MODELLING

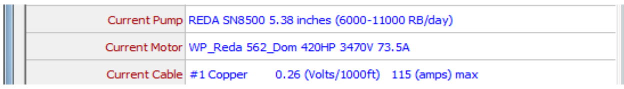
ESP Calculations in PROSPER

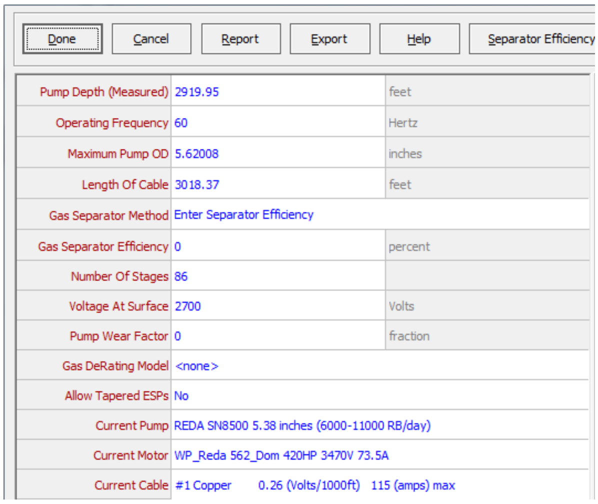
Introduction

ESPs are the most commonly used pumps in the oil industry for artificially lifting wells. The approach taken within **PROSPER** to capturing the impact of and ESP is described in this article. The objective is to provide an overview of the calculations used by the ESP model along with a validation against published references.

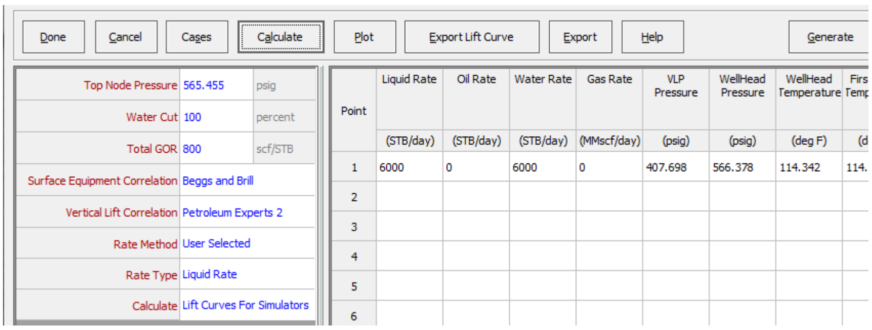
Context

The following presents a comparison of hand calculations with the equivalent **PROSPER** calculation. The calculation was conducted for the following pump, motor and ESP data:





The calculation was conducted by performing a VLP calculation for a WHP of 565.5 psig (40 Bara), a water cut of 100% and a fixed user specified rate of 6000 STB/day (6060 RB/day *in situ*):



The following presents a summary of the steps that are taken in the comparison with the **PROSPER** results:

1. Pump head is calculated using head curves
2. Pump dP evaluated from head
3. Pump power requirement calculated from HP curves
4. Power transferred to fluid evaluated from the mass flowrate and head
5. Pump efficiency evaluated from 3 and 4
6. Motor current, speed and efficiency calculated on the basis of the Motor curves and the pump power requirements
7. Cable voltage loss calculated from resistivity and the surface voltage requirement evaluated.

Please note that the Head and HP curves that are entered into the ESP database are for pure water (i.e. a salinity of 0 ppm).

MODELLING

ESP CALCULATIONS IN PROSPER

Comparison of PROSPER ESP calculations with a hand calculation

1. Pump Head Calculation

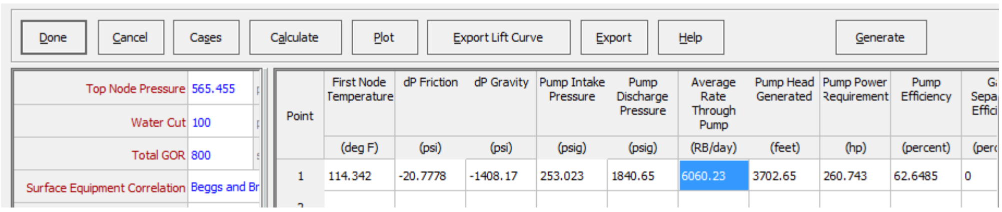
The first task we need to perform is to determine the head based on the *in situ* rate through the pump. This is done using the head coefficients.

PROSPER CALCULATION

In **PROSPER**, the head is determined by discretising pump into smaller sections of a few stages. This is necessary as the fluid properties (and hence the *in situ* rate) change through the pump as the conditions change. For each section, an iterative search is carried out to find an average rate through the pump section (based on the known inlet conditions and unknown outlet condition). Guessing an average *in situ* rate allows a head value to be determined from the curves which allows the outlet conditions to be calculated and therefore the average *in situ* rate to be calculated. Once converged, the assumed rate will match the calculated rate and then **PROSPER** proceeds to the next pump section until it reaches the last stage and therefore calculates the pump discharge conditions.

A VLP calculation is performed for a single rate of 6,000 STB/day of water (100 % water cut). The salinity of the water in the PVT section is 0 ppm.

This 6000 STB/day is equivalent to an average rate of 6060 RB/day through the pump for the conditions in the case below:



The head calculated by **PROSPER** is 3702 ft.

HAND CALCULATION

Assumptions

The calculation is being performed for pure water (0ppm 100% WCT). This allows us to make a simple hand calculation comparison as the properties of water are such that treating the pump as a single section should yield comparable results to the more rigorous approach undertaken by **PROSPER**.

If we assume the average rate through the pump is constant (i.e. the liquid is perfectly incompressible) and treat it as isothermal (no heating from motor or pump) then the head can be obtained for a single stage and multiplied by the number of stages to obtain a rough estimate of the total head gain provided by the pump.

Calculation

The head is calculated using the head coefficients for the pump in question:

Head Coefficients for Reda SN8500

C1	-1.21E-19
C2	1.02E-16
C3	1.23E-11
C4	3.28E-08
C5	-0.00355
C6	61.4764

$$C1Q^5 + C2Q^4 + C3Q^3 + C4Q^2 + C5Q^1 + C6$$

Where the average *in situ* rate is 6060 RB/day and the coefficients are:

$$-1.21x10^{-19}x6060^5 + 1.02x10^{-16}x6060^4 + 1.23x10^{-11}x6060^3 + 3.28x10^{-8}x6060^2 - 0.00355x6060 + 61.4764 = 43.05ft$$

This results in 43.05 ft per stage. Over 86 stages this amounts to 3702.3 ft (43.05x86) of head which compares well with the value reported in **PROSPER** (3702.65ft).

For an oil system, the PVT correction for each discretisation of the pump would be significant and therefore the above approach (carried out by hand) will not yield as accurate results.

2. Convert the Head to Pressure

Next, we can convert the head to pressure by taking into account of the gravity of fluid, which gives a DP of 1589.7 psig and therefore an outlet pressure of 1843 psig. **PROSPER** more accurately calculates a value of 1840 psig.

This is because of the more rigorous approach which discretises the pump into sections allowing the PVT to be corrected. The PVT properties are adjusted in each discretised section allowing an average rate to be calculated through each section along with the head and discharge pressure. This then proceeds into the next section and so on until the pressure at the end of the last section is calculated.

3. Pump Power Calculation

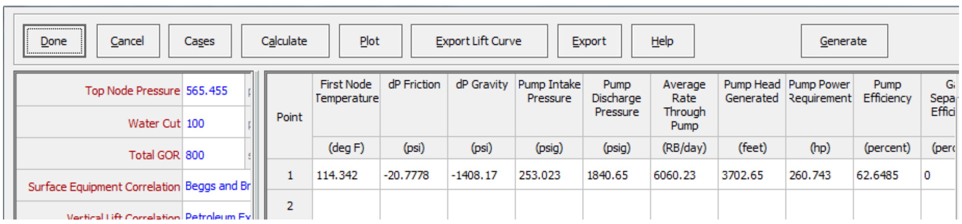
The power required by the pump can be determined using the HP curves for the pump using a similar approach to that outlined above:

$$C1Q^5 + C2Q^4 + C3Q^3 + C4Q^2 + C5Q^1 + C6$$

HP Coefficients for Reda SN8500	
C1	-8.14E-23
C2	-2.32E-17
C3	-9.54E-14
C4	2.86E-09
C5	8.15E-05
C6	2.51661

PROSPER CALCULATION

PROSPER reports a value of 260.7 HP as the pump power requirement.



HAND CALCULATION

The HP curves can be used to determine the HP requirement per stage of the pump:

$$-8.14x10^{-23}x6060^5 - 2.32x10^{-17}x6060^4 - 9.54x10^{-14}x6060^3 + 2.86x10^{-9}x6060^2 + 8.15x10^{-5}x6060 + 2.51661 = 3.06\ HP/stage$$

This gives a value of 263 HP (3.06x86) for the simplified calculation (i.e. non-discretised without PVT adjustment).

MODELLING

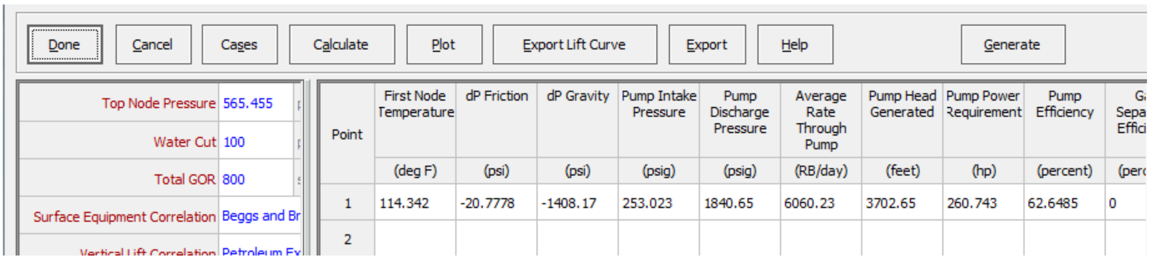
ESP CALCULATIONS IN PROSPER

4. Power transferred to fluid and pump efficiency

Only some of this energy is transferred to the fluid. The amount of energy transferred to the fluid can be determined on the basis of mass flow rate and the head. The efficiency is calculated on the basis of the ESP power requirement calculated above and the power transferred to the fluid.

PROSPER CALCULATION

The **PROSPER** calculation reports an efficiency of 62.5 %. This means that approximately 163 HP has been transferred to the fluid (0.62x260):



Point	First Node Temperature	dP Friction	dP Gravity	Pump Intake Pressure	Pump Discharge Pressure	Average Rate Through Pump	Pump Head Generated	Pump Power Requirement	Pump Efficiency	G Sepa Effic
	(deg F)	(psi)	(psi)	(psig)	(psig)	(RB/day)	(feet)	(hp)	(percent)	(perc
1	114.342	-20.7778	-1408.17	253.023	1840.65	6060.23	3702.65	260.743	62.6485	0
2										

HAND CALCULATION

A simple hand calculation can be performed:

$$Power = mgHead$$

$$Power = Q_{SC}\rho_{SC}\,gHead$$

The head is 3702 ft (1128.46m) from above. The rate at standard conditions is 6000 STB/day (0.011041 m3/s). The fluid density at standard conditions is 62.4569 lb/ft3 (1000.47 kg/m3).

Therefore, the total power is 1128.46x9.81x1000. 0.011041 /1000 =122.3 kW

Which is equal to 122.294x1.341 = 163.9 HP

This results in an efficiency of 163.9/263x100=62.3% which again compares favourably to the more rigorous **PROSPER** calculation.

5. Motor Calculations

The power required by the ESP is transferred from the Motor. The current, motor speed and efficiency can then be calculated in a manner similar to the head and ESP power requirement. The coefficients for the motor are shown below.

	Current	Speed	Efficiency
C1	2.41E-01	4.54E+00	7.57E+00
C2	9.20E-01	-5.46E+02	-2.35E+01
C3	-2.89E+00	1.01E+03	2.79E+01
C4	2.33E+00	-4.37E+02	-1.59E+01
C5	1.16E-01	-1.41E+02	4.46E+00
C6	2.81E-01	3.59E+03	3.58E-01

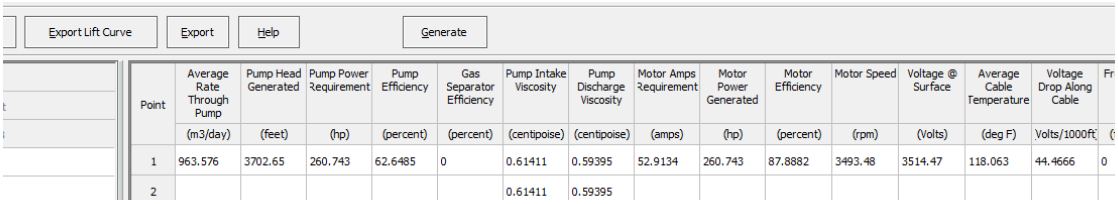
PROSPER

The motor current, speed and efficiency are all calculated from the motor curves and in **PROSPER** give the following results

Motor Current 52.9 A

Speed 3493 RPM

Efficiency 87.9%



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Point	Average Rate Through Pump (m3/day)	Pump Head Generated (feet)	Pump Power Requirement (hp)	Pump Efficiency (percent)	Gas Separator Efficiency (percent)	Pump Intake Viscosity (centipoise)	Pump Discharge Viscosity (centipoise)	Motor Amps Requirement (amps)	Motor Power Generated (hp)	Motor Efficiency (percent)	Motor Speed (rpm)	Voltage @ Surface (Volts)	Average Cable Temperature (deg F)	Voltage Drop Along Cable (Volts/1000ft)	Fr
1	963.576	3702.65	260.743	62.6485	0	0.61411	0.59395	52.9134	260.743	87.8882	3493.48	3514.47	118.063	44.4666	0
2						0.61411	0.59395								

Hand Calculation

The power required by the ESP (263 HP) is transferred from the Motor.

The fraction of the nameplate power (263/420) = 0.627 (P) is used to calculate the current, motor speed and efficiency from the motor curves:

$$C1P^5 + C2P^4 + C3P^3 + C4P^2 + C5P^1 + C6$$

For example, the current requirement can be calculated as follows:

$$2.41x10^{-1}x0.627^{\ 5} + 9.20x10^{-1}x0.627^{\ 4} - 2.89x0.627^{\ 3} + 2.33x0.627^{\ 2} + 1.16x10^{-1}x0.627 + 2.81x10^{-1}$$

= 0.724

This gives a current fraction of 0.724 which is multiplied by the nameplate current (73.5 A) to get the motor current requirements (53 Amps).

The speed can be determined in a similar manner:

MODELLING

ESP CALCULATIONS IN PROSPER

$$4.54x0.627^{5} - 5.46x10^{2}x0.627^{4} + 1.01x10^{3}x0.627^{3} - 4.37x10^{2}x0.627^{2} - 1.41x10^{2}x0.627 + 3.59x10^{3}$$

= 3493 RPM

and likewise the motor efficiency:

$$7.57x0.627^{5} - 2.35x10^{1}x0.627^{4} + 2.79x10^{1}x0.627^{3} - 1.59x10^{1}x0.627^{2} + 4.46x0.627 + 3.58x10^{-1}$$

= 0.879

These values again compare favourably with PROSPER:

	PROSPER	Hand Calc
Current A	52.9	53
Motor Speed RPM	3493	3493
Motor Efficiency %	87.9	87.9

6. Cable Voltage Calculations

PROSPER CALCULATIONS

PROSPER reports a Voltage drop of 44.5 Volts and a surface voltage of 3514.47 V:

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Point	Average Rate Through Pump	Pump Head Generated	Pump Power Requirement	Pump Efficiency	Gas Separator Efficiency	Pump Intake Viscosity	Pump Discharge Viscosity	Motor Amps Requirement	Motor Power Generated	Motor Efficiency	Motor Speed	Voltage @ Surface	Average Cable Temperature	Voltage Drop Along Cable	Fr
	(m3/day)	(feet)	(hp)	(percent)	(percent)	(centipoise)	(centipoise)	(amps)	(hp)	(percent)	(rpm)	(Volts)	(deg F)	Volts/1000ft	(
1	963.576	3702.65	260.743	62.6485	0	0.61411	0.59395	52.9134	260.743	87.8882	3493.48	3514.47	118.063	44.4666	0
2						0.61411	0.59395								

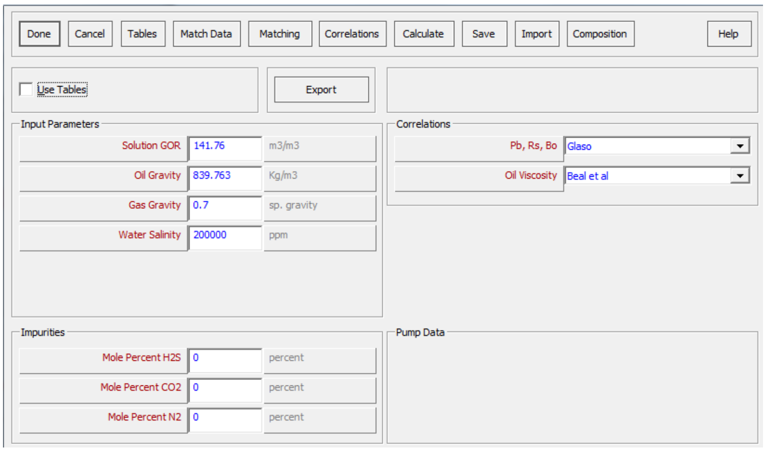
HAND CALCULATIONS

The voltage losses in the cable are calculated on the basis of the cable resistivity and length. This is done using a correction to the resistivity based on the average cable temperature. This provides (for an average cable temperature of 118 °F a total resistivity of 0.85 Ohms. This means that the voltage loss in the cable is 45 V.

The surface voltage requirements are calculated using the nameplate voltage requirement (3470 V) plus the losses in the cable (3470V + 45V) 3515 V.

7. Changing fluid density

Now consider a denser fluid. This can be done in our simplified system by changing the water salinity:



A salinity of 200,000 ppm is chosen. The fluid now has an SG of 1.1506 (*versus* 1 before) and therefore a density at standard conditions of 1151.15 kg/m3.

PROSPER Calculation

For our 6000 STB/day, the pump intake pressure is slightly different as the fluid is now denser. This means that the *in situ* rate is comparable but slightly less (6052.3 RB/day)

The ESP calculation results from **PROSPER** for the same VLP calculation with the denser fluid is shown below:

Pump Intake Pressure	Pump Discharge Pressure	Average Rate Through Pump	Pump Head Generated	Pump Power Requirement	Pump Efficiency
(psig)	(psig)	(RB/day)	(feet)	(hp)	(percent)
205.133	2034.96	6052.59	3704.31	300.322	62.6108

Notice the substantial increase in the Pump Power requirement (300 HP *versus* 260 HP previously) and that the head as remained more or less the same (3704 ft *versus* 3702 ft).

The motor calculations are shown below:

Motor Amps Requirement	Motor Power Generated	Motor Efficiency	Motor Speed	Voltage @ Surface	Average Cable Temperature	Voltage Drop Along Cable
(amps)	(hp)	(percent)	(rpm)	(Volts)	(deg F)	Volts/1000ft
57.7722	300.322	88.5454	3491.37	3518.6	118.533	48.597

Hand Calculation

The same calculations as outlined previously were repeated for water with a salinity of 200,000 ppm. This increases the stock tank fluid density to 1151.15 kg/m3.

Modelling

ESP Calculations in PROSPER

Head and Discharge pressure

The manual head calculation following the above methodology returns almost the same value of head as the previous manual hand calculation (3704 ft *versus* 3702 ft before) due to a small change in rate caused by the different fluid properties and inlet conditions. Accounting for the increased fluid density, the DP is slightly higher at 1831 psig (it was 1590 psig before) and a pump discharge pressure of 2036 psig that is calculated which compares well with the **PROSPER** calculation (**PROSPER** calculates 2035 psig).

Power transferred to the fluid

The power transferred to the fluid can be calculated from the mass flowrate and the head provided as outlined above. Almost the same head is provided and almost the same *in situ* rate but as the fluid is denser it means a greater mass flow rate of fluid and therefore more energy is being transferred to the fluid.

Previously it was calculated that 163 HP of power was transferred to the fluid on the basis of the mass flow rate and head. For the denser fluid, with an increased mass flowrate for the same volumetric flowrate, 188 HP needs to be transferred to the fluid to provide this head.

Determining the ESP Power Requirement

Transferring more power to the fluid requires more power from the motor. The pump curves are for pure water (i.e. 0 ppm salinity). We need to scale the pump HP curves from the pure water curve to that of our fluid (200,000 ppm) on the basis of the increase in fluid density.

The power required for providing this quantity of head to pure water (0 ppm) can be found from the HP curves. This gives a value of 263.3 HP – which is almost the same as before due to the volumetric flowrate being almost identical. However, for this same volumetric flowrate we are passing a much greater mass due to the much greater density. Multiplying the pure water value calculated as above by the specific gravity accounts for the increase in mass for the same volume of fluid and gives a value of 302 HP (and therefore an efficiency of 62.2%).

Note that the efficiency remains the same. More energy is transferred to fluid which requires a greater energy input but the efficiency is constant. In terms of our calculations, this occurs because both the energy transferred to the fluid on the basis of the constant head and the energy provided to the pump are scaled by the changing gravity. Therefore, when we divide one by the other the gravity cancels and efficiency is the same.

Motor and Cable Calculations

This power is transferred by the motor, which allows the motor calculations to be performed as before. The hand calculations return the following values and can be observed to be in good agreement with **PROSPER**:

Amps	Speed RPM	Eff %	dV V	Surface Voltage
58	3491	88.5	49	3519

1. Summary of Results

	0 PPM Salinity (less dense)		200,000PPM salinity (more dense)	
	PROSPER	Hand	PROSPER	Hand
Head ft	3702.6	3702.6	3704	3704
DP psig	1587.6	1590	1829.9	1831
Pdischarge	1840	1843	2035	2036
Power HP	260	263	300.3	302
Pump Efficiency %	62.6	62.3	62.6	62.2
Current A	52.9	53	57.7	58
Motor Speed RPM	3493	3493	3491.4	3491
Motor Efficiency %	87.9	87.9	88.5	88.5
Surface Voltage	3514.5	3515	3518	3519

2. A note on the Temperature change due to the Motor and Pump

In our hand calculations isothermal conditions were assumed. In reality, **PROSPER** uses the pump and motor efficiency, the mass flowrate and the heat capacity to account for the heat given to the fluid by the motor and pump. The wasted power is assumed to be converted into heat. This forms part of the PVT correction along with the pressure correction described above.

In the Rough Approximation this temperature change is not reported and the outlet temperature is the same as the inlet temperature. If Improved Approximation or Enthalpy Balance is selected, then the temperature change caused by the motor and pump is reported and used to determine the downstream temperature.