Theory, testing and modelling of a Clark pump

Murray Thomson and Marcos Miranda

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CREST
Centre for Renewable Energy Systems Technology
Angela Marmont Renewable Energy Laboratory
Loughborough University of Technology
Loughborough
Leicestershire
LE11 3TU
UK

Murray Thomson
M.Thomson@Lboro.ac.uk
Tel: 44 (0) 1509 228144
Fax: 44 (0) 1509 610031

1 Introduction

The Clark pump is a new and extremely elegant device for use in reverse-osmosis desalination systems. It recovers the mechanical energy from the concentrate flow and returns it directly to the feed flow. The Clark pump has been developed by Spectra Watermakers of California, USA over the last five years and is covered by US patents 5,462,414 and 5,628,198.

This report and the accompanying Excel file describe theory, testing and modelling of the Clark pump. An appendix briefly discusses a system using a hydraulic motor for energy recovery and compares this to the Clark pump. The intellectual property contained in this report and the accompanying Excel file remain the property of CREST, Loughborough University, UK.

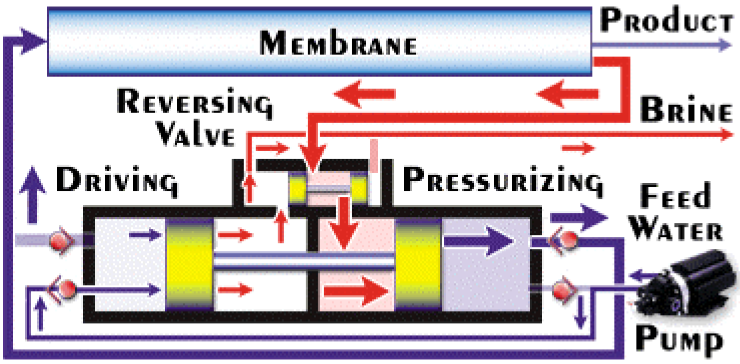

Figure 1 – General configuration of a Clark pump is a reverse-osmosis desalination system

The above figure is one slide taken from an animation that may be found on the Spectra web site: www.spectrawatermakers.com

2 Theory

2.1 Ideal (lossless) Clark pump

An *ideal* Clark pump would have no leakage, pressure or frictional losses. The reversal, at the end of the stroke, would be instantaneous and lossless. Thus, all flows and pressures would be perfectly constant (assuming constant external conditions). Also, due to symmetry, the flows and pressures of an *ideal* Clark pump can be fully understood by considering the pistons moving in only one direction.

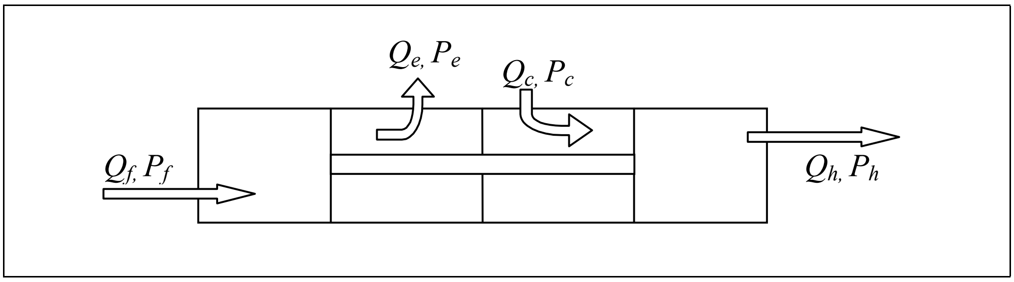

Figure 2 – Ideal Clark pump

Q is the flow and *P* the pressure. The suffixes stand for *feed, exhaust, concentrate and high-pressure*.

2.1.1 Flows

Equating the velocity of the pistons gives:

$$\frac{Q_f}{A_p} = \frac{Q_e}{A_p - A_r} = \frac{Q_c}{A_p - A_r} = \frac{Q_h}{A_p} \tag{1}$$

where A_p is the area of the piston and A_r is that of the rod.

Thus:

$$Q_f = \frac{Q_e}{1 - R_t} = \frac{Q_c}{1 - R_t} = Q_h \tag{2}$$

where R_t is the theoretical recovery ratio given by:

$$R_t = \frac{A_r}{A_p} \tag{3}$$

Rearranging equation 2 gives:

$$R_t = \frac{Q_f - Q_f(1 - R_t)}{Q_f} = \frac{Q_f - Q_c}{Q_f} = \frac{Q_p}{Q_f} \tag{4}$$

2.1.2 Pressures

Summing the forces acting on the piston gives:

$$\sum f = P_f A_p - P_e(A_p - A_r) + P_c(A_p - A_r) - P_h A_p = 0 \tag{5}$$

So:

$$P_f + P_c(1 - R_t) = P_e(1 - R_t) + P_h \tag{6}$$

2.1.3 Powers

Combining equations 2 and 6 gives:

$$P_f Q_f + P_c Q_c = P_e Q_e + P_h Q_h \quad (7)$$

which simply confirms that:

$$\textit{Power in} = \textit{Power out} \quad (8)$$

as expected for a lossless system.

2.2 Leakages (flow losses)

Firstly, leakages past the pistons (Q_{fe} and Q_{hc}) and through the central rod seal (Q_{ce}) may be considered.

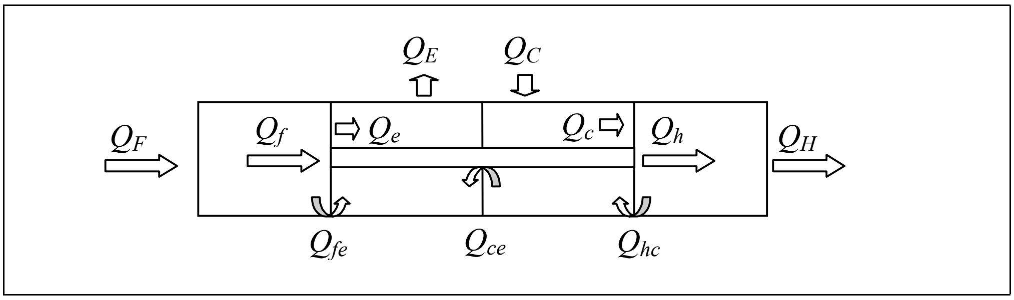

Figure 3 – Leakages

The lowercase suffixes indicate the net flows that act on the piston (the ideal flows, as before) and the uppercase suffixes indicate the total flows that may observed at the external pipe connections. Thus, for example, the net feed flow acting on the piston would equal the total flow less the leakage: $Q_f = Q_F - Q_{fe}$.

In practice, various other leakages are possible, particularly through the valve gear, and, in general, it is possible that any one of the four chambers could leak into any other. This gives a total of six possible leakage flows and the following relationships.

$$Q_f = Q_F + Q_{hf} + Q_{cf} - Q_{fe} \quad (9)$$

$$Q_e = Q_E - Q_{he} - Q_{fe} - Q_{ce} \quad (10)$$

$$Q_c = Q_C + Q_{hc} - Q_{cf} - Q_{ce} \quad (11)$$

$$Q_h = Q_H + Q_{hc} + Q_{hf} + Q_{he} \quad (12)$$

The directions of the leakage flows, and hence the signs appearing in the above equations, are chosen such that positive flow is always from the higher pressure to the lower. Thus, all six leakage flows may be expected to be positive.

2.2.1 Effect on recovery ratio

Combining equations 2, 9, 10, 11 and 12 gives:

$$Q_F + Q_{hf} + Q_{cf} - Q_{fe} = \frac{Q_E - Q_{he} - Q_{fe} - Q_{ce}}{1 - R_t} = \frac{Q_C + Q_{hc} - Q_{cf} - Q_{ce}}{1 - R_t} = Q_H + Q_{hc} + Q_{hf} + Q_{he} \tag{13}$$

Where, as before, R_t is the *theoretical* recovery ratio.

Rearranging equation 13 gives:

$$\begin{aligned} Q_C &= (Q_F + Q_{hf} + Q_{cf} - Q_{fe})(1 - R_t) - Q_{hc} + Q_{cf} + Q_{ce} \\ &= Q_F + Q_{hf} + 2Q_{cf} - Q_{fe} - R_tQ_F - R_tQ_{hf} - R_tQ_{cf} + R_tQ_{fe} - Q_{hc} + Q_{ce} \end{aligned} \tag{14}$$

And:

$$Q_H = Q_F + Q_{cf} - Q_{fe} - Q_{hc} - Q_{he} \tag{15}$$

Thus, the measured recovery ratio is given by:

$$R_m = \frac{Q_P}{Q_F} = \frac{Q_H - Q_C}{Q_F} =$$

$$\frac{Q_F + Q_{cf} - Q_{fe} - Q_{hc} - Q_{he} - Q_F - Q_{hf} - 2Q_{cf} + Q_{fe} + R_tQ_F + R_tQ_{hf} + R_tQ_{cf} - R_tQ_{fe} + Q_{hc} - Q_{ce}}{Q_F}$$

$$= R_t - \frac{Q_{he} + Q_{ce} + (1 - R_t)(Q_{cf} + Q_{hf}) + R_tQ_{fe}}{Q_F} \tag{16}$$

Or:

$$R_m = R_t - \frac{Q_L}{Q_F} \tag{17}$$

where Q_L is the combined leakages:

$$Q_L = Q_{he} + Q_{ce} + (1 - R_t)(Q_{cf} + Q_{hf}) + R_tQ_{fe} \tag{18}$$

Interestingly, Q_{hc} should have no effect on the measured recovery ratio.

Notice also that, the other five leakages will *all* serve to *reduce* the recovery ratio from its theoretical value (they are all positive in the expression for Q_L).

Also, from equation 17:

$$R_mQ_F = R_tQ_F - Q_L \tag{19}$$

In words this is:

measured product flow = theoretical product flow – leakages

The leakages may be expected to include two forms: Firstly, *pressure-driven* leakages that may be expected to increase with pressure. Secondly, *fixed-volume-per-cycle* leakages that may be expected to increase with frequency and, therefore, with flow.

2.2.2 Volumetric efficiency

The *volumetric efficiency* η_V of a Clark pump may be defined as:

$$volumetric\ efficiency = \frac{measured\ product\ flow}{theoretical\ product\ flow} \tag{20}$$

More specifically:

$$\eta_V = \frac{Q_P}{Q_F R_t} \tag{21}$$

Or:

$$\eta_V = 1 - \frac{Q_L}{Q_F R_t} \tag{22}$$

2.2.3 Useful flow relationships

$$Q_P = Q_F - Q_E = Q_H - Q_C = R_m Q_F = R_t Q_F - Q_L \tag{23}$$

$$Q_E = Q_F - Q_P = Q_F (1 - R_m) = Q_F (1 - R_t) + Q_L \tag{24}$$

$$Q_F + Q_C = Q_H + Q_E \tag{25}$$

2.3 Pressure Losses

The feed will experience a slight pressure loss in the pipes and valves on its way in to the chamber. Likewise, the high-pressure, on its way *out* of the chamber, etc.

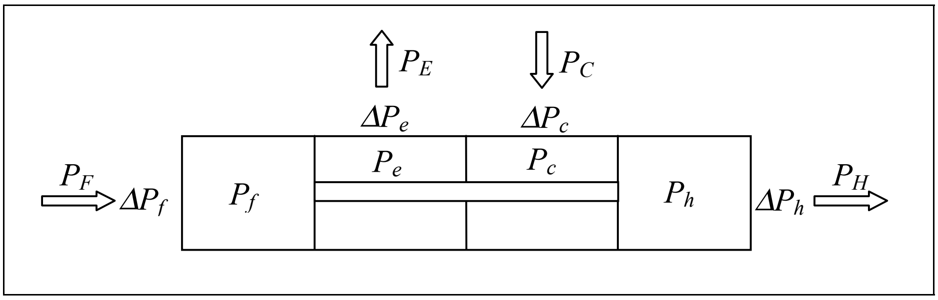

Figure 4 – Pressure losses

$$P_f = P_F - \Delta P_f \tag{26}$$

$$P_e = P_E + \Delta P_e \tag{27}$$

$$P_c = P_C - \Delta P_c \tag{28}$$

$$P_h = P_H + \Delta P_h \tag{29}$$

where lowercase suffixes indicate the pressures that act on the piston and uppercase suffixes indicate the pressures that may observed at the external pipe connections.

Friction F will also give rise to a pressure loss.

Thus, equation 6 becomes:

$$P_F + \Delta P_f + (P_C - \Delta P_c)(1 - R_t) = (P_E + \Delta P_e)(1 - R_t) + (P_H + \Delta P) + \frac{F}{A_p} \tag{30}$$

Or:

$$P_F + P_C(1 - R_t) - P_E(1 - R_t) - P_H = P_L \tag{31}$$

where P_L is the combined pressure losses:

$$P_L = \Delta P_f + (\Delta P_e + \Delta P_c)(1 - R_t) + \Delta P_h + \frac{F}{A_p} \tag{32}$$

The combined pressure losses, including the friction, may be expected to increase with flow, or perhaps flow squared.

2.3.1 Mechanical efficiency

The *mechanical efficiency* η_M of a Clark pump may be defined as:

$$mechanical\ efficiency = \frac{effective\ net\ input\ pressure}{net\ input\ pressure} \tag{33}$$

More specifically:

$$\eta_M = \frac{P_F - P_E(1 - R_t) - P_L}{P_F - P_E(1 - R_t)} = 1 - \frac{P_L}{P_F - P_E(1 - R_t)} \tag{34}$$

2.3.2 Useful pressure relationship

$$P_F = P_H + (1 - R_t)(P_E - P_C) + P_L \tag{35}$$

2.4 Overall efficiency

To define the overall efficiency of an energy-recovery mechanism used in a reverse osmosis system, it is necessary to consider more than just the energy-recovery device itself.

2.4.1 System without energy recovery

Consider first a basic set up without energy recovery.

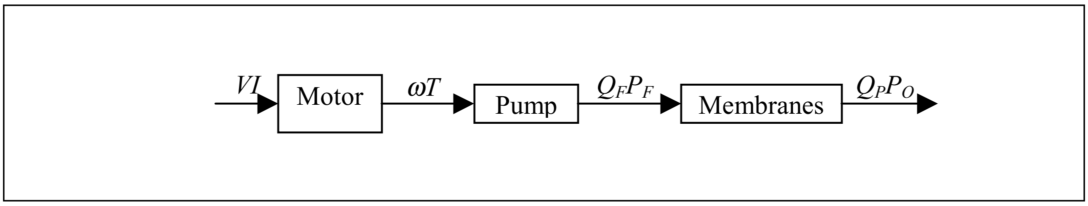

Figure 5 – Power inputs and outputs without energy recovery

Q_P is the product flow and P_O is the osmotic pressure of the feed. (The osmotic pressure of the product is assumed to be zero.)

If an AC motor is used, the power factor would have to be included.

The following efficiencies may be defined from this diagram:

$$\eta_{Motor} = \frac{\omega T}{VI} \tag{36}$$

$$\eta_{Pump} = \frac{Q_F P_F}{\omega T} \tag{37}$$

$$\eta_{P.Mem.} = \frac{Q_P P_O}{Q_F P_F} \tag{38}$$

According to this primitive definition, the efficiency of the membranes is a typically between 3 and 6 %. However, this is a little unfair since most of the energy is actually lost in the needle valve restrictor.

The needle valve may be added to the diagram:

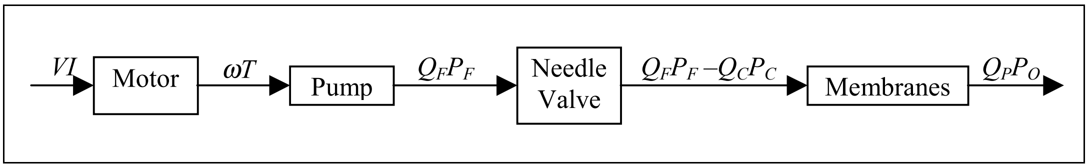

Figure 6 – Power inputs and outputs, including a needle valve

NB. In this *energy-efficiencies* diagram, the needle valve is shown *in front* of the membranes. In practice of course, it is fitted in the concentrate steam, after the membranes.

Now, the efficiency of the membranes may be defined as:

$$\eta_{Mem.} = \frac{Q_P P_O}{Q_F P_F - Q_C P_C} \tag{39}$$

which is much more generous, typically between 30 and 60 %.

To complete this picture, the efficiency of the needle valve must now be defined as:

$$\eta_{Needle} = \frac{Q_F P_F - Q_C P_C}{Q_F P_F} \tag{40}$$

This is typically around only 10 % (for a system with a single membrane), which is a reflection of the losses incurred by using a needle valve – that is by failing to use any energy recovery mechanism.

2.4.2 System with Clark pump energy recovery

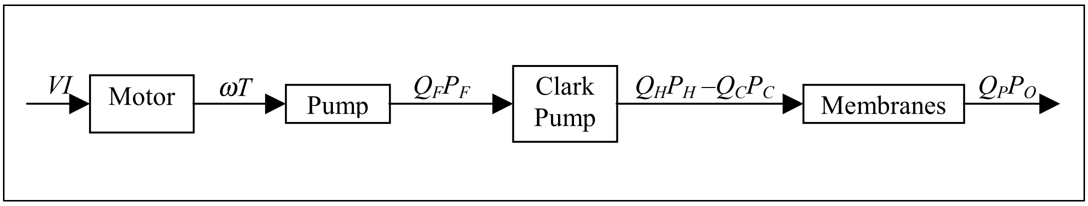

Figure 7 – Power inputs and outputs in a system with a Clark pump

It is now necessary to distinguish between the *feed* (subscript F) and the *high-pressure* (subscript H).

From Figure 7, the overall efficiency of the Clark pump can be defined similarly to that of the needle valve. However, it is useful, at this stage, also to include the effect of any backpressure on the exhaust. And, thus the overall efficiency of the Clark pump is defined

$$\eta_{Clark} = \frac{Q_H P_H - Q_C P_C}{Q_F P_F - Q_E P_E} \tag{41}$$

2.4.2.1 Clark pump efficiency relationships

The above definition of *overall* Clark pump efficiency may be compared with the product of the *volumetric* and *mechanical* efficiencies defined earlier:

Multiplying equations 22 and 34:

$$\eta_V \times \eta_M = \frac{Q_P}{Q_F R_t} \times \frac{P_F - P_E(1-R_t) - P_L}{P_F - P_E(1-R_m)} \tag{42}$$

Substituting from equations 16 and 31:

$$\eta_V \times \eta_M = \frac{Q_P}{Q_F R_t} \times \frac{P_F - P_E(1-R_t) - P_F - P_C(1-R_t) + P_E(1-R_t) + P_H}{P_F - P_E\left(1 - \frac{Q_P}{Q_F}\right)}$$

$$= \frac{Q_P\left(\frac{P_H - P_C}{R_t} + P_C\right)}{Q_F P_F - (Q_F - Q_P)P_E} \tag{43}$$

And substituting from equation 23:

$$\eta_V \times \eta_M = \frac{(Q_H - Q_C)\left(\frac{P_H - P_C}{R_t} + P_C\right)}{Q_F P_F - Q_E P_E} \tag{44}$$

Comparing this with equation 41 it is clear that

$$\eta_V \times \eta_M = \eta_{Clark} \quad \textbf{\textit{only if}} \quad P_H = P_C \tag{45}$$

Fortunately, in the normal application of a Clark pump in a reverse osmosis system, $P_H \cong P_C$ and so

$$\eta_V \times \eta_M \cong \eta_{Clark} \tag{46}$$

2.4.2.2 Overall system efficiency

The definition of Clark-Pump efficiency already proposed in equation 41 is good because it allows the overall system efficiency to be determined simply by multiplying all the component efficiencies together.

$$\eta_{System} = \frac{Q_P P_O}{VI} = \eta_{Motor} \times \eta_{Pump} \times \eta_{Clark} \times \eta_{Mem.} \tag{47}$$

This, apparently trivial, statement is actually rather important.

2.4.2.3 Alternative Clark pump efficiency definition

One might, naïvely, propose the following definition for Clark pump efficiency. (Initially, we made this mistake.)

$$\eta_{ClarkN} = \frac{\sum power\,out}{\sum power\,in} = \frac{Q_H P_H + Q_E P_E}{Q_F P_F + Q_C P_C} \tag{48}$$

This definition generally gives much more flattering results. However, it is not a very useful or sound definition in the context of a reverse osmosis system.

3 Testing

3.1 Hardware configuration

In order to characterise the Clark pump itself, the test rig was re-plumbed such that two manually operated valves were connected in place of the reverse osmosis modules.

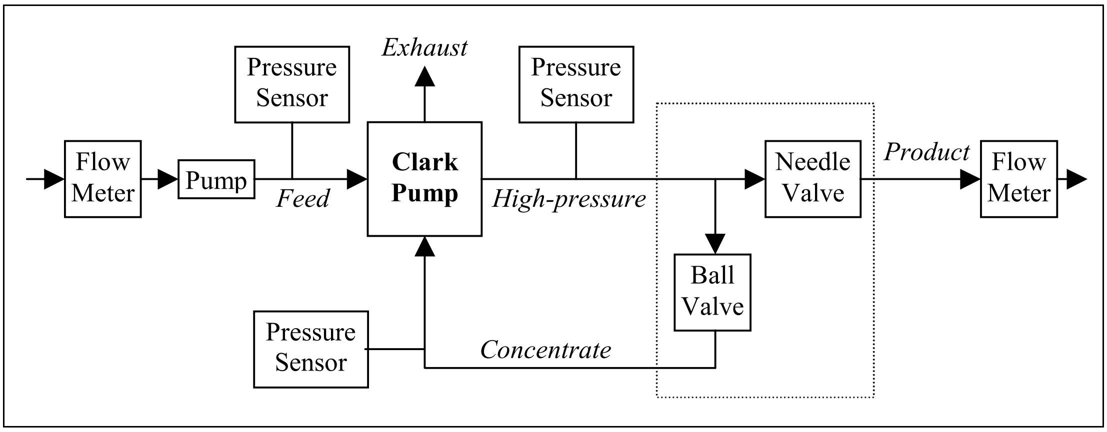

Figure 8 – Configuration used for Clark pump testing

The dashed box indicates the usual location of the modules. The terms *Product* and *Concentrate* are retained simply to identify the various flows – obviously, no actual desalination is taking place.

The needle valve is used to emulate the pressure drop of water passing *through* the membranes. In practice, this pressure drop would be large (> 30 bar), since it includes both the osmotic pressure and the mechanical-viscosity pressure.

The ball valve emulates the *delta pressure*: the pressure drop of the water passing *across* the membranes. In practice, this pressure drop would be very small (< 1 bar).

The pump used for the tests was a positive-displacement plunger pump (CAT 317). It was driven by a variable-speed induction motor.

Thus, the test configuration allowed independent control of:

- feed flow (from 0.04 to 0.21 L/s),
- high pressure (from 10 to 60 bar) and
- delta pressure (from 0 to 4 bar).

3.2 Results and analysis

The results and analysis of the testing are presented in the accompanying Excel file.

The first worksheet *Orig&Calcs* contains the original data, logged by the LabView data acquisition system, and some addition columns, calculated in Excel. More specifically, each row represents the average of data acquired over at least a minute of steady operation. Columns A and B indicate the exact moment that the average was written to file. Columns D through AC contain *raw* data such as voltages and frequencies from the numerous sensors. Generally, this raw data is offset, scaled, linearised and combined in LabView to give results in degrees-C, bar, Newton-meters, litres/second, Watts and percentage, as appropriate. These results are logged in columns AD through AW.

The remaining columns are calculated in Excel:

Columns AY through BE include the delta pressure (high pressure less concentrate pressure); exhaust pressure (1 metre of head = 0.1 bar); the four powers (Q_FP_F, Q_HP_H, Q_CP_C, and Q_EP_E) and the *measured* recovery ratio Q_P/Q_F. (The very slight differences between these figures and those already calculated by LabView and shown in the earlier columns are due to differences in the sequences of averaging and combining the data.)

Column BF contains the theoretical recovery ratio R_t, calculated from the design dimensions of the Clark pump: the diameters of the rod and the piston are 0.875 and 2.75 inches respectively.

The differences between the *theoretical* recovery ratio and the *measured* value are due to leakages and these are calculated in column BG, according to equation 18.

Column BH shows volumetric efficiency, according to equation 22.

The pressure losses and mechanical efficiencies, in columns BI and BJ, are calculated according to equations 32 and 34 respectively.

Column BK shows the product of the volumetric and mechanical efficiencies, while column BL shows the overall Clark pump efficiency as defined in equation 41. The figures in these two columns are very similar, as predicted by equation 46.

Columns BO through BQ were used simply to group and sort the data in preparation for plotting charts.

The remaining columns contain data derived from the Matlab-Simulink model described later.

The second worksheet, *Sorts,* contains duplicate copies of most of the data from the first worksheet. Its purpose is to allow the date to be sorted, in three different ways, in preparation for the charts in the next three sheets.

3.2.1 Leakages and pressure losses

Worksheets PQD, QPD and DPQ all present the *same* data – they differ only in regard to the *order* of the data from left to right. The top two charts (pressures and feed flow) on each worksheet show the *input* conditions of the tests. The bottom two charts show the resulting leakages and pressure losses.

Inspection of sheet PQD suggests the leakages are dependent mainly on the *product* of the high-pressure and the feed flow. The expectation had been that the leakages would increase with the *sum* of pressure and flow components. However, regression calculations (see later) confirm that the product is indeed the dominant term. The delta pressure (up to 4 bar) has no significant effect on leakages – this is more easily seen on sheet DPQ.

Inspection of sheet QPD suggests the pressure losses are dependent on the feed flow and feed flow squared. This was anticipated. Also, a relationship to delta pressure is clearly evident on sheet DPQ.

The next worksheet, *RegrSort*, contains further duplication of data from the first worksheet. Its purpose is to facilitate and confirm the regression calculations that appear on the following sheet: *RegrCalc.*

RegrCalc computes the coefficients shown in the following equations.

$$Q_L = 1.77 \times 10^{-4} \times Q_F P_H \; + \; 1.56 \times 10^{-5} \tag{49}$$

$$P_L = 49.2 \times Q_F^{\;2} \; + \; 7.09 \times 10^{-2} \times \Delta P \; + \; 0.528 \tag{50}$$

In which, the units are litres/second and bar. And, $\Delta P = P_H - P_C$

These expressions will be used to estimate the leakages and pressure losses in the Matlab-Simulink model of the Clark pump, presented later. They may also be useful in the further refinement of the Clark pump design.

(*RegrCalc* applies standard *least-squares* techniques to find coefficients for a selection of candidate formulations. Equations 49 and 50 are considered to offer the most appropriate balance of precision and simplicity.)

3.2.2 Efficiencies

The next two sheets, *PQD Eff* and *QPD Eff*, present charts of the Clark pump efficiencies as defined earlier. They represent identical data, just sorted differently from left to right.

The volumetric efficiency, *EffVolu*, is calculated from equation 22, while the mechanical efficiency, *EffMech*, is from equation 34. *EffMult* is simply the product of these two, and is virtually the same as *EffCP*, as defined in equation 41, particularly when ΔP is small.

From these charts, it is apparent that the volumetric efficiency is very high throughout and that the overall efficiency of the Clark pump is dominated by the mechanical efficiency (pressure and frictional losses). Also, it is apparent that the overall efficiency is highly dependent on flow, pressure and delta pressure.

These efficiency charts cover a wide range of operation and should prove useful in the design of basic reverse-osmosis systems employing the Clark pump. However, with non-standard arrangements, such as those with additional feed pumps, the definitions of efficiencies, presented earlier and on which the charts rely, may need to be reconsidered. Equations 49 and 50, on the other hand, are not dependent on system configuration and are, therefore, more broadly applicable.

4 Modelling

The preceding theory and test results were used to build a software model of the Clark pump in the Matlab-Simulink environment.

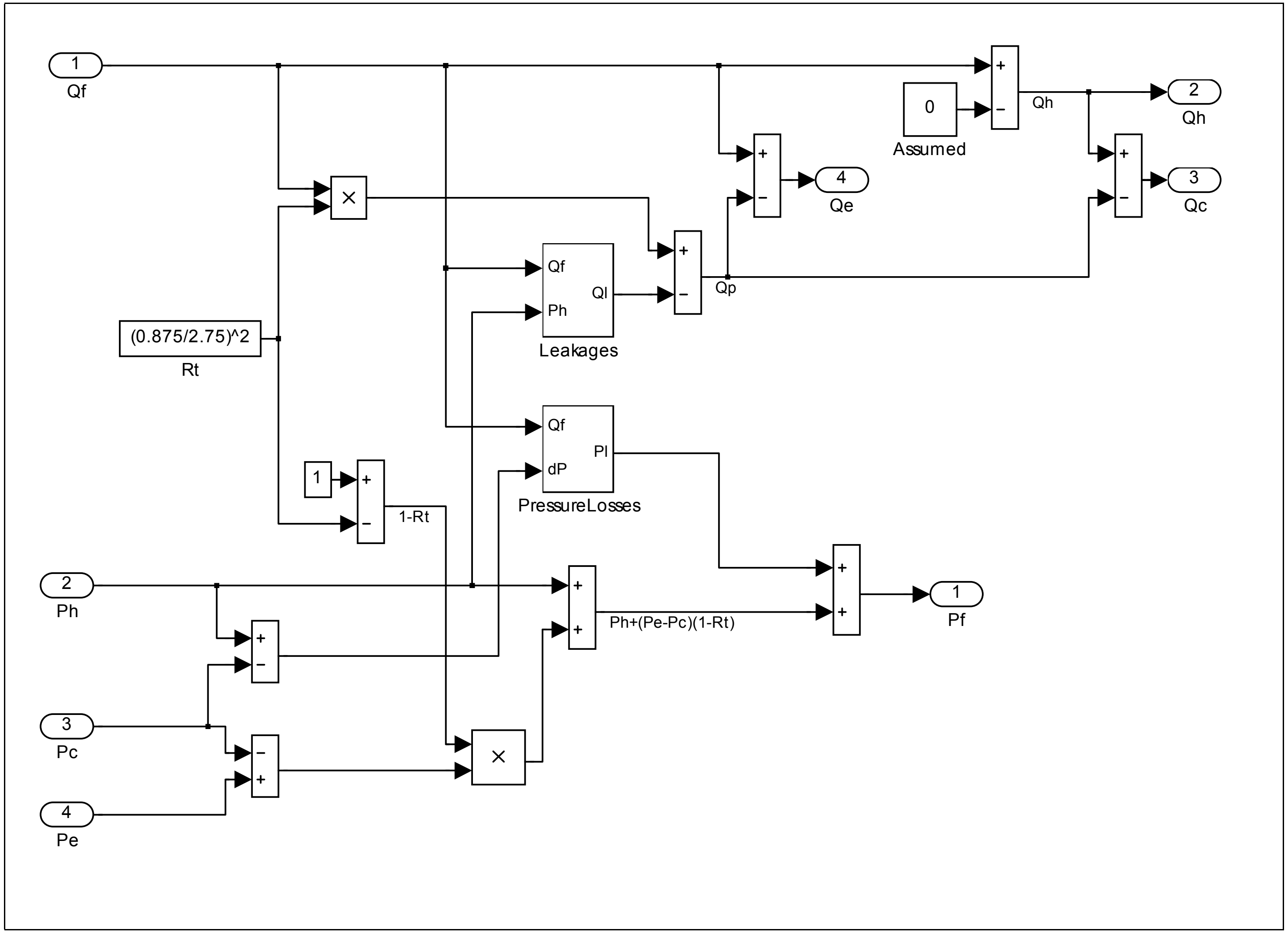

Figure 9 – Simulink model of Clark pump

4.1 Simulink model of Clark pump

The inputs to the model are on the left of the Simulink diagram in Figure 9.

Qf is the feed flow, previously denoted by Q_F in this document (Simulink does not allow subscripts.)

Ph, Pc and Pe are the pressures of the high-pressure, the concentrate and the exhaust respectively.

Rt is a constant. It is the theoretical recovery ratio, calculated from the design dimensions of the pistons and the rod (see equation 3).

The boxes labelled Leakages and Pressure Losses are subsystems that implement equations 49 and 50 respectively.

The rest of the model shown in Figure 9 implements equations 23 and 31.

The zero shown in the box labelled Assumed represents the difference between the feed flow and the high-pressure flow. In an *ideal* Clark pump, there would be no difference, see equation 2. In practice, there probably is a slight difference but this was not measurable since the oval-gear flow meters on the test rig are limited to 20 bar. Fortunately, the overall efficiency as defined in equation 41 is barely affected by this assumption. Thus, very little of the precision of the model is lost.

The software model was tested by using the Q_F, P_H and P_C data collected during the original hardware testing as inputs to the model. The output data from the model was then compared against the original test results. Unsurprisingly, the match is very good, see worksheets PfMatlab and OpMatlab in the accompanying Excel file.

4.2 Reverse-osmosis system model

The following diagram indicates how the Simulink model of the Clark pump, just described, can be used within a larger system model. In this example, a photovoltaic (PV) array is used to power the main pump, the insolation (solar radiation intensity) is an input and the quantity and quality of product water are outputs.

The configuration shown in this example reflects the current configuration of the test rig at CREST. Clearly, the use of two feed pumps and three membrane modules with just one Clark pump is not intended as a final working system.

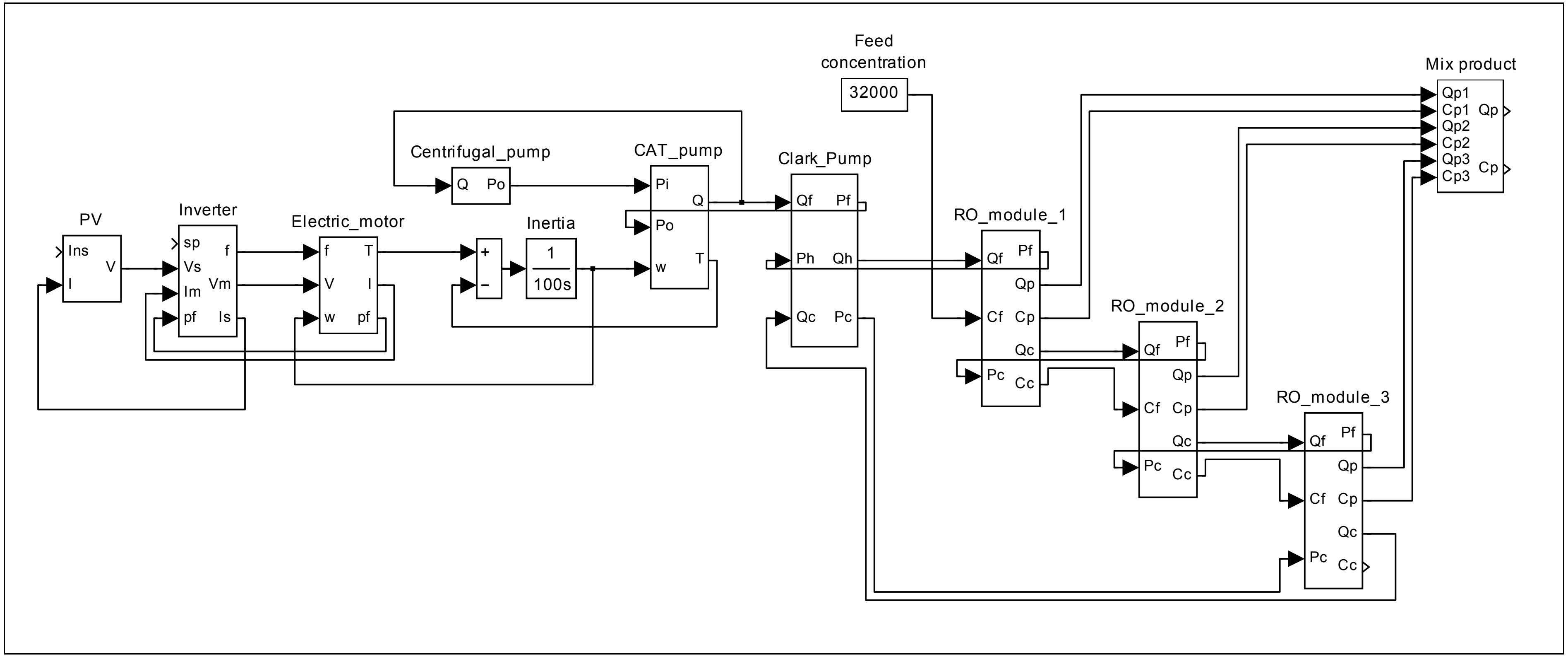

Figure 10 – Simulink model of a reverse-osmosis system including a Clark pump

Appendix – Hydraulic motor energy recovery

In order to compare the efficiency of a reverse-osmosis system using a hydraulic motor for energy recovery against one using a Clark pump, it is necessary to consider carefully how the efficiencies are defined.

With a hydraulic motor (or indeed a turbine, as is often used in large reverse-osmosis systems) the recovered energy is converted to rotational torque, which is then used (directly or otherwise) to drive the main high-pressure pump. Thus, the efficiency of the main high-pressure pump (and any other components in the line) must be included in considering the efficiency of the overall energy-recovery mechanism.

One way of achieving this is to conceptually split the main high-pressure pump into two parts as shown in the figure below.

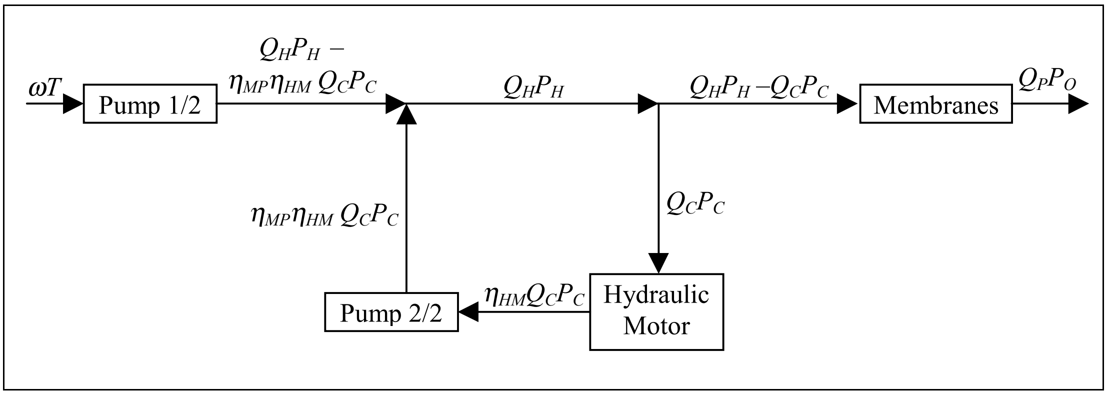

Figure 11 – Power inputs and outputs in a system with a hydraulic motor

η_{MP} is the efficiency of the main pump. η_{HM} is the combined efficiency of the hydraulic motor itself and any other components involved in returning the power to shaft of the main pump.

The components of the overall energy-recovery mechanism shown in Figure 11 may be combined as shown in Figure 12.

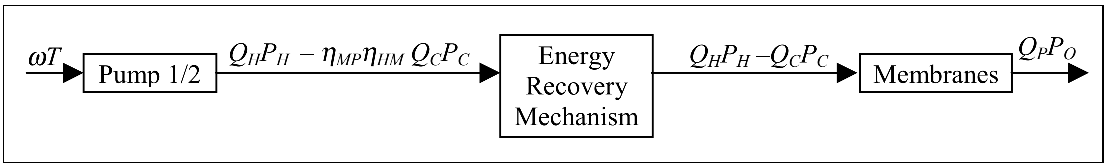

Figure 12 – Power inputs and outputs to the overall energy-recovery mechanism in a system with a hydraulic motor

Thus, the output of the main pump is given by:

$$\eta_{MP}\omega T = Q_H P_H - Q_C P_C \eta_{MP}\eta_{HM} \tag{51}$$

Which implies that the input is:

$$\omega T = \frac{Q_H P_H}{\eta_{MP}} - Q_C P_C \eta_{HM} \tag{52}$$

as expected.

Also from Figure 12, the overall efficiency of the energy-recovery mechanism is:

$$\eta_{OERHM} = \frac{Q_H P_H - Q_C P_C}{Q_H P_H - Q_C P_C \eta_{MP} \eta_{HM}} \tag{53}$$

Assuming that $P_C = P_H$, which is reasonable in a typical reverse-osmosis system, equation 53 becomes:

$$\eta_{OERHM} = \frac{R}{1-(1-R)\eta_{MP}\eta_{HM}} \tag{54}$$

where R is the recovery ratio.

Typical figures

The efficiency of a CAT 317 pump, measured by CREST, is around 85%. For a Danfoss MAH 5 hydraulic motor, the manufactures claim an efficiency of around 75% at 50 bar and 2000 rpm. Taking these figures and a recovery ratio of 10%, equation 54 gives η_{OERHM} = 23%.

Recent measurements made by CREST on a Danfoss MAH 5 hydraulic motor and the associated toothed belt indicated a combined efficiency of only 65%. This would give η_{OERHM} = 20%.

Increasing the pressure improves the efficiency of the hydraulic motor. For example, at 70 bar and 2000 rpm Danfoss claim around 80% for the MAH 5. This gives η_{OERHM} = 26%.

Increasing the recovery ratio has a dramatic affect on the overall efficiency of the energy-recovery mechanism. For example, using a recovery ratio of 30% in the previous case gives η_{OERHM} = 57%.

Conclusions

The preceding section indicates that, **for a system with a recovery ratio of 10%**, the overall efficiency of an energy-recovery mechanism based on a Danfoss MAH 5 hydraulic motor is likely to be between 20 and 26%. These figures may be directly compared against figures of between 42 and 80% for the Clark pump, see worksheets, *PQD Eff* and *QPD Eff* in the accompanying Excel file. This comparison indicates that a reverse osmosis system based on a Clark pump will require 2 to 3 times less energy input than a similarly sized system employing a hydraulic motor.

If, however, the recovery ratio may be increased, by changing the pulley ratio connecting the hydraulic motor to the main pump, the overall efficiency of an energy-recovery mechanism based on a hydraulic motor improves dramatically. The down side of increasing the recovery ratio is that membrane fouling is also likely to be increased.

For a small, low-maintenance, PV-powered reverse-osmosis system, the Clark pump appears to be the strongest candidate.