# Measurements and analysis on the performance of the rope pump

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| Author: | A. Blanken |
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| Department: | Sustainable Energy Technology |
| Course: | Internal research traineeship (0C921) |
| Supervisor: | dr.ir. C.C.M. Rindt |
| Support: | P.T. Smulders |

# List of symbols

| | |
|---|---|
| $A$ | internal pipe area [$m^2$] |
| $D$ | internal pipe diameter [m] |
| $D_p$ | piston diameter [m] |
| $D_w$ | pump wheel diameter [m] |
| $F_g$ | gravity force of water column [$kgm/s^2$] |
| $F_p$ | pump force [$kgm/s^2$] |
| $H$ | total pumping head [m] |
| $L$ | pump pipe length [m] |
| $L_a$ | arm length [m] |
| $N$ | number of pistons per unit length of rope [$m^{-1}$] |
| $P_h$ | hydraulic output power [J/s] |
| $P_p$ | pump input power [J/s] |
| $Q_p$ | pump torque [$kgm^2/s^2$] |
| $V_c$ | critical piston speed [m/s] |
| $V_p$ | piston speed [m/s] |
| $g$ | gravitational constant [$m/s^2$] |
| $t$ | gap between piston and pipe [m] |
| $\eta_p$ | (mechanical) pump efficiency [−] |
| $\eta_{vol}$ | volumetric efficiency [−] |
| $\varphi$ | flow rate [m/s] |
| $\varphi_{id}$ | flow rate of ideal pump [$m^3/s$] |
| $\varphi_l$ | leakage flow rate [$m^3/s$] |
| $\rho$ | density of water [$kg/m^3$] |

# Contents

# 1. Introduction

In many developing countries water is a scarce commodity. Often there is insufficient clean water available and people have to walk for miles to find some water. Easy access to clean water could give rural communities better opportunities. The water can be used for drinking, washing, cattle watering and irrigation.
The rope pump is a solution for water shortage especially in developing countries. The pump can be built at low cost using standard materials. The construction is so simple that users can easily repair it themselves. According to evaluations more than 95% of the pumps stay working for many years. In 2008 more than 3 million people were already using the rope pump. This number will most probably increase tremendously in the near future. [1, 2]

Although the pumping principle remains the same, there are different ways of driving the rope: by hand, pedal, horse, low-speed electric motor or diesel engine, but also by wind or solar power. In order to obtain a better insight in the factors that determine the quality and performance of the rope pump a hydrodynamic model has been suggested by Smulders and Rijs [3]. This model is particularly relevant for wind or solar driven rope pumps as these are sources with unusual design conditions.

A test facility for the rope pump is available at the Eindhoven University (Netherlands). It has been used by several groups of students as an object of study. The collected data from these projects however remained vague and incomplete. Therefore the goal of this project is to obtain reliable measurements on the rope pump and to make a comparison with the results of the hydrodynamic model.

In chapter 2 the basic principle of a rope pump is explained. Furthermore the test facility is described in detail in this chapter. Chapter 3 gives a short summary of the article ‘A hydrodynamic model of the rope pump’ by P.T. Smulders and R.P.P. Rijs. In chapter 4 the principles and procedures of the measurements are discussed. The results of the measurements are explained in chapter 5 and in chapter 6 these results are compared to the results of the hydrodynamic model.

# 2. Rope pump test facility

## 2.1. Pump principle

The main parts of a rope pump are the endless rope with pistons, the pump pipe and the drive wheel. If the drive wheel is turned around (by hand, motor etc.) the rope with pistons will be pulled upward through the pipe. Because the bottom of the pipe (water inlet) is under water and the piston diameter matches the internal pipe diameter with a small gap water will be pumped upwards. The amount of water that is delivered depends on several parameters, like the piston speed and the piston diameter.

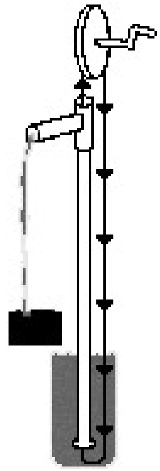


**Figure 1**

## 2.2. Basic set-up

The set-up of the rope pump is as follows (see figure 2 and table 1). An electric motor drives the drive wheel by means of a chain (for more details see §2.3). The drive wheel contains rubber to provide grip for the rope. The rope has two knots per piston to support the pistons on each side (see figure 3). Down in the reservoir a guide piece made from concrete is mounted on the pipe at the water inlet providing a smooth turning point and serving as a weight to keep the pump pipe in its place. At the top of the pump pipe the water falls into a small open vessel and from there via a return pipe into a larger vessel which is used for measuring the amount of liters pumped. This vessel is connected to the big reservoir in the cellar by means of a return pipe so the water can be transported back. The vessel contains a valve to open or close the connection to the reservoir.

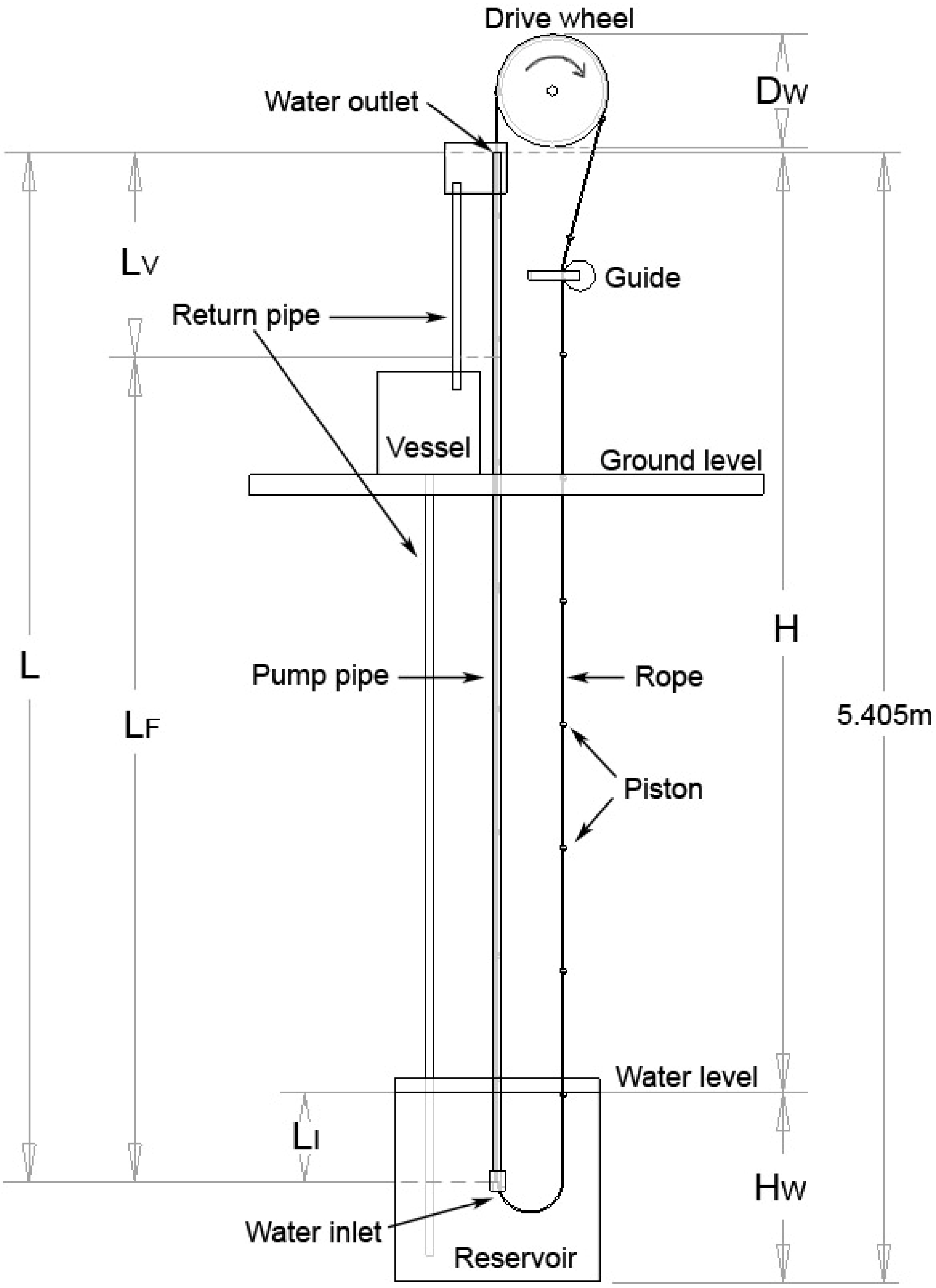



**Figure 2: An overview of the test facility**

The test facility has several important parameters. In table 1 these parameters have been structured.

**Table 1**

| **Parameter** | **Symbol** | **Variable, constant or formula** | **Base case values** | **Varied values** | **Unit** | **Measured or theory** |
|---|---|---|---|---|---|---|
| Total pipe length | L | $L_f + L_v$ | 5.015 | - | m | Measured |
| Varying pipe length | $L_v$ | Variable | 1.0 | 0.55, 0.85 and 1.35 | m | Measured |
| Fixed pipe length | $L_f$ | Constant | 4.015 | - | m | Measured |
| Drive wheel diameter | $D_w$ | Constant | 0.50 | - | m | Measured |
| Effective pumping head | H | $5.405 - H_w$ | 4.505 | - | m | Measured |
| Tank water level | $H_w$ | Variable | 0.90 | - | m | Measured |
| Immersed length | $L_i$ | $L - H$ | 0.51 | 0.06, 0.36 and 0.86 | m | Measured |
| | | | | | | |
| Pipe diameter | D | Constant | $36*10^{-3}$ | - | m | Measured |
| Piston diameter | $D_p$ | Variable | $34*10^{-3}$ | 33 and 35 | m | Measured |
| Leakage gap width | t | $(D - D_p)/2$ | 1 | 1.5 and 0.5 | mm | Measured |
| Piston distance | $L_p$ | Variable | 0.6 | 1.0, 1.5 and 2.0 | m | Measured |
| Number of pistons per unit length | N | $1/L_p$ | 1.67 | 1, 0.67 and 0.5 | $m^{-1}$ | Measured |
| Piston/rope velocity | $V_p$ | Variable | - | 0 to 1.4 | m/s | Measured |
| | | | | | | |
| Gravitational constant | g | Constant | 9.81 | - | $m/s^2$ | - |
| Density of water | ρ | Constant | 998 | - | $kg/m^3$ | - |
| Pump force | $F_p$ | $\rho \cdot g \cdot H \cdot D^2 \cdot \pi / 4$ | 44.9 | - | N | Theory |
| Pump torque | $Q_p$ | $F_p \cdot D_w / 2$ | 11.2 | - | Nm | Theory |
| Ideal output flow rate | $\varphi_{id}$ | $V_p \cdot D^2 \cdot \pi / 4$ | - | - | $m^3/s$ | Theory |
| Leakage flow rate | $\varphi_l$ | $\pi \cdot D \cdot t \cdot \sqrt{(2 \cdot g / N)}$ | - | - | $m^3/s$ | Theory |
| Effective flow rate | $\varphi$ | $\varphi_{id} - \varphi_l$ | - | - | $m^3/s$ | Theory |

## 2.3. Important parts of the test facility

The most interesting parameters to measure are the flow rate, torque and the piston speed. The parts of the test facility that are important for measurements of these parameters are described below.

### Pump pipe

The pump pipe consists of a 'fixed' part and an 'exchangeable' part with a certain length ($L_f$ and $L_v$, see figure 2). The exchangeable part is mounted on top of the fixed part. As the exchangeable part is changed, the water outlet is kept at the same height in order to keep the effective pumping head constant. The parameter that changes if the exchangeable part is replaced is the immersed length ($L_i$) of the pump pipe in the water in the reservoir downstairs.

### Rope

Four different ropes are used during the measurements; each rope holding pistons with a different diameter ($D_p$ = 33, 34 or 35 mm); one rope differs because it has tubes to support the pistons as can be seen in figure 4. The distance between the pistons ($L_p$) can be changed.
The velocity of the rope is controlled using a sensor on the drive wheel axis. The measured data from this sensor is sent to a laptop via an encoder. The laptop runs a control program in Matlab Simulink with which the velocity can be adjusted and read in terms of the piston speed (Vp).

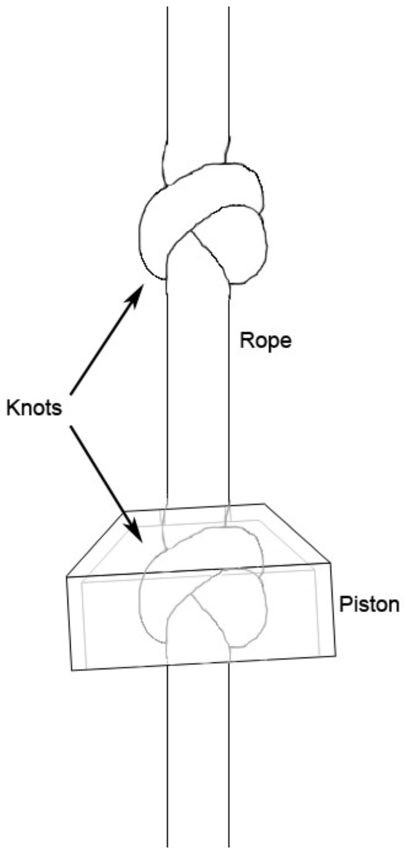



**Figure 3: piston supported by knot**

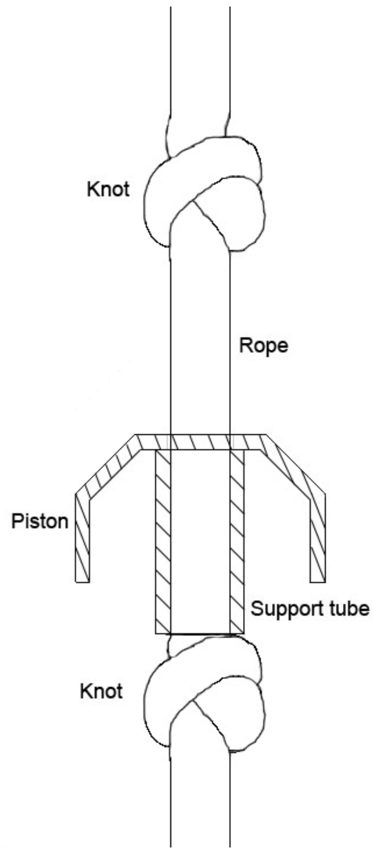



**Figure 4: piston supported by tube**

## Motor housing and strain gauge

The motor housing is mounted on a balance which is held in place by two bearings. The axes of the bearings are almost perfectly in line with the axis of the motor, as shown in figure 6. This construction allows the motor housing to rotate around the axes of the construction.
The pump force (or gravitational force) exerts a torque on the drive wheel. This torque is transferred to the motor shaft through the chain. The drive torque is delivered by the motor in the opposite direction to keep forces in balance.
As the motor delivers the drive torque the motor housing will experience about the same torque but in the opposite direction. Figure 5 shows a strain gauge that is connected to the motor housing. It is connected in such a way that it will only experience a tension force as a result of the reaction torque on the motor housing. The strain gauge uses the resistance of thin wires to measure the force and is kept under tension using a small weight. The tension force is converted to a voltage and, by means of calibration using weights; the voltage is converted into a torque.

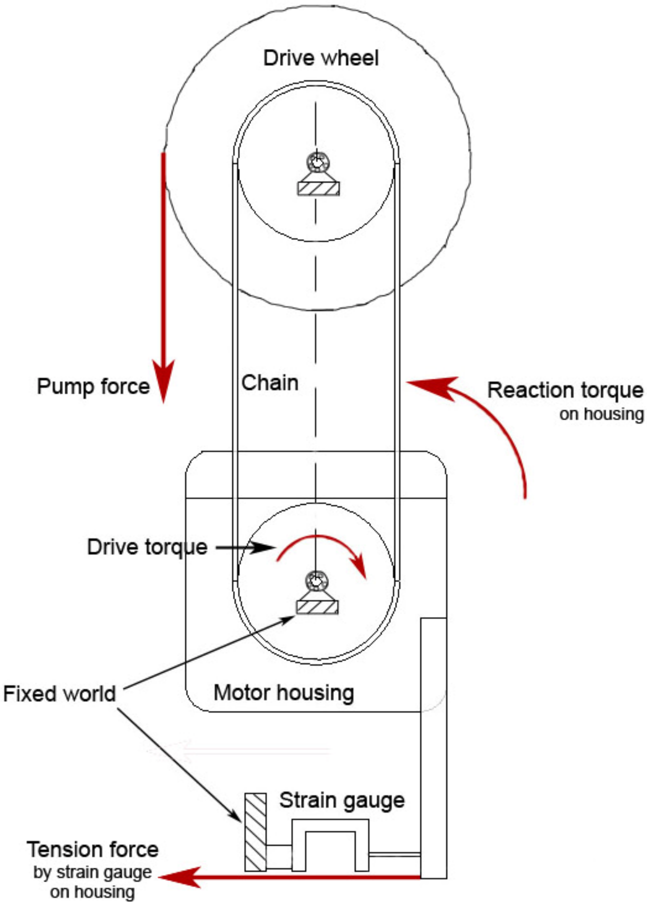



**Figure 5: Drive wheel, motor housing and strain gauge - front view**

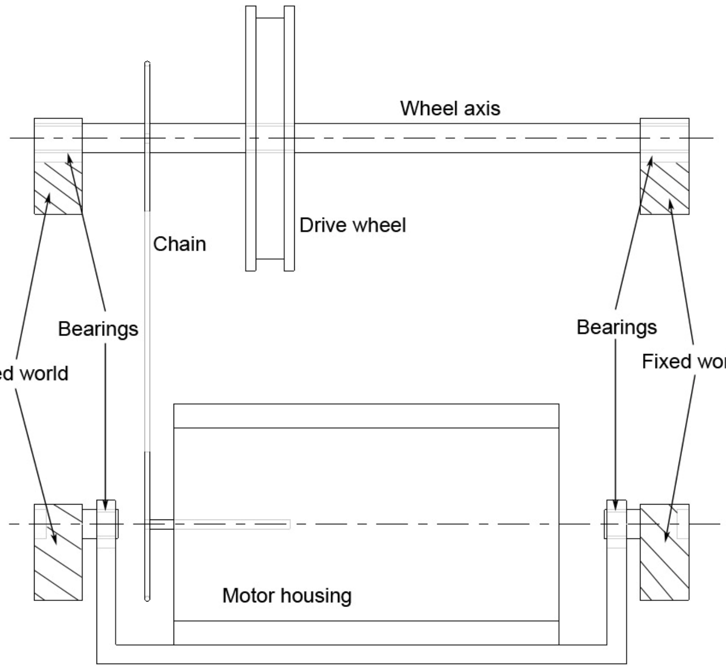



**Figure 6: Drive wheel, motor housing and strain gauge - side view**

# 3. Hydrodynamic model of the rope pump

The article ‘A hydrodynamic model of the rope pump’ has been written by P.T. Smulders and R.P.P. Rijs. This chapter shortly discusses chapter 3 of the article. [1]

Assuming a constant inner pipe area A and a negligible piston and rope volume the ideal flow rate $\varphi_{id}$ can be calculated:

$$\phi_{id} = V_p A \quad (3.1)$$

where $A = \frac{\pi}{4} D^2$

The piston diameter is smaller than the inner pipe diameter to avoid mechanical friction. The small gap that remains causes a leakage flow $\varphi_l$. Therefore the real flow rate becomes:

$$\phi = \phi_{id} - \phi_l \quad (3.2)$$

Using several assumptions, Bernoulli’s law, the continuity equation and momentum conservation the leakage flow is calculated to be:

$$\phi_l \approx \pi \cdot tD\sqrt{\frac{2gH}{NL}} \quad (3.3)$$

Showing that for a given pump, the leakage is constant and independent of the rope velocity.

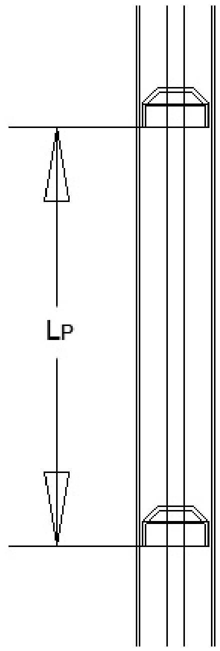



**Figure 7: Piston distance**

Because in many practical cases the pipe length L is approximately equal to the pumping head H this formula in this case reduces to:

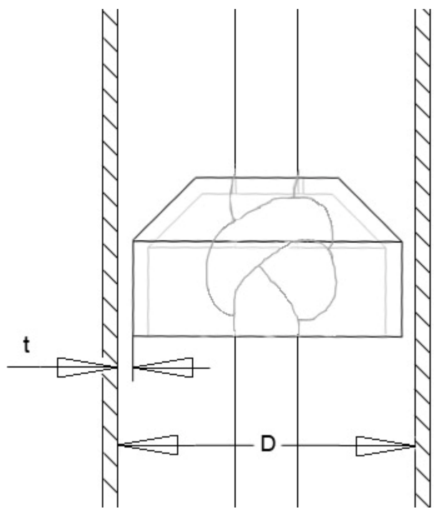



**Figure 8: Piston in pump pipe**

$$\phi_l = \pi \cdot tD\sqrt{\frac{2g}{N}} \quad (3.4)$$

The critical piston speed $V_c$ is the rope speed at which the leakage flow is equal to the ideal flow rate. If the piston speed is equal to or below the critical piston speed the flow rate will be equal to zero. If the piston speed is above the critical piston speed the pump will deliver water. From 3.1, 3.2 and 3.3 the critical piston speed follows directly:

$$V_c = \frac{4t}{D}\sqrt{\frac{2g}{N}} \quad (3.5)$$

The authors further show under the assumptions made (including the neglect of hydrodynamic wall friction) that the force in the rope $F_p$ is equal to the weight of the water in the pipe over the pumping height H.

$$F_p = \rho gHA \quad (3.6)$$

The power needed to drive the pump is the product of the rope force and the piston speed:

$$P_p = V_p \cdot F_p = V_p \cdot \rho g H A \qquad (3.7)$$

The torque that is needed to turn the drive wheel is product of the pump force and the wheel radius, which is a constant. Therefore the required torque is also constant:

$$Q_p = F_p \cdot D_w / 2 = \rho g H A \cdot D_w / 2 \qquad (3.8)$$

The volumetric efficiency is calculated using the ideal pump flow and the leak flow:

$$\eta_{vol} = \frac{\phi}{\phi_{id}} = 1 - \frac{\phi_l}{\phi_{id}} \qquad (3.9)$$

and can be simplified to:

$$\eta_{vol} = 1 - \frac{V_c}{V_p} \quad (V_p \geq V_c) \qquad (3.10)$$

These results have been used to calculate the flow rate, torque and the volumetric efficiency for the base case (see table 1, column 4 on page 7).

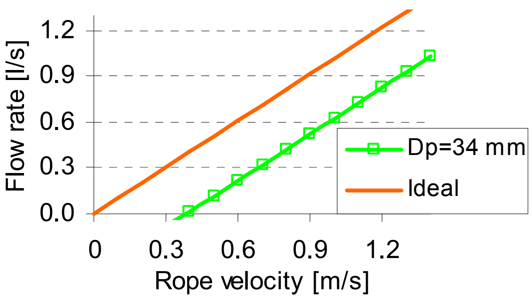



**Figure 9: Theoretical flow rate – base case**

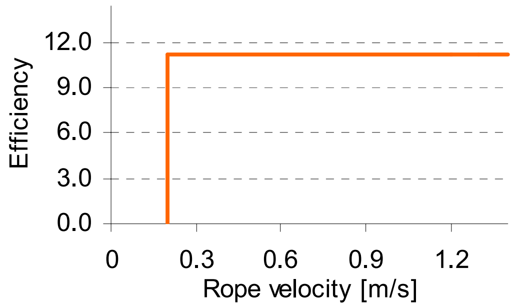



**Figure 10: Theoretical torque – base case**

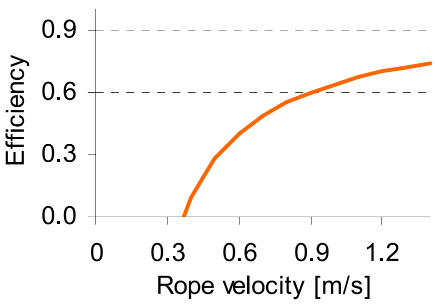



**Figure 11: Theoretical volumetric efficiency – base case**

# 4. Performing measurements

## 4.1. Varying parameters

Several measurements have been carried out of the flow rate and the torque as a function of the piston speed while different parameters have been changed. One configuration has been taken as a base case. Only one parameter is changed at a time starting from this base case in order to see the clear effect of the change. In this way the parameters 'piston diameter', 'piston distance' and 'immersed length' have been varied. Also one measurement was performed using the rope with little tubes to support the pistons (see figure 4). In table 2 the different measurements are displayed schematically.

**Table 2**

| Varied parameter | $D_p$ [mm] | $L_p$ [m] | $L_v$ [m] | $L_i$ [m] | $H_w$ [m] | Piston support tube |
|---|---|---|---|---|---|---|
| Piston diameter | ***33*** | 0.6 | 1 | 0.51 | 0.9 | No |
| | ***34*** | 0.6 | 1 | 0.51 | 0.9 | No |
| | ***35*** | 0.6 | 1 | 0.51 | 0.9 | No |
| Immersed length | 34 | 0.6 | ***0.55*** | ***0.06*** | 0.9 | No |
| | 34 | 0.6 | ***0.85*** | ***0.36*** | 0.9 | No |
| | 34 | 0.6 | ***1.35*** | ***0.86*** | 0.9 | No |
| Piston distance | 34 | ***1*** | 1 | 0.51 | 0.9 | No |
| | 34 | ***1.5*** | 1 | 0.51 | 0.9 | No |
| | 34 | ***2*** | 1 | 0.51 | 0.9 | No |
| Piston support tube | 34 | 0.6 | 1 | 0.51 | 0.9 | ***Yes*** |

*Base case*
The configuration of the base case is:
Piston diameter = 34 mm
Piston distance = 60 cm
Immersed length = 51 cm

*Piston diameter*
In order to change the piston diameter different ropes are used. Three ropes are used for varying the piston diameter (33,34 and 35 mm) and one for investigating the effect of the supporting tubes (piston diameter = 34 mm).

*Immersed length*
The immersed length is changed by changing the exchangeable pipe part. Four lengths are used: 55, 85, 100 and 135 cm, resulting in respectively an immersed length of: 6, 36, 51 and 86 cm.

*Piston distance*
The piston distance is changed using the rope containing 34mm pistons. The knots and pistons are simply displaced in order to create a different piston distance. The different distances are: 60, 100, 150 and 200 cm.

## 4.2. Calibrations and procedure

### Piston speed

The piston speed is measured by a sensor on the drive wheel axis. The signal is converted to a graph on the laptop. In this graph (see figure 12) the measured (green/distorted line) and assigned (blue/straight line) piston speeds are compared. During the measurements the accuracy of the piston speed is verified visually using this graph. The data coming from the sensor is calibrated in the following way: by measuring the time that it takes for the rope to make 4 or 5 complete rounds the corresponding piston speed can be calculated. This is done for all velocities between 0 and 1.4 m/s in steps of 0.1 m/s. This data is compared to the measurements of the sensor (see figure 13). The calibration shows a variation of about 1 – 1.5%.

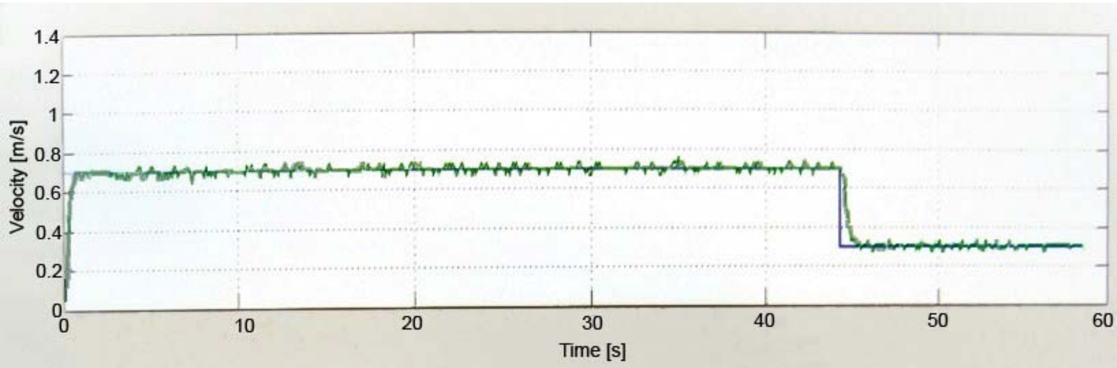



**Figure 12: The blue/straight en green/distorted lines represent respectively the assigned and measured piston speed**

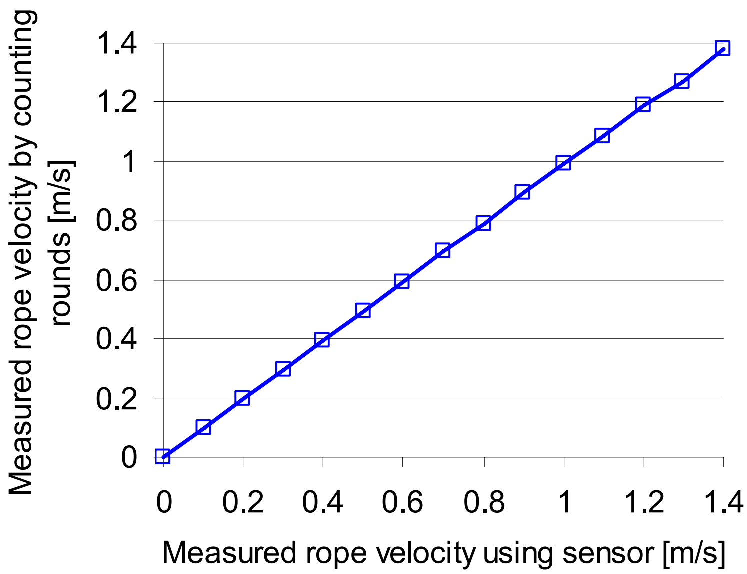



**Figure 13: Rope velocity calibration.**
**Comparing measured data from the sensor (x-axis) and measured data using a stopwatch (y-axis).**

## Torque

The torque is measured using the strain gauge as explained in §2.3 (see figure 5). The computer stores 10 measurement points per minute during a torque measurement; the piston speed is kept constant. The average of these values represents the voltage measured at that velocity. Using the data of the calibrations the voltage is converted into a torque. In order to measure an average value for the torque, the measurement is done as long as it takes for the rope to make at least one cycle.

A torque calibration is carried out before starting a new measurement and is done in the following way. A metal bar (see figure 14) is mounted on the motor housing. At the end of the bar weights can be placed. In this way a torque is exerted on the motor housing and therefore a tension force on the strain gauge. The measurements are done in steps of 0.5 kg from 0 to 5 kg, using an arm length of 0.405m. As the data from the strain gauge is plotted against the calculated torque the slope of the graph is found.

The metal bar itself has a certain weight and it is attached in such a way that it exerts a torque on the motor housing. During the actual torque measurements the metal bar is not used and therefore removed. To be able to compare the calibrations with the measurements, the torque induced by the metal bar has to be compensated for. Therefore at the start of the calibration the torque is first measured without the metal bar attached to the motor housing. This point represents the point of the graph where the value for torque is 0 Nm. The slope of the graph is combined with the starting point and the exact relation between measured voltage and exerted torque is found.

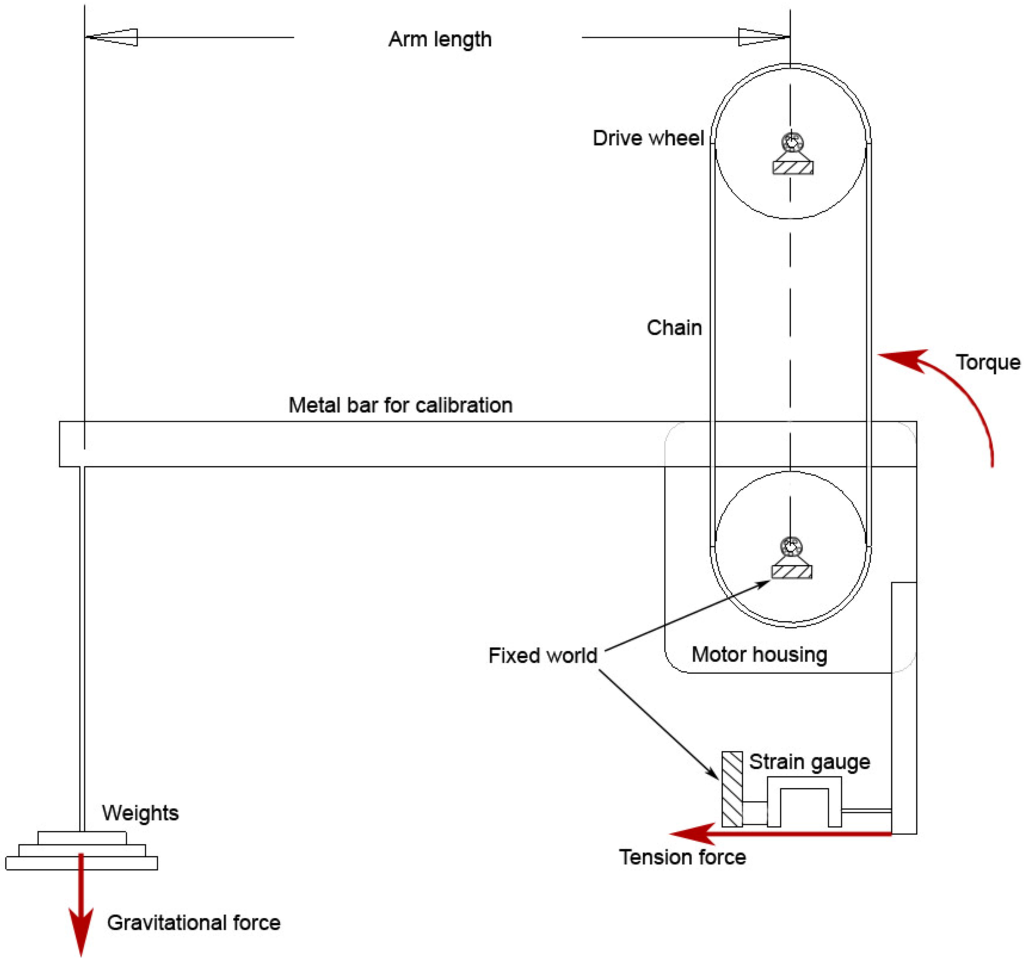



**Figure 14: Construction and forces for calibration**

The calibration graph (figure 15) shows the relation between the voltage coming from the strain gauge and torque exerted on the motor housing. During the measurements we are interested in the torque on the drive wheel. As frictional losses in the bearings and chain are assumed to be zero the torque on the drive wheel is assumed to be equal to the torque on the motor housing. The graph shows several measurements with the same result. Therefore it can be concluded that the torque measurements are reliable concerning the strain gauge (accuracy<1%).

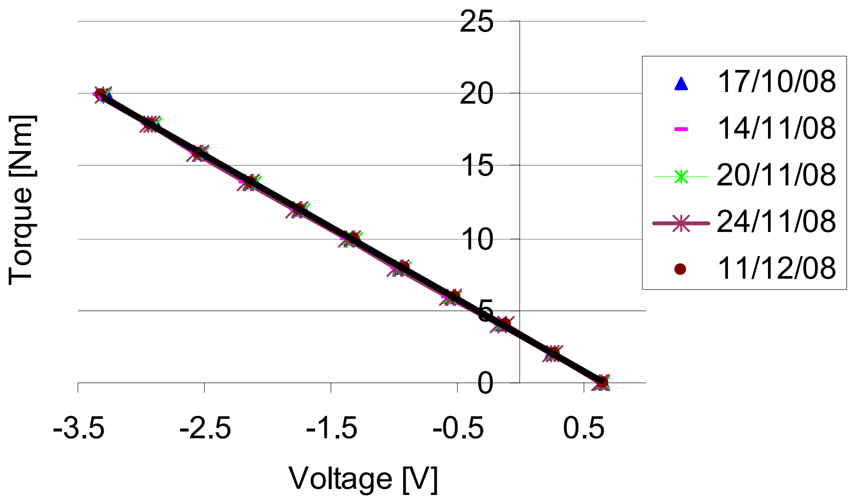



**Figure 15: Torque calibration**

The torque is calculated using:

$$T = g \cdot L_a \cdot m \qquad (4.1)$$

Where
g = 9.81 m/s$^2$ (gravitational constant)
$L_a$ = 0.405 m (arm length)
m = mass of the weights in kg

## Flow rate

The flow rate is measured using a vessel (see figure 2). Keeping the rope velocity constant the vessel is filled up to a certain level and the time is measured using a stopwatch. The time starts when water is coming out of the pipe that is above the vessel and is stopped if the water level reaches the required water level. The vessel had been calibrated earlier when it was installed (accuracy<1%).

## Measurement procedure

In order to obtain reliable measurements the following measurement procedure was used.
Before starting a new measurement a calibration of the strain gauge for the torque is carried out. In this way it is made sure that the torque measurement that follows has the correct values. The water level in the reservoir downstairs is checked so it has the correct height.
First the critical piston speed is measured: the pipe is totally filled with water by increasing the piston speed. Then the velocity is decreased until the flow rate is as small as possible (>0); at that point the critical piston speed is reached. The torque is measured at this velocity.
After that another interesting piston speed is found. If the pump is started and the pump pipe is empty the average water level in the pipe will start to rise from a certain piston speed. This piston speed can be higher or lower than the critical piston speed depending on the configuration of the parameters (like piston distance or immersed length). If this piston speed is higher than the critical piston speed hysteresis will occur (see paragraph 5.1). The accuracy of the value of this velocity is not very high as the increase of the water level in the pipe is verified visually from the ground floor looking at a small mirror in the cellar. The torque is measured again at this point.
Now the rest of the measurements can be carried out. The electric motor is started with the required velocity and the valve of the vessel is closed in order to measure the flow rate. The stopwatch is started from the moment that water comes out of the water outlet above the vessel. Then the torque measurement is started, lasting several seconds varying from 6 to 35 seconds. The piston speed is monitored visually at all times. The rope pump is stopped if the required water level in the vessel is reached. The time and amount of liters water is written down in Excel. This is repeated increasing the velocity in steps of 0.1 m/s starting from the critical piston speed up to 1.4 m/s.

# 5. Measurement results

## *5.1. Torque*

The torque has been measured as a function of the piston speed. According to the model (indicated as ideal in the figures) the torque should remain constant. Measurements show a gradually increasing torque with an increasing piston speed.

### Piston diameter

Figure 16 and 17 show a slight increase in the torque as a result of increasing piston diameter. Also an increase in torque as a result of increasing rope velocity can be observed. The increased torque as a result of the piston diameter is caused by hydraulic and/or mechanical friction in the system.

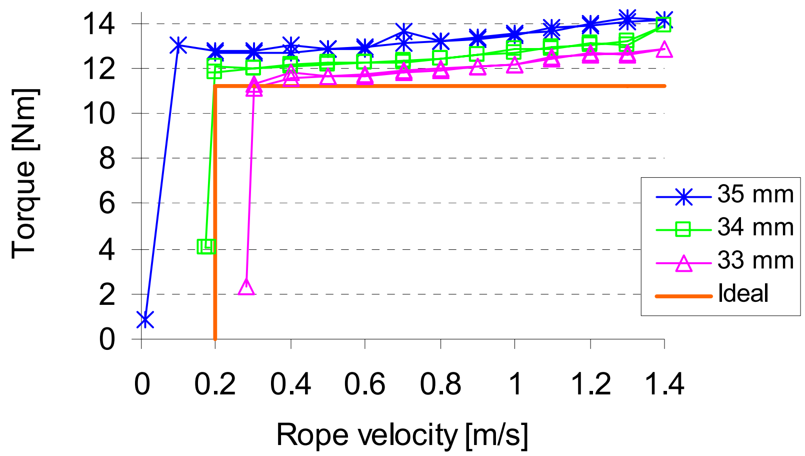



**Figure 16: Torque - varying piston diameter.**
**Immersed length = 51cm, piston distance = 60cm.**

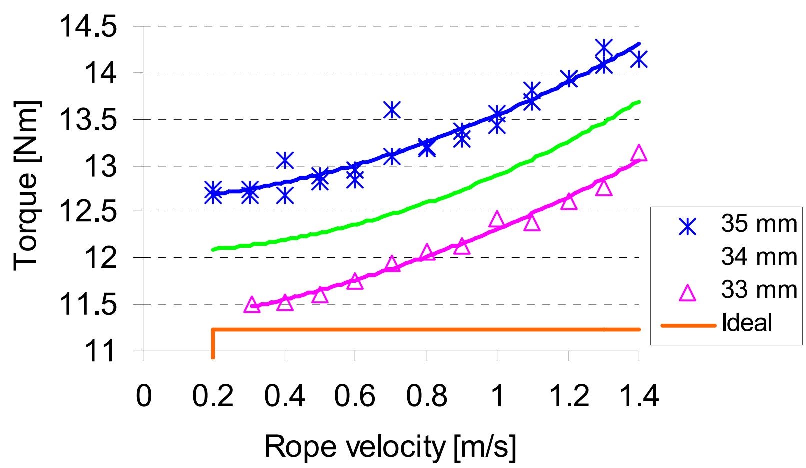



**Figure 17: Torque - varying piston diameter.**
**Immersed length = 51cm, piston distance = 60cm.**

## Piston support tubes

Using the piston support tubes the torque is significantly lower. Due to the support tubes the pistons remain aligned in the pipe causing less friction. It was observed that without the support tubes the pistons tend to slide skew through the pipe (see figure 3 and 4). This phenomenon has been observed by a student group who had worked on the rope pump earlier. From the results it can be concluded that the decrease in torque is caused by a decrease of friction between piston and pipe and/or a decrease in hydraulic friction. It is remarkable to see that the torque (see figure 20 and 21), for the rope with support tubes, at critical velocity matches the ideal torque which represents the model.

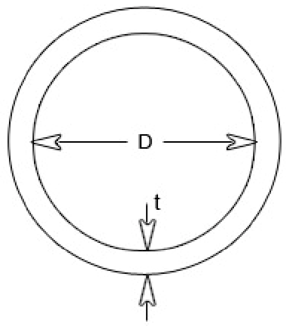



**Figure 18: Piston aligned - gap area:** $t \cdot D$

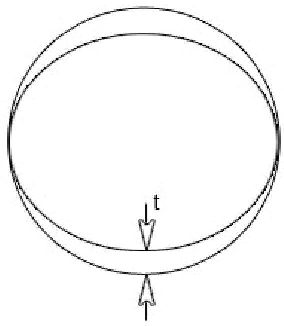



**Figure 19: Piston skew - gap area:** $\frac{1}{2} \cdot t \cdot D$

A second reason for torque reduction could result from the change of the gap area. In figure 18 and 19 we see the situation with the piston aligned and that with the piston skew, touching the pipe wall. On the aligned situation the effective gap is approximately twice that of the skewed case. Now the results shown in figure 16 and 17 suggest a slight increase in torque, if the gap area decreases. This is consistent with the results of figure 20 and 21.

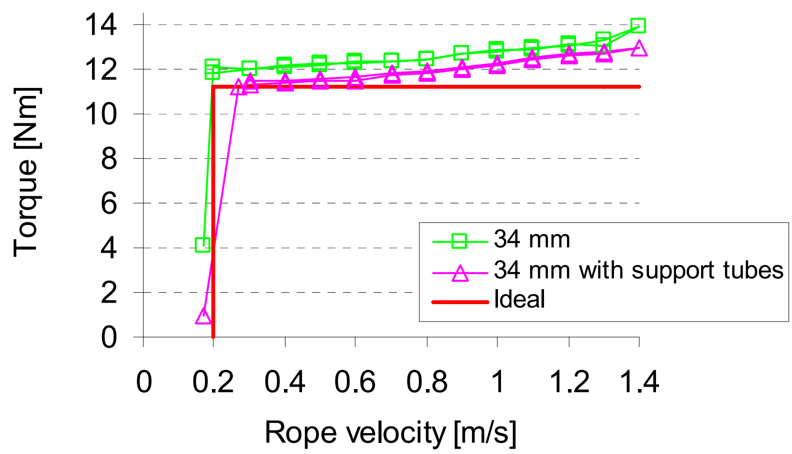



**Figure 20: Torque - piston support tubes.**
**Immersed length = 51cm, piston distance = 60cm.**

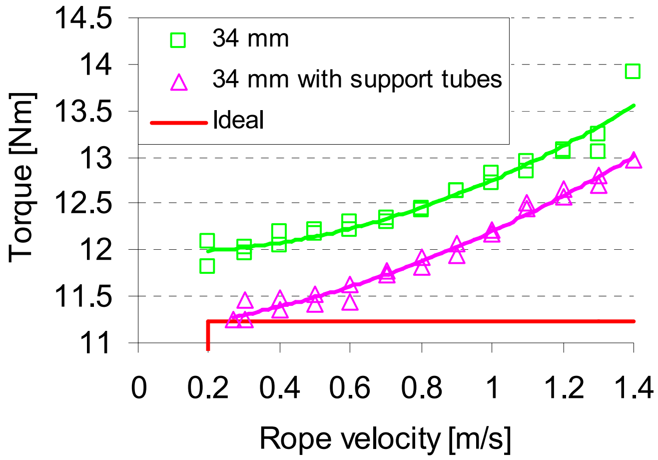



**Figure 21: Torque - piston support tubes.**
**Immersed length = 51cm, piston distance = 60cm**

## Piston distance

As the piston distance increases the torque decreases. If the piston distance increases the number of pistons per unit length of rope decreases. Therefore less friction is caused by the total number of pistons on the rope.

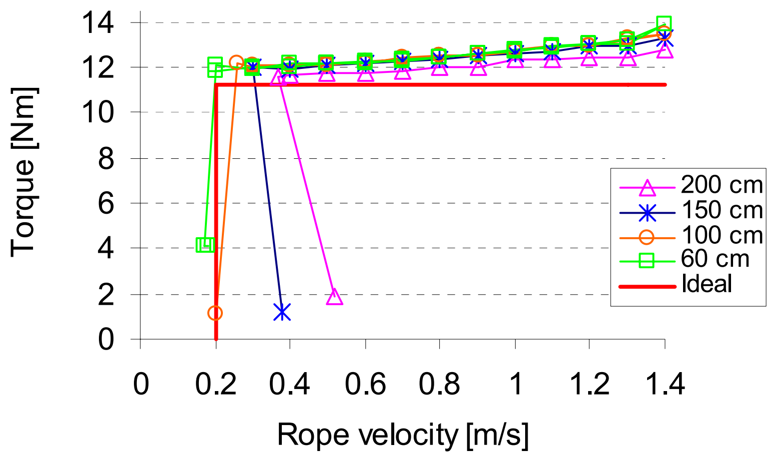



**Figure 22: Torque - varying piston distance.**
**Piston diameter = 34mm, immersed length = 51cm.**

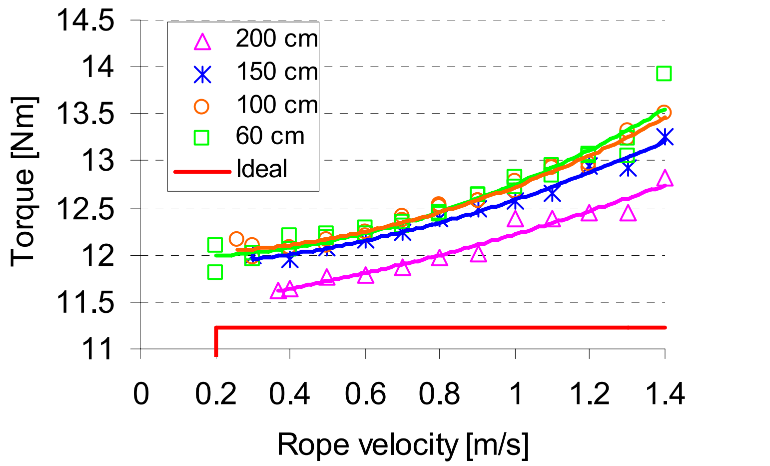



**Figure 23: Torque - varying piston distance.**
**Piston diameter = 34mm, immersed length = 51cm.**

## Immersed length

This graph shows a slight increase in the torque as a result of an increasing velocity. At higher velocities the torque is also a function of the immersed length. The differences at higher velocities are probably caused by hydraulic friction. As the pipe is deeper under water, the pistons experience more friction.

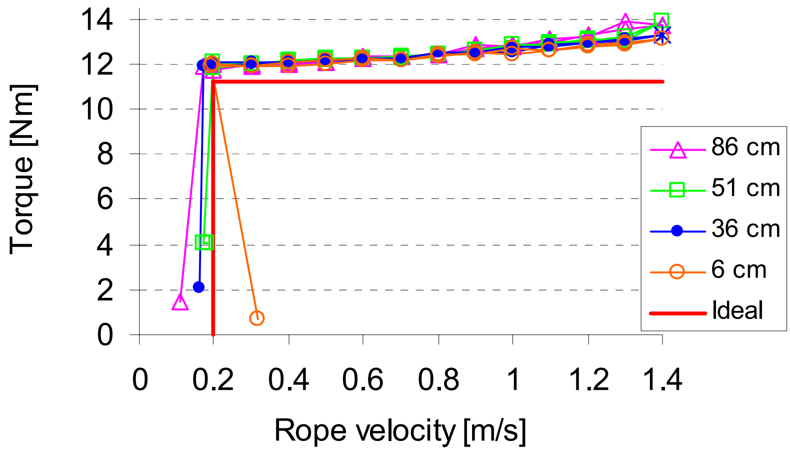



**Figure 24: Torque - varying immersed length.**
**Piston diameter = 34mm, piston distance = 60cm.**

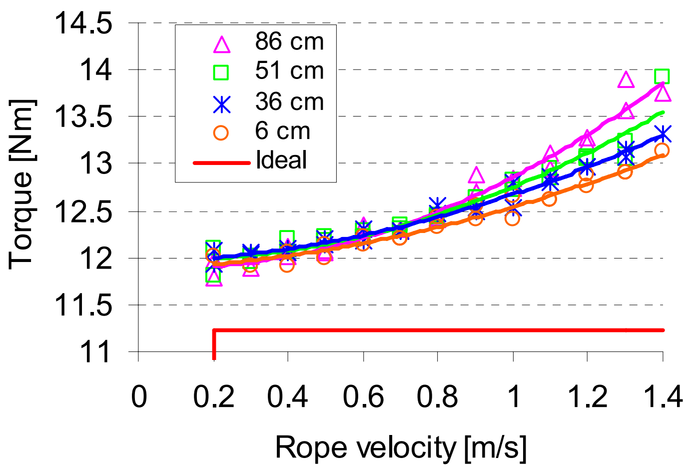



**Figure 25: Torque - varying immersed length.**
**Piston diameter = 34mm, piston distance = 60cm.**

## Critical velocity and hysteresis

The critical velocity is the piston speed at which the pump has almost zero flow rate (>0). This point is found, starting with a full pump pipe and a piston speed above the critical velocity, by decreasing the piston speed until the flow rate is about zero.
If the pump is started with an empty pipe and the piston speed is increased steadily the pump will not always start to deliver water from the critical velocity. In some cases the piston speed needs to be higher than the critical velocity in order for the pump to deliver water. This phenomenon is called hysteresis.
The starting point of each graph in for instance figure 24 represents the velocity from which the empty pump pipe is started to be filled (see paragraph 4.2 for more details). If the critical velocity is lower than the starting velocity then hysteresis exists (for instance figure 24 where $L_i$= 6cm).
The hysteresis seems to be a function of the immersed length and the piston distance. Because the differences are quite insignificant for the practical rope pump this phenomenon has not been investigated any further. It should be mentioned that due to measurement procedure the starting points of the graphs are not 100% reliable.

## *5.2. Flow rate*

The flow rate is the amount of water in liters per second that the pump delivers. The flow rate has been measured as a function of the rope velocity, while the parameters ‘piston diameter’, ‘piston distance’ and ‘immersed length’ have been varied.

### Piston diameter

Figure 26 clearly shows the linear increase of flow rate versus rope velocity starting at the measured critical velocity. The critical velocities can be found in the figure being the points where the graphs cross the x-axis. The larger the piston diameter the lower the critical velocity. Note that the ideal line and the measured ones are almost parallel.

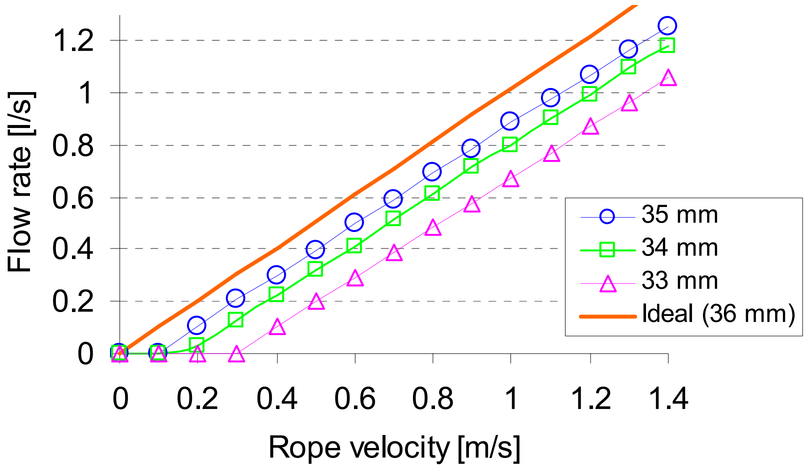



**Figure 26: Flow rate - varying piston diameter.**
**Immersed length = 51 cm, piston distance = 60cm.**

### Piston support tubes

The support tubes keep the pistons from sliding skew through the pipe. The leakage gap is in this case larger than without support tubes and therefore the flow rate is lower. Skew pistons form an ellipse formed sealing in stead of a round one, therefore the slit area is smaller (in fact twice as small, see figure 19).

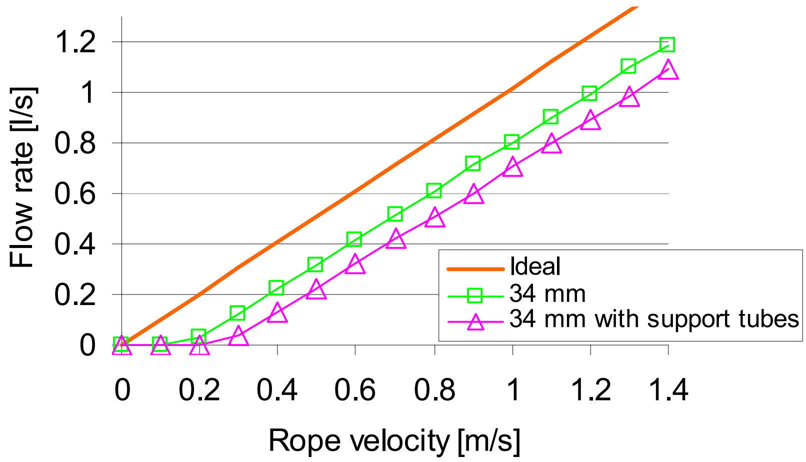



**Figure 27: Flow rate - piston support tubes.**
**Immersed length = 51 cm, piston distance = 60cm.**

## Piston distance

Increasing the piston distance causes the flow rate to decrease. This is caused by the fact that there are less pistons in the pipe to keep the water from flowing back. Note again that all lines are almost parallel.

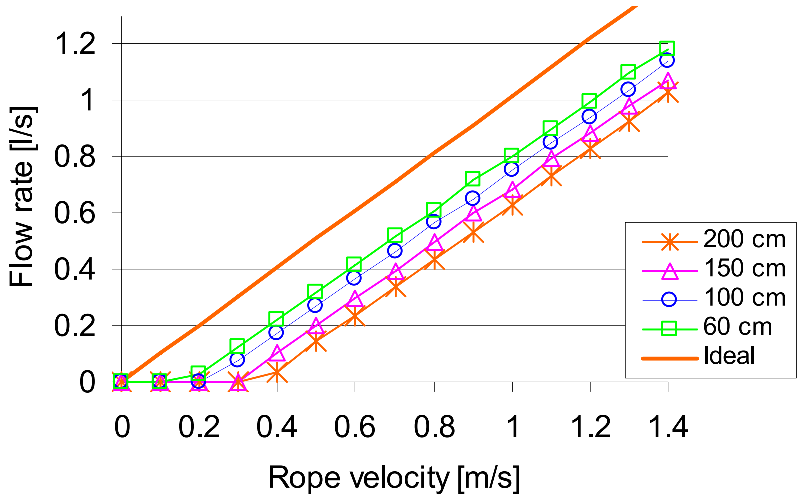



**Figure 28: Flow rate - varying piston distance.**
**Immersed length = 51 cm, piston diameter = 34 mm.**

## Immersed length

Changing the immersed length does not have any effect on the flow rate as can be seen in figure 29.

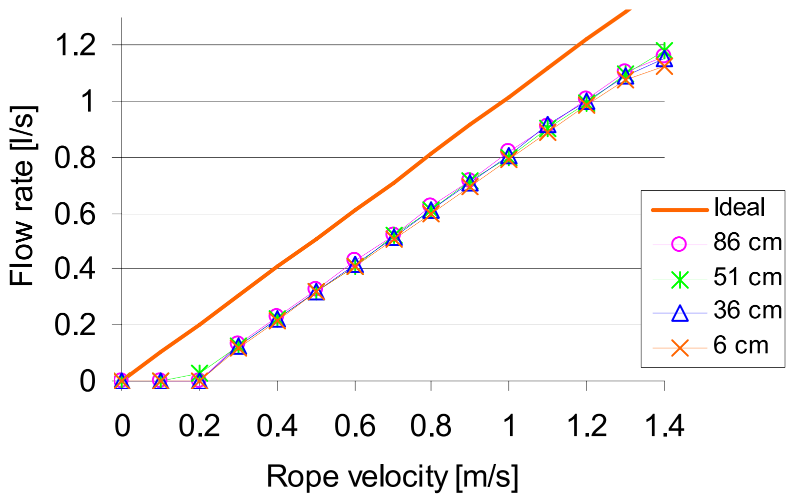



**Figure 29: Flow rate - varying immersed length.**
**Piston diameter = 34mm, piston distance = 60cm.**

## 5.3. Efficiencies

The volumetric efficiency is the ratio between the real flow rate and the ideal flow rate:

$$\eta_{vol} = \frac{\phi}{\phi_{id}} = 1 - \frac{\phi_l}{\phi_{id}} \qquad (5.1)$$

From this formula the shape of the graph in figure 31 can be easily explained. According to the theory the leakage flow rate is independent of the rope velocity, in reality the leakage flow rate increases very slightly (see figure 30). At low velocities the flow rate is so low that the leakage flow is relatively high. At higher velocities the flow rate increases and the leakage flow becomes less significant.

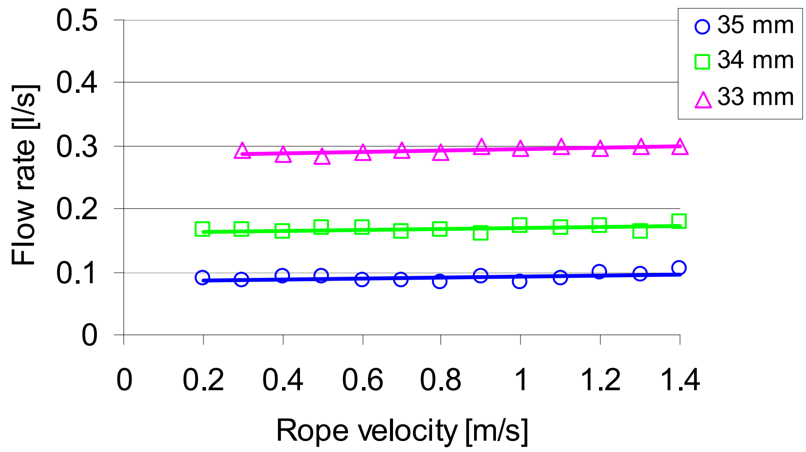



**Figure 30: Leakage - varying piston diameter.**
**Immersed length = 51cm, piston distance = 60cm.**

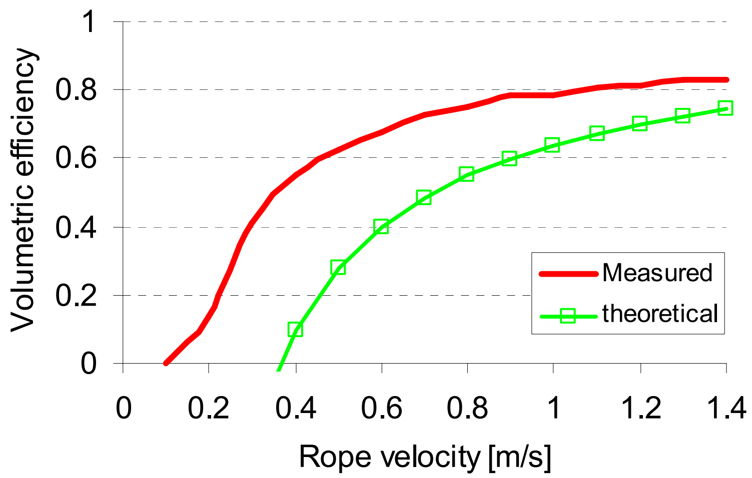



**Figure 31: Volumetric efficiency - base case**

The power efficiency (figure 32) is the ratio between hydraulic output power and mechanical input power:

$$\eta_p = \frac{P_h}{P_p} \tag{5.2}$$

The hydraulic output power can be written as:

$$P_h = \rho g H \varphi \tag{5.3}$$

The input power is the product of the pump force and the speed:

$$P_p = F_p \cdot V_p = \frac{2Q_p}{D_w} \cdot V_p \tag{5.4}$$

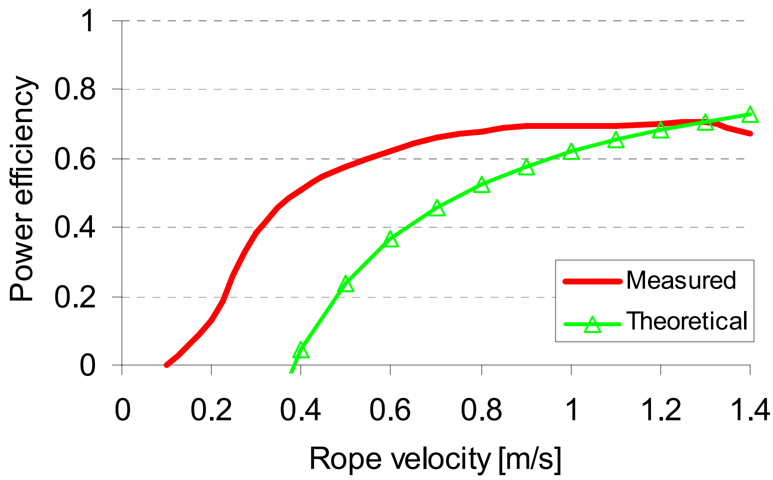



**Figure 32: Power efficiency - base case**

# 6. Comparing the model and the measurements

## *6.1. Torque*

The model only takes the weight of the water into account as it describes the torque neglecting all friction. The torque is calculated as a product of the weight of the water column and the perpendicular distance from that force to the drive wheel axis:

$$Q_p = \rho g A H \cdot \frac{D_w}{2}$$

According to the model (see equation 3.7 and figure 10) the torque is constant for all rope speeds above the critical one. In reality friction occurs at several places in the pump, for instance friction between pipe and pistons, friction between rope/pistons and guiding points and hydraulic friction. An increase in piston speed causes a slight increase in friction and therefore an increase in torque. Looking at the varied parameters during the measurements it is concluded that the piston diameter has the most effect on the torque (see figures 16 & 17) while theory predicts no influence due to piston size. Also placing piston support tubes has a great effect on the torque (figures 18 & 19). Varying piston distance has less effect (figures 20 & 21) and varying immersed length only influences the torque at high rope velocities (figures 22 & 23).

## *6.2. Flow rate*

Figure 33 shows a comparison of the flow rate between the model and the measured data of the base case. Surprisingly the measured flow rate shows a higher flow rate than the model. There can be several explanations for this, for instance the fact that in the base case the pistons move skew through the pump pipe (see figure 27). As we have seen the effective gap area for a skewed piston is half that of the aligned piston. So the critical speed for the skewed piston is half that of an aligned piston which we assume in the theoretical model. So $V_c$(skew) ~ $V_c$(aligned). According to equation 3.4 this is confirmed by the measurements of figure 33.

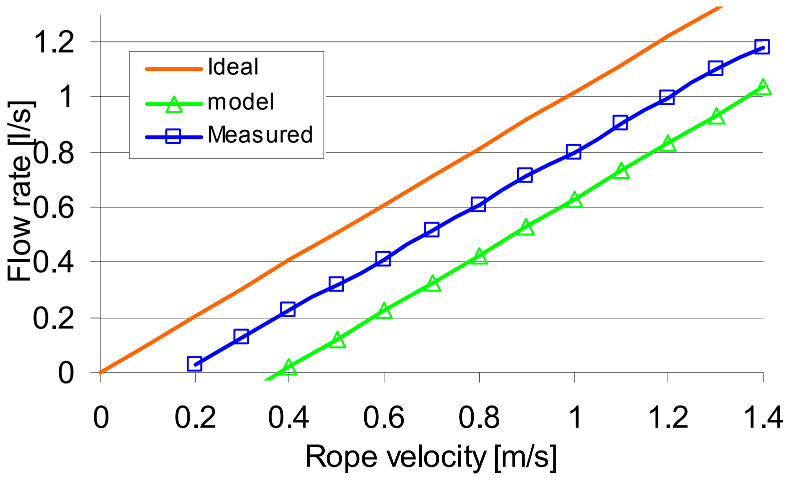



**Figure 33: Flow rate - theoretical and measured for the base case.**

The slit width is determined by the inner pipe diameter and the piston diameter. As the inner pipe diameter is constant the piston diameter determines the slit width. From the graph in figure 26 it can be seen that in reality the linear relation between flow rate and piston diameter according to the model (see figure 34) is confirmed quite accurately.

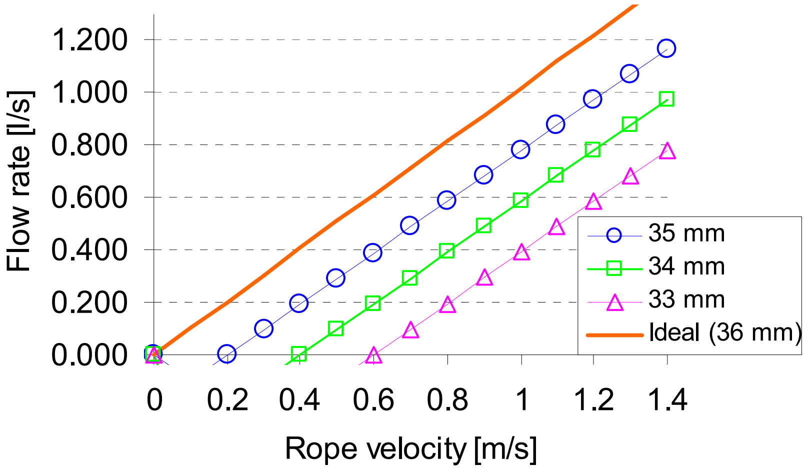



**Figure 34: Theoretical flow rate - varying piston diameter.**
**Immersed length = 51 cm, piston distance = 60cm.**

Varying number of pistons per unit length of rope shows a clear relation between flow rate and piston distance according to the model, figure 35, and also according to the measurements, figure 28.

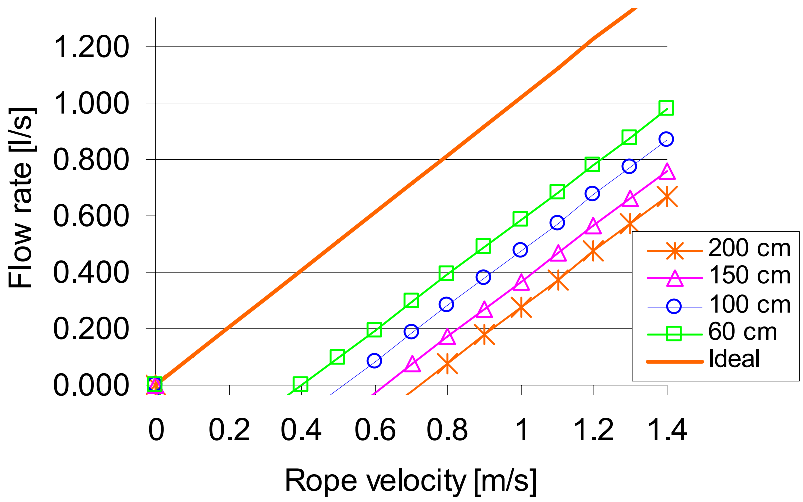



**Figure 35: Theoretical flow rate - varying piston distance.**
**Immersed length = 51 cm, piston diameter = 34 mm.**

The critical velocity depends, according to the model, in the same way on the slit width and the number of pistons per unit length (see equation 3.5). In the graphs the critical velocities are found there where the flow rate is equal to zero. Also here the measurements show that the basis of the relation is correct.

# 7. Conclusions

The goal of this project was to obtain reliable measurements on the rope pump and to make a comparison with the hydrodynamic model. Looking at the varied parameters several conclusions can be drawn:

Torque

- The piston diameter has a great effect on the torque: increasing the piston diameter results in an increased torque.
- Using piston support tubes also has a great effect on the torque: the torque decreases as support pipes are used.
- Varying the piston distance has a small effect on the torque: a greater distance results in a smaller torque.
- The immersed length has almost no effect on the torque: increasing the immersed length results in a higher torque only for high piston speeds.

Flow rate

- Increasing the piston diameter results in an significantly increased flow rate.
- Using support tubes causes the flow rate to drop. This is caused by the fact that skew pistons have an elliptical sealing and pistons supported by tubes are aligned and therefore have a smaller round sealing.
- Increasing the piston distance results in a decrease of the flow rate.
- The immersed length has no effect on the flow rate.

As the model and the measurements are compared it is found that the measured flow rate is significantly higher than the theoretical flow rate. This can be due to the fact that the pistons slide skew through the pump pipe. The basis of the relations between leakage flow rate, critical velocity, slit width and number of pistons per unit of length seem to be correct.
The measured torque has the same order of magnitude as the theoretical torque. The measured torque shows a gradual increase with increasing rope velocity as opposed to the theoretical torque which is constant.

In general it may be concluded that the measurements confirm the validity of the model, if we take account of the effect on gap area reduction if the piston moves skewed relative to the pipe. Flow rate and critical velocity are well predicted. In reality torque measured is 10%-20% higher than that predicted, which is probably caused by mechanical and hydro dynamical wall friction.

It is not understood why measured torque depends on piston diameter, this effect not being predicted by theory. Finally, the rope pump shows to be a very ingenious design, confirmed both by theory and measurements:

- Very low mechanical loading and the absence of dynamic loads as in piston pump,
- The main load is the tension force in the rope, being almost constant.
- The pump pipe: no longitudinal stresses; and radial stresses are almost zero.
- The pump has in a wide range very good efficiencies 60-80% which is more than double that of small centrifugal pumps.

# References

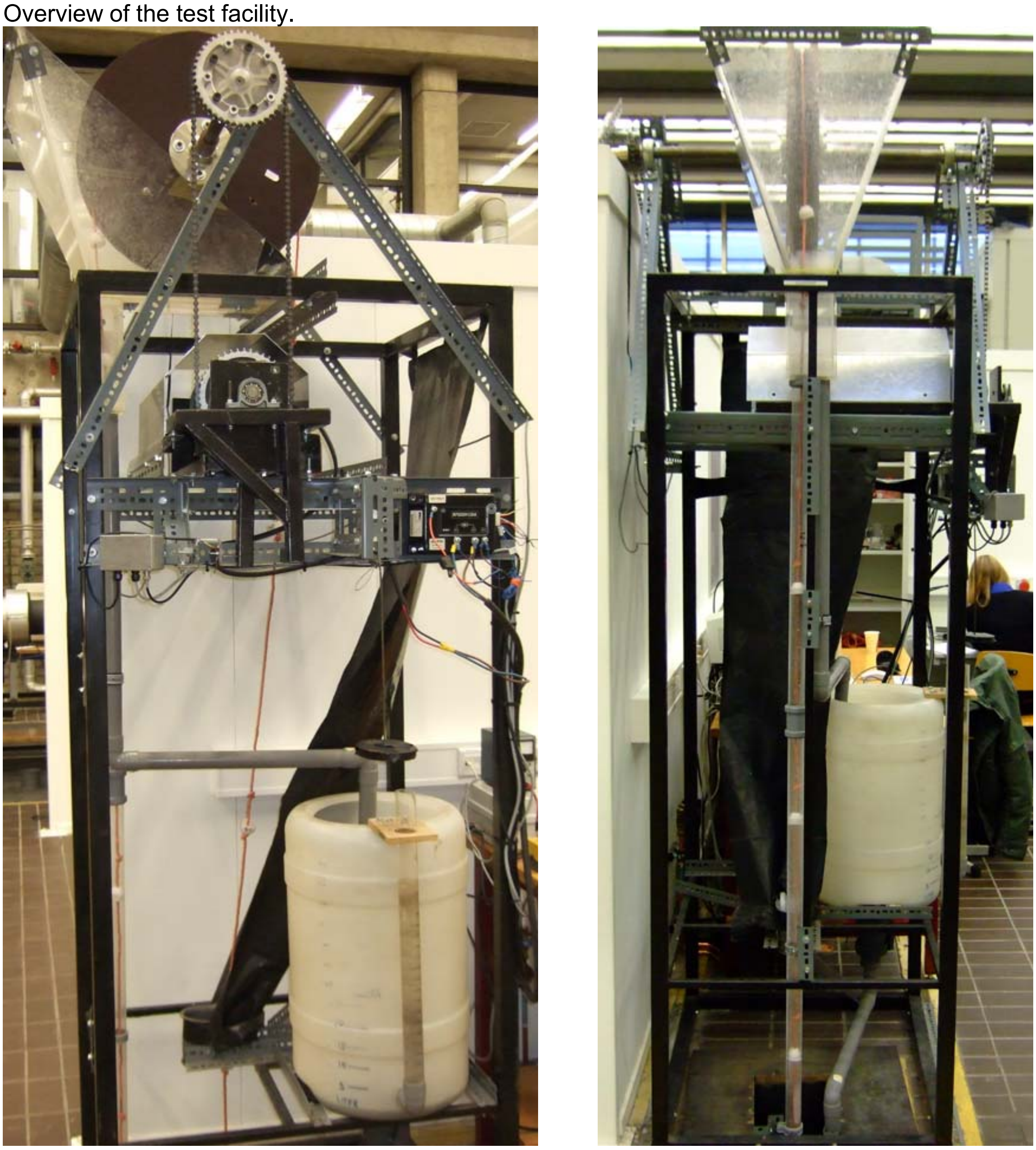
[1] http://www.ropepumps.org accessed on 19 December 2008.

[2] http://www.pumpaid.org accessed on 19 December 2008.

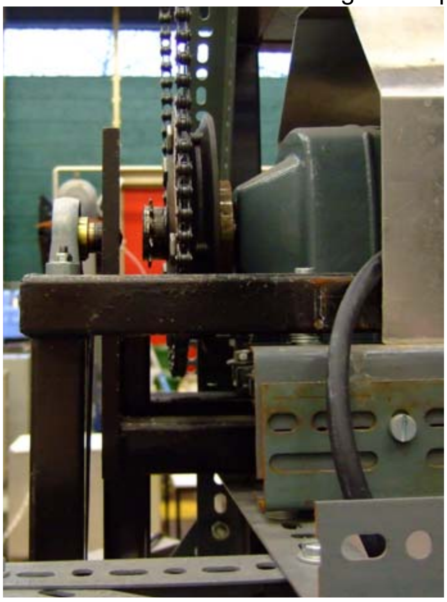
[3] Smulders, P.T., Rijs, R.P.P. *A Hydrodynamic Model of the Rope Pump*, Eologica, The Netherlands (2006), http://publications.eologica.com or http://www.arrakis.nl

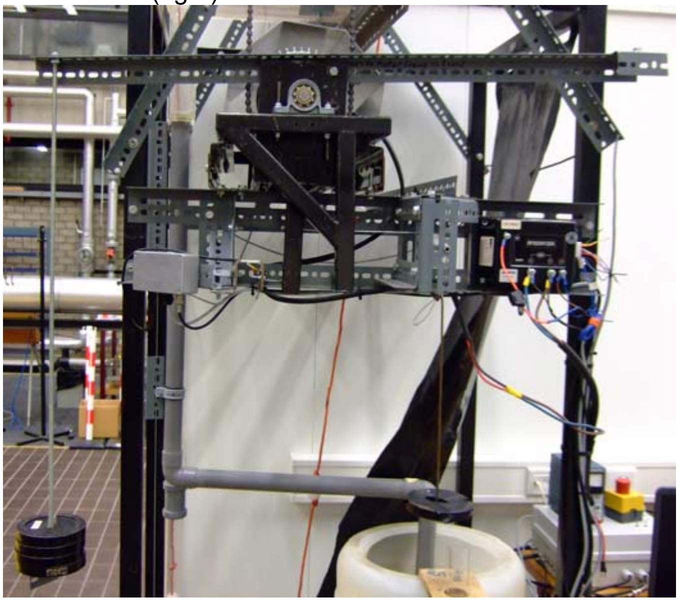
# Appendix 1: Pictures of the test facility

Overview of the test facility.

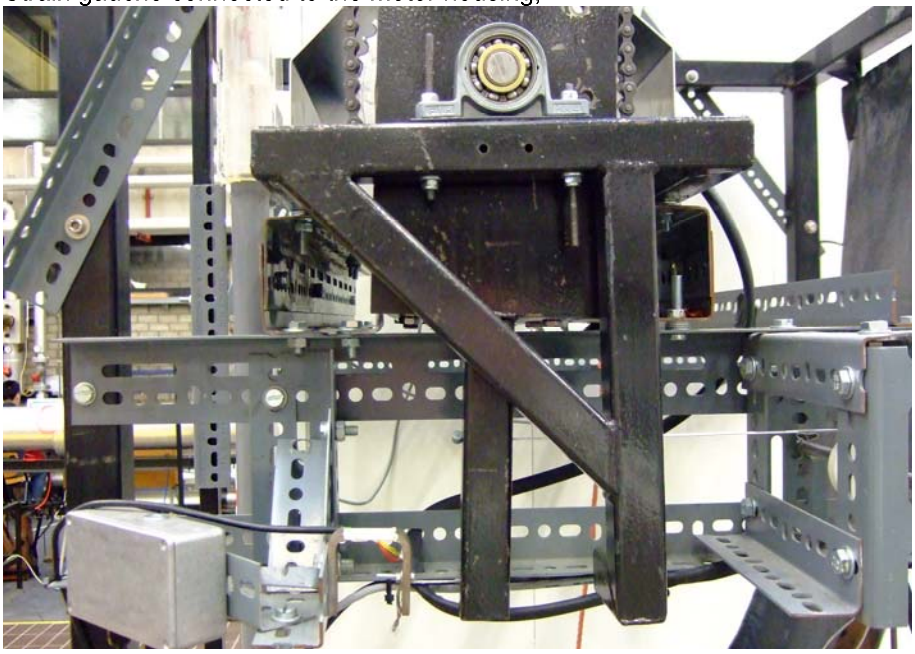


Alignment motor shaft and bearings that support the motor housing (left). Metal bar with weights mounted on the motor housing for torque calibration(right).



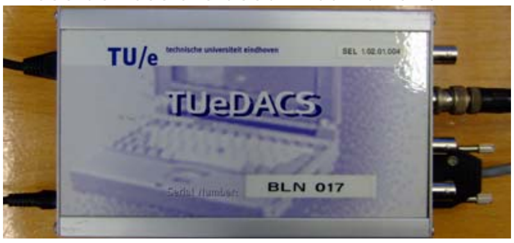


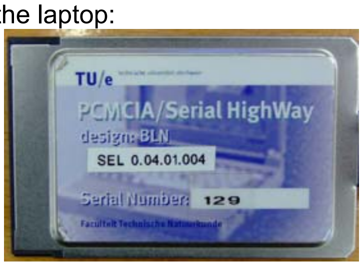
Strain gauche connected to the motor housing,



The reservoir in the cellar:


These devices are used in combination with the laptop:




# Appendix 2: Manual rope pump test facility

1. Connecting and using the laptop and TUeDACS:

- Use the card to connect the laptop to the TUeDACS
- Be sure the usb-stick is in the laptop
- Connect cables to the TUeDACS
- Start up the laptop:
    - Open terminal program (shell console) and type the following exactly (press enter after each line):
    - sudo mount /sda
    - cp /mnt/sda/regelaar3.mdl .
    - then open matlab from desktop (click once)
    - open regelaar3.mdl in Matlab
    - click simulation/simulation parameters, change stop time to 1200 and press ok
    - press ctr+B ( = build in matlab)
    - Pull emergency knob, put switches to 'on'
    - go back to console and type: sudo .sda/regelaar3 –w
    - go back to matlab and click:
    - simulation/connect to target and
    - simulation/start program
    - double click gain and use it to control speed
    - In order to stop click simulation/stop sequence
    - In order to start again go back to console and type sudo .sda/regelaar3 –w or use arrow up, and press enter
    - Back to matlab and repeat steps from simulation/connect to target etc.

2. Using the PC:

- Start computer
- Start up labview: start/labview
- Open c://touwpomp/SignalExpress Data/koppel.seroj
- Run…stop after a few seconds (7 or 8 sec..)
- Click the plus of the last log (left down in the corner)
- Right click voltage-file and export to excel
- Copy second row into your torque measurement file

3. Ropes:

- there are 4 different ropes
- the three ropes without piston support tubes need extension parts as the immersed length is changed.
- The piston distance can be changed by simply re-knotting the rope and moving the pistons