidly to 425 ft-lb and the system had to be stopped. Three more attempts were made using a 60-second ramp up, but the torque increased beyond 300 ft-lb with no rotation at the polished rod, so the further attempts were aborted. After confirming with Can-K, a fifth attempt was made, but with no ramp-up (i.e. the system was started by applying a sudden torque). This time C-FER was able to achieve relatively stable operation at 270 rpm for about 80 seconds. The torque initially fluctuated around 230 ft-lb but went up again to 426 ft-lb and the system was stopped. As per Can-K's request, a sixth and final attempt was made with the same results (this time the operation was stopped when the torque reached 346 ft-lb).

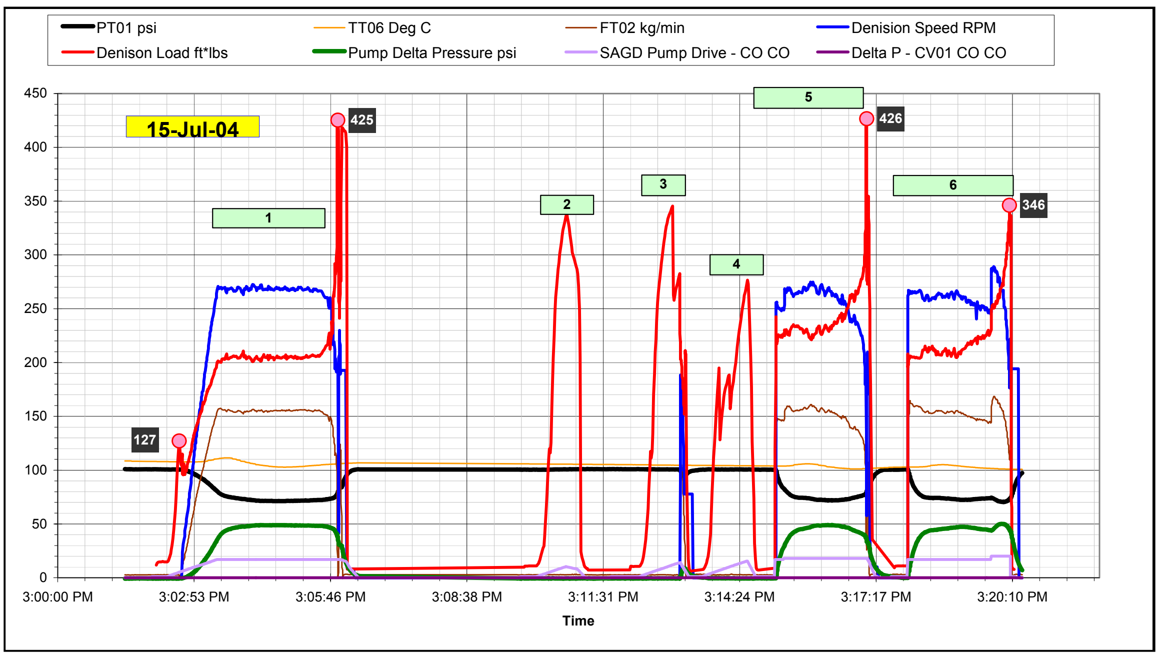


Figure 23

Conclusions

- C-FER was able to complete only limited testing with the Can-K pumping system. Two pump curves were built, at 250 and at 375 RPM, both with oil and at 120°C. At 375 RPM, a NPSH test was also completed.
- The testing program had to be interrupted because of unexpected increases in the torque demanded by the Can-K pumping system.
- At all times, the maximum torque applied to the pumping system did not exceed the maximum capacity of the hydraulic motor, of approximately 425 ft-lb.

- An erratic fluctuation in the torque measured at the hydraulic motor was recorded since the first day of operation.

- The limited testing conducted with the Can-K pumping system allowed C-FER to further troubleshoot the experimental loop control systems.

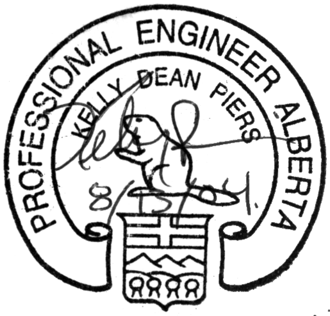
- Difficulties were encountered in achieving stable operational periods; it is unknown to what extent difficulties can be attributed to the erratic fluctuations observed in the torque required by the pumping system.

- C-FER had to install/disassemble the Can-K pumping system in the experimental loop twice: first for the original installation and second to trouble shoot the torque fluctuations and replace the Can-K stuffing box with the R&M stuffing box. Additionally, a third partial disassembly was needed to install a second rod centralizer just below the stuffing box.

Yours sincerely,

for

Jorge Robles, MSc
Senior Researcher



Kelly Piers, PEng
Research Engineer

JR/acp/jmk

APEGGA Permit Number: P 04487

Reviewed by,

Francisco Alhanati, PhD, PEng
Manager, Production Technology

APPENDIX B

FLOW LOOP PID

C-01
AIR COMPRESSOR SKID
MAX DISCHARGE PRESSURE: 3448 kPag
FLOW: 1982 slpm

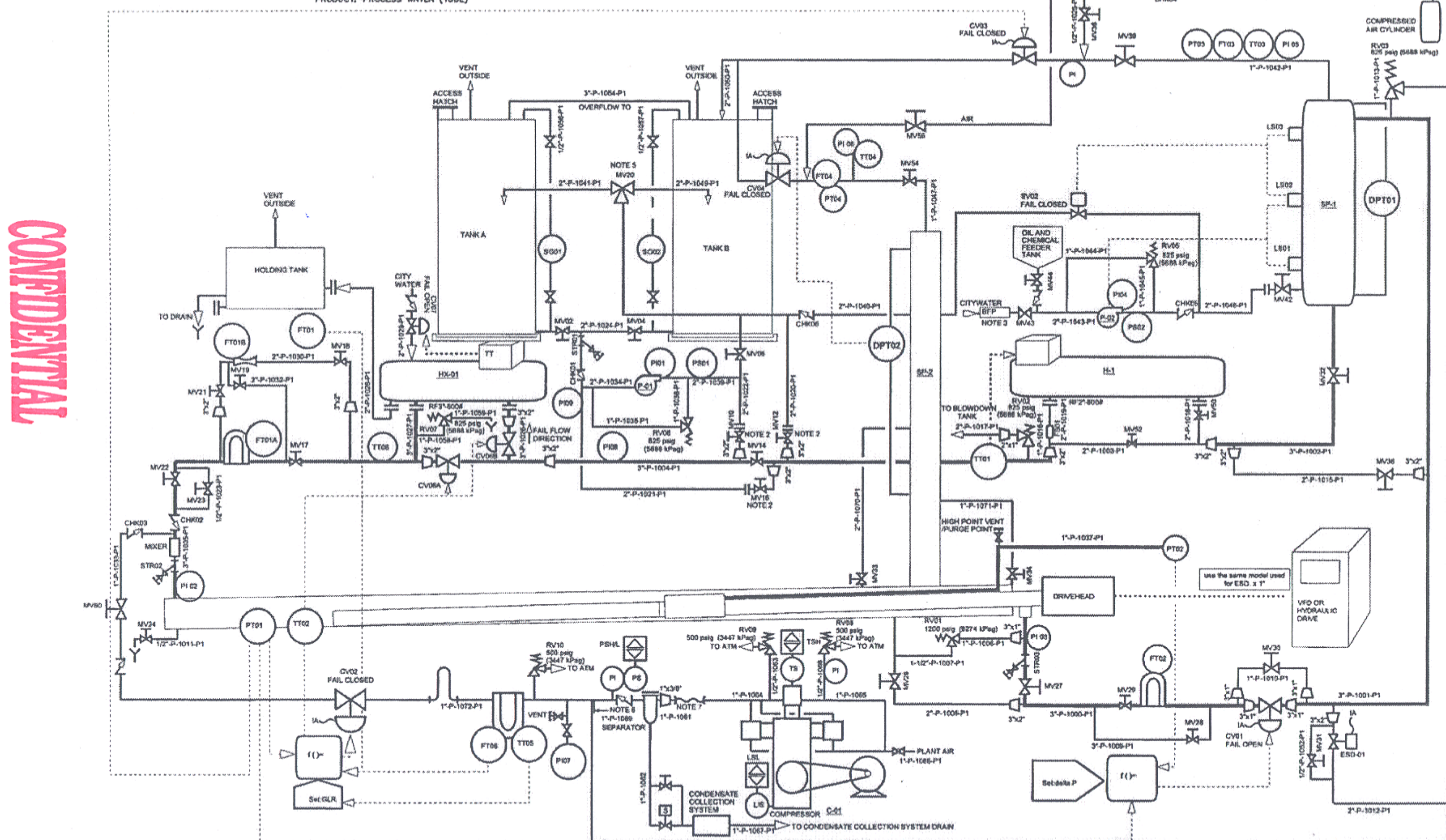
HX-01
WATER COOLER
DESIGN PRESSURE: 1,338 kPag (SHELL) / 6,205 (TUBE)
DESIGN TEMP.: 100 deg C (SHELL) / 288 deg C (TUBE)
EFFECTIVE SURFACE AREA: 42.1 SQ. M.
PRODUCT: COOLING WATER (SHELL)
PRODUCT: PROCESS WATER (TUBE)

P-01
PUMP
FLOW: 75.7L/min
RATING: 6,205 kPag @230 deg C

H-1
CIRCULATION HEATER
DESIGN PRESSURE: 6,205 kPa
DESIGN TEMP.: 230 deg C

P-02
PUMP
FLOW: 37.9 L/min
RATING: 6,895 kPag @100 deg C

SP-1
VERTICAL 2 PHASE SEPARATOR
DESIGN PRESSURE: 8,274 kPa
DESIGN TEMP.: 260 deg C
VOLUME: 810 L



NOTES:
1. REFER TO STANDARD INSTRUMENT INSTALLATION DETAILS
2. LOCK VALVES CLOSED DURING PUMP TESTS
3. POTABLE WATER CERTIFIED BACK FLOW PREVENTER
4. LOW POINT DRAINS AND HIGH POINT VENTS TO BE INSULATED WHERE REQUIRED
5. VALVE TO BE MAKE BEFORE BREAK
6. AIR COMPRESSOR VENDOR SCOPE
7. PARKER 29.5 MPA FLEXHOSE (MSHA)
8. FITTINGS ON C01 ARE PARKER PNEUMATIC FITTINGS RATED FOR SERVICE

REV NO	REVISION DESCRIPTION	DATE	BY	CHK	APP
1	IFC – CONSTRUCTION UPDATE	04-04-28	DK	DW	DW
0	ISSUED FOR REGISTRATION	04-03-01	DK	DW	DW
B	ISSUED FOR CLIENT REVIEW	04-02-20	DK	DW	DW

ENGINEER AND PERMIT STAMPS

PERMIT: APEGGA PERMIT NUMBER: P 7364

STAMP: PROFESSIONAL ENGINEER ALBERTA

ENGINEERING RECORD

	DATE	BY
DRAWN	04-04-28	DK
DESIGNED	04-04-28	DW
CHECKED	04-04-28	DW
APPROVED	04-04-28	DW
CLIENT APPROVED	04-04-28	JR

C-FER Technologies

ECO-Technica Inc. Edmonton, Alberta, Canada www.eco-technica.com

TITLE: CFER Technologies Test Loop PROCESS & INSTRUMENT DIAGRAM

SCALE: NTS | DRAWING: CFER-PID-01 | REV: 1