Wear Mechanisms of Piston Seals in Reciprocating Hand Pumps for Rural Drinking Water Supply

Michael Lubwama[1], Brian Corcoran[2], John Baptist Kirabira[3], Kimmitt Sayers[4]

[1] Graduate Student, School of Mechanical and Manufacturing Engineering, Dublin City University, Dublin 9, Ireland
[2] Lecturer, School of Mechanical and Manufacturing Engineering, Dublin City University, Dublin 9, Ireland
[3] Senior Lecturer, Faculty of Technology, Makerere University, P. O. BOX 7062, Kampala, Uganda
Corresponding author email: jbkirabira@tech.mak.ac.ug
[4] Lecturer, Department of Mechanical Engineering, Dundalk Institute of Technology, Dundalk, Ireland

ABSTRACT
In Uganda 63% of the rural population depend on improved water sources for drinking water; 36% depend on unimproved water sources. The hand pump is a robust technology that can provide safe water from groundwater resources. However, the large number of non-functioning hand pumps indicates that a holistic approach may be necessary to tackle this problem and ensure functional sustainability of rural water supply. Most hand pump technical failures are due to wearing of piston seals, which results in low delivery rates of pumped water and more pumping effort indicating low pump efficiency. With regard to reciprocating hand pumps for rural water supply, little evidence of tribological analysis of wear behaviour of piston seals has been found in the literature. This paper is aimed at demonstrating wear behaviour of piston seals in reciprocating hand pumps. The purpose is to provide a basis for predicting piston seal lifetime. Practical surveys and analysis are based on hand pumps installed in Makondo parish, Masaka District. This paper therefore determines and identifies the wear mechanisms and modes that piston seals for reciprocating hand pumps undergo. First level surface analysis is used for this determination. Comparative analyses of abrasive wear models for nitrile rubber is discussed when surface roughness and loading are varied.

Keywords: First level surface analysis; Piston seals; Reciprocating hand pump; rural drinking water supply; Wear mechanisms

1.0 INTRODUCTION
According to the Joint Monitoring Programme Report (2010), 63% of the rural population in Uganda depend on improved water sources for drinking water; 36% depend on unimproved water sources. The hand pump is a robust technology that can provide safe water from groundwater resources in a cost effective manner (Reynolds, 1992). However, recent observations in Africa have shown that many hand pumps have fallen into disuse shortly after installation (Harvey, 2003).

A recent survey of Makondo Parish has ascertained that less than one –third of all hand pumps installed to supply the locality with safe water are functional. The hand pump mechanics attribute the piston seal as the component that is replaced most frequently. Figure 1 shows the functionality distribution of hand pumps in Makondo Parish, Lwengo District.

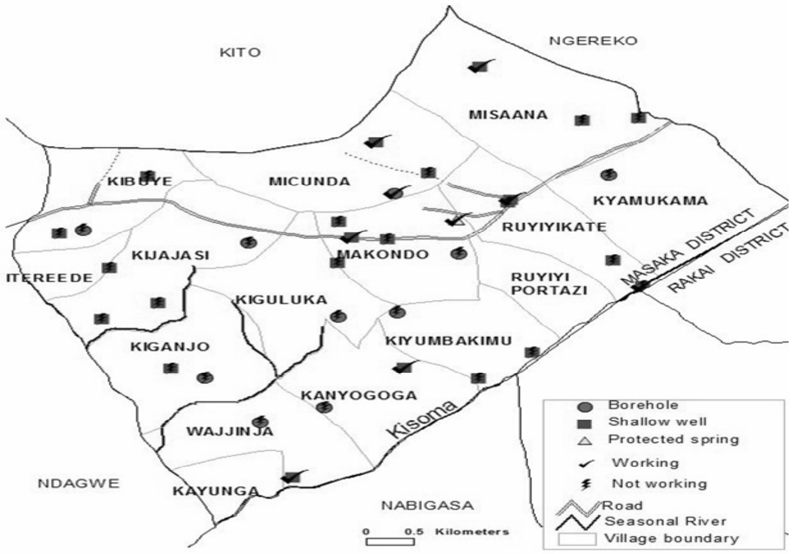

Figure 1: Functionality of hand pumps in Makondo parish

According to Aspegren et al. (1987) and Reynolds (1992) the wearing of the piston seal is singly responsible for 25 percent of all hand pump failures, representing the highest proportion of all maintenance interventions. A worn piston seal presents real problems for the hand pump users as replacing of these piston seals requires specialized mechanics, since the Village Level Operation and Maintenance concept pioneered by research during the first water decade does not seem to be practical in sub-Saharan Africa (Baumann, 2005).

Yau (1985) performed studies on hand pumps with Polyvinylchloride (PVC) and high density polyethylene (HDPE) rising mains and piston seals of nitrile rubber, polyethylene and leather materials and determined the tribological behaviour of the piston seals with regard to wear and frictional forces involved in upstroke and down stroke motions of a reciprocating hand pump. Aspegren et al. (1987) performed macroscopic analyses in piston seals for reciprocating hand pumps for seals for application in rural water supply. From his field investigation, Yau (1985) found significant wear on the piston seals calculated as a change in thickness divided by original thickness as a function of total work output. Aspegren et al. (1987) concluded that the eventual cost of a high quality seal material would be a good investment as the availability of the hand pump will be increased, with a longer operation time of the seal. Both Yau (1985) and Aspegren et al. (1987) performed their analyses at macro-level and no classification of the wear mechanisms and modes involved in the reciprocating motion of a reciprocating hand pump have been identified. Also, no specific model has been developed to better understand the wear mechanisms that take place in hand pumps. The wear rate in any tribological interaction varies depending on the contact conditions, including, contact pressure, sliding velocity, contact shape, suspension stiffness, environment, lubrication and counterpart material (ASM Handbook, 1992). Most studies published on the behaviour of polymers have been focussed on sliding against steels in dry sliding (Yu et al., 2008). The presence of water as the working medium, which presents as water lubricant, has been discussed by few authors who have shown that water lubrication generally increases wear of polymeric materials (Yamamoto and Takashima, 2002). However, a specific discussion that delves into the interaction between the piston seal and cylinder in a reciprocating hand pump that specifies the probable wear mechanism is yet to be found in literature. Also, the formation of wear models specifically incorporative of the wear mechanism in elastomers is yet to be found in the literature.

In this work, the wear mechanisms that occur on nitrile rubber piston seals of a reciprocating hand pump for rural water supply were identified. First level of surface examination that entailed visual inspection analysis and microscopy analysis (X10) based on Ludema's (1996) steps for carrying out any tribological study were used. Also, different wear models of polymers for abrasive wear of polymers were compared in terms of the calculations of wear rates. This study shows the influence of loading and surface roughness on wear rates of piston seals based on specific wear models. Typical operational and material parameters for reciprocating hand pumps (based on values in literature) and elastomeric piston seals (nitrile rubber type) were used. This level of analysis is simplistic but highly indicative in quantifying the wear rates calculated using different models for typical operational and material parameters encountered in the application of reciprocating piston seals for hand pumps.

2.0 MATERIALS AND METHODS

In order to determine the wear mechanisms and modes that occur in piston seals in reciprocating hand pumps for rural water supply, the complexity of the problem was first understood. Figure 2 shows a schematic representation of the conditions under which a piston seal operates.

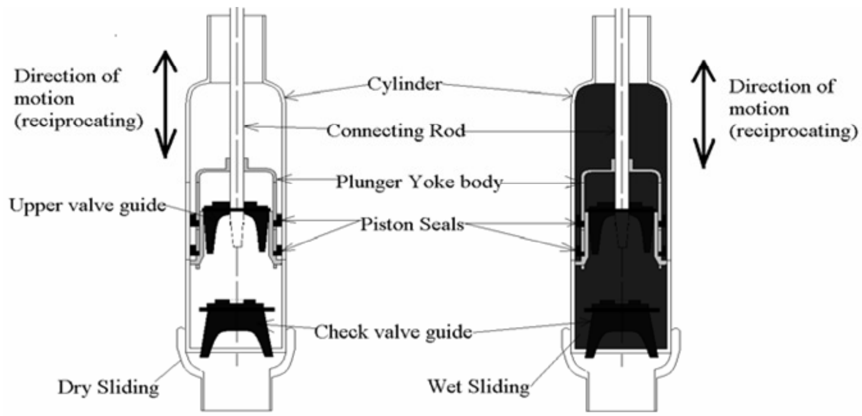

Figure 2: Schematic of dry sliding and wet sliding in the cylinder assembly

A representative sample of six piston seal samples was obtained from recently non-functional hand pumps in Makondo parish. First level of surface examination as described by Ludema (1996) was used to diagonise the tribological problem to identify the possible wear mechanisms and modes involved as follows:

(i) The hand pump was dismantled and worn piston seal surfaces cleaned.
(ii) Sensory judgment (using visual inspection, touch, smell, etc) to make a first judgment of the environment in which the surfaces are operating
(iii) Observation of particular patterns using a 10X eyepiece magnifying glass was used.
(iv) Determination of surface physical characteristics and the processes that produce them based on the observation of pits, ploughed ridges, and cracks on the surface.

In the comparative analysis of different abrasive wear models, the normal wear loading was varied from 10 to 1000 N. Also, the surface roughness values were varied from 0.225 to 0.7 μm. The other parameters were held constant. Typical operational and material parameters for reciprocating hand pumps (based on values in literature) and elastomeric piston seals (nitrile rubber type) were used. The sliding distance and sliding velocity were obtained after considering the cylinder height of 125 mm and 40 strokes per minute respectively (Baumann and Erpf, 2005). Table 1 shows the typical material properties for nitrile rubber and the operational hand pump parameter values.

Table 1: Typical material properties and operational parameters

Material Property (Nitrile rubber) and operational parameters (hand pump)	Typical values
Coefficient of friction	0.14 -1.1 (Budinski, 1997;)
Wear factor	10^{-7} (mm^3/Nm)
Normal Load	10 – 1000 N
Sliding distance	4800000mm in one day
Hardness	35 – 65 Shore A (ASM International, 2003)
Sliding velocity	10000mm/minute (Baumann and Erpf, 2005)
Ultimate tensile strength	30 MPa (Ashby and Jones, 1996)
Elongation to break	150 – 450 % (Ashby and Jones, 1996)
Surface roughness	0.15 – 0.7 μm (Mofidi, 2009)
Sliding duration	8 hours in one day

3.0 RESULTS AND DISCUSSION

3.1 Wear Mechanisms

From Figure 3, wave patterns typical to rubber abrasion were observed. These wave patterns were also noted by Schallamach (1958). The direction of the wave patterns is parallel to the sliding direction of the piston seals. These wave formations provide evidence of roll formation stemming from adhesive frictional behaviour. This suggests that adhesive wear is a possible wear mode. Also, a deep plough was observed. This is an indication of micro-cutting which suggests that a third-body must have interacted between the piston seal and the cylinder wall. This third body may be solid particles in the water. A deep crack indicative of fatigue wear was also observed. Points of crack initiation were identified. Cracks are evidence of crack initiation, propagation and fracture, which implies that the wear mechanism is mechanical wear. The wear of this piston seal shows that the wear modes taking place in this piston seal are mainly fatigue wear and abrasive wear. However, adhesive wear cannot be discounted as the interaction of surface asperities at a micro-level is not known. Figure 4 shows similar trends to the observations made concerning Figure 3. However, the formation of wear debris (wear particle) was observed. Figure 5 also shows the formation of a wear particle which seems to form in a spiral or twist. The difference in the thickness of the flange between Seal A and Seal B was noted. The exact time it takes for this reduction is not known by the hand pump mechanics as planned maintenance is not carried out. Also, the brownish-reddish colour observed on the piston seal (Figure 5) is indicative of the environment in which these seals operate. The rising main of most hand pump in Makondo is made of galvanized iron. This oxidation of the iron to form rust presents as a surface complex, making the tribological problem a third-body one. This is an indicator of chemical wear.

From the results of the first level analysis, it was noted that fatigue wear and abrasive wear seem to be the dominant wear modes occurring during the wear of piston seals. However, as noted previously, adhesive wear cannot be discredited. These results are in line with the wear mechanisms highlighted by Mofidi (2009) who showed, based on the work of Moore (1980), the relation between friction and wear mechanisms in elastomers. He accordingly classifies the wear mechanisms in elastomers as roll formation, which is related to waves of detachment and scratches parallel to the sliding direction (Schallamach, 1958) abrasion and fatigue. This was also acknowledged by Moore (1972) who noted that wear is a mixed mode process.

Due to the interaction between the seal and the piston, adhesive wear is present due to the variation in surface roughness at a micro level leading to asperity deformation. Also, the difference in hardness between the piston seal and counterface leads to abrasive wear by two-body abrasion. However, due to the presence of solid particles in the water and oxide formation on the cylinder, three body abrasive wear occurs. The embedment of particles in the piston seal presents a point of stress concentration that leads to points for crack initiation, propagation and fracture. This leads to fatigue wear of the piston seal. Also, the loading of the piston seals during the cyclic movement of the piston during upstroke and down stroke is a contributing factor to fatigue wear.

From the discussion above the following model (Meng and Ludema, 1995) describing the wear of piston seals as a mixed mode situation can be postulated:

$$V_{wear\_total} = V_{abrasive\_wear} + V_{adhesive\_wear} + V_{fatigue\_wear} \quad (1)$$

Figure 3: Indicators of fatigue and abrasive wear

Figure 4: Indicators of fatigue and adhesive wear

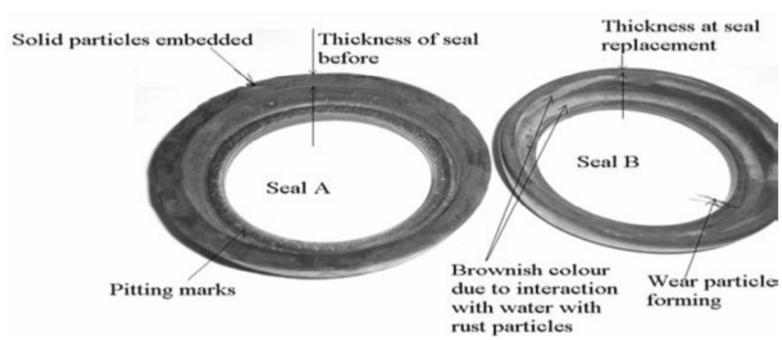

Figure 5: Dimensional difference in Seal B compared to Seal A

3.2 Abrasive Wear Models

From the above discussion it is apparent that any wear model must incorporate aspects of adhesion, abrasion and fatigue modelling. This can be realistically achieved by empirical means that simulate actual conditions and the real tribo-system as much as possible. In predictive analyses of wear of polymers, abrasive wear models are used. In this section, the models presented by Archard (1953), Ratner's and Lancaster correlation (1964) and Wang et al., (1995) are used for comparative analysis of the abrasive wear volumes of elastomers, in particular nitrile rubber. Archard wear law (1953) and Ratner's and Lancaster correlation (1964) are typical linear wear models whereas; the model presented by Wang et al., (1995) is a non-linear model. Table 2 shows the parameters involved in these wear models.

Table 2: Some abrasive wear models of polymers

Abrasive wear model	
$V = \dfrac{KWd}{H}$	Archard wear law (1953)
$V = \dfrac{K\mu Wv}{HSe}$	Ratner (1964) and Lancaster (1969) correlation
$V = \dfrac{KW^{3/2}R_a^{3/2}}{S^{3/2}e}$	Wang et al. (1995)

Where K is the wear factor, W is the normal load, d is the sliding distance, H is the hardness of the softer material (polymer), v is the sliding velocity, μ is the coefficient of friction, S is the ultimate tensile strength, e is the elongation to break, d is the sliding distance, R_a is the surface roughness.

Figure 6 shows the impact of variation in loading and surface roughness in the wear models. Wang et al., model incorporates the surface roughness of the counterface, while Archard's model and Ratner and Lewis' correlation incorporate hardness of the polymer, specifically lacking in the model by Wang et al. (1995). From the above analysis the apparent inconsistency in the current wear models becomes clear. These models are empirically derived for specific conditions and are not a reflection of the real tribo-system. This implies that understanding of this system will necessitate the construction of a specific test rig that simulates the operation of the hand pump as closely as possible.

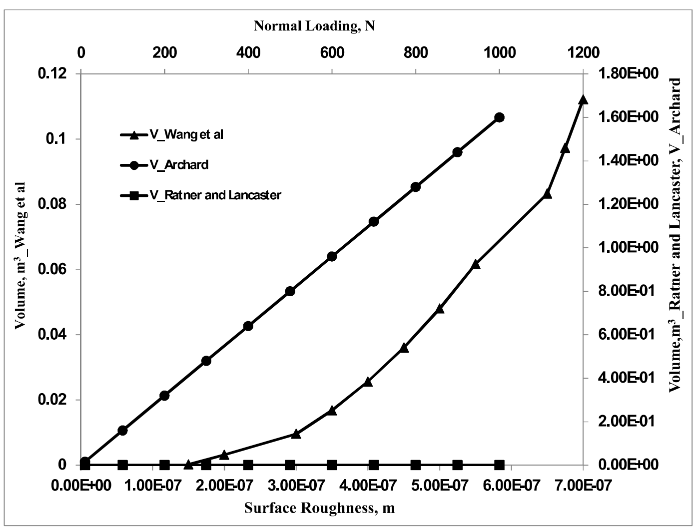

Figure 6: Wear volume as a function of applied load and surface roughness

4.0 CONCLUSIONS

The aim of this work was to determine the wear mechanisms and modes that occur on nitrile rubber piston seals of a reciprocating hand pump for rural water supply. These mechanisms and modes of wear were determined based on Ludema's (1996) method for first level surface analysis of tribological systems. The purpose of understanding these wear mechanisms was so that any further work on this tribological problem is based on first level analysis. Wear volumes were calculated using different polymeric wear models for typical operational and material parameters encountered in the application of reciprocating piston seals for hand pumps. Analysis using the different wear models has shown the need for development of a specific model for piston seals in hand pumps. The research has shown the validity of the first level of analysis as a means of validating the direction to take in solving the tribological contact. The discernment of the wear mechanisms further indicates that wear in this specific application is mixed and the next step of the research should be progression towards understanding the dominant wear mechanism. Mechanical and chemical wear mechanisms were identified and the wear modes identified included fatigue wear, abrasive wear and adhesive wear. However, the answer to the question regarding the dominant wear mechanism still persists.

5.0 ACKNOWLEDGEMENTS

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