Design and Optimization of a Photovoltaic Powered Grain Mill

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ABSTRACT

In Africa most rural people still use hand milling methods to prepare their daily food. This takes a lot of time and is an arduous work mainly carried out by woman and children. Therefore the introduction of motorized mills can improve their living conditions. However, typical diesel-driven mills have a capacity of 25 to 1,800 kg of grain per hour. For scattered rural settlement structures this is very high, since the average daily consumption per family is only 2.5 kg. Therefore a new PV-driven stone mill with a millstone-diameter of 150 mm and a maximum capacity of 3 kg per hour was constructed and optimized. Comparing the flour from the new mill with that from hand-milled samples from Zambia, Niger and Chad, showed that the fineness of the product obtained meets the preferences of the local people. By optimizing the design and operation of the mill the maximum power requirement could be reduced to less than 100 W. Using two 50 Wp PV-panels and a battery of 85 Ah, 15-60 kg of grain can be processed per day at a global radiation of 4-6 kWh/m². This paper describes the influence of the type of grain, the moisture content, the rotational speed of the millstone, the millstone gap and the feed rate on the driving torque and the power requirement of the mill.

Keywords: PV, Milling, Stone Mill, Solar Power, Grain, Food

1. INTRODUCTION

In African countries many postharvest operations such as threshing, oil extraction and milling are still accomplished manually. In particular, grain milling using saddlestone, pestle or mortar is arduous and time consuming, carried out exclusively by women and children. These milling techniques are more than 3 000 years old (Pomeranze, 1986) and allow only low grinding rates of less than 1 kg per hour (Carruthers and Rodriguez, 1992). Therefore, milling 2.5 kg of grain which is the average daily consumption of an African family takes about three hours (Chinsman, 1985). Besides that, milling is also done in small commercially operated mills. The most common and widely used types are hammer and stone mills with a capacity of 100 to1 800 kg/h and 25 to 1 200 kg/h, respectively (Jonsson et al, 1994). These mills are usually operated as customer mills, where people bring their grain and pay for the milling service. However, the available capacity is sufficient for 150 to 10 000 families. Since the flour is only prepared for a couple of days in advance to avoid degradation, such mills are limited to areas with a certain infrastructure and population density. However, in rural areas with a more scattered population distribution, people often have to walk long distances if a motorized mill is available at all. This indicates that the milling process takes a considerable amount of time, irrespective of the method of milling. Reducing the time and energy spent on milling could increase the time available for other more productive activities. Therefore, the development of inexpensive motorized mills with a low capacity of 2 to 5 kg/h could help to improve the living conditions and the livelihood in rural areas of developing countries.

However, while the power requirement to drive such a mill is 50 to 200 W, the smallest available standard diesel or petrol engines provide 2 to 3 kW. Furthermore the investment and operation costs are high and the fuel and spare parts supply is unreliable. In contrast to this electric drives are cheaper, available at almost any power rating, require almost no maintenance and are simple in operation. However, an electrical grid connection is not available in most cases. Therefore, considering the low power requirement and the typically high daily solar radiation of 5 to 6 kWh per m² in many tropical and subtropical areas, a DC-motor with a power supply from a PV-generator is a promising and cost effective alternative for the drive (see also GTZ, 1992; Hulscher and Fraenkel, 1994). To reduce the size of the required PV-generator, the most important goals of this work were to reduce the energy and the maximum power requirement of the mill. At the same time the influence of parameters such as the millstone gap, the type and moisture content of the grain, the milling capacity and the speed of the millstone, on the power and energy requirement, as well as the fineness of the product and the driving torque were analyzed. For design and planning of the experiments former work on stone mills known from literature was considered (Hopf, 1950; Kaeck, 1990; Hensel, 1995).

2. MATERIALS AND METHODS

The analyzed mill consists of a feeding mechanism, two vertically arranged millstones with a gap adjusting mechanism, a 12 V DC-motor with a spur-gear transmission and a battery buffered PV-generator as a power source, figure 1.

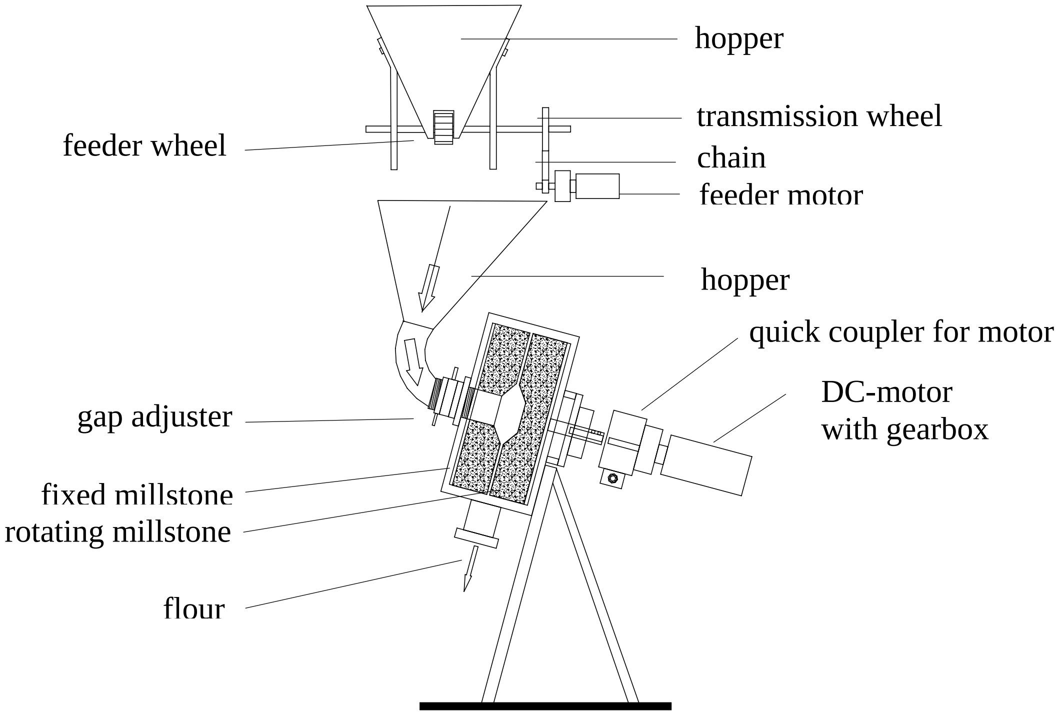

Figure 1. Milling set up with the feeding mechanism. Drawn not to scale.

While one of the millstones is fixed, the other rotates with a speed of about 400 rpm. According to literature a millstone diameter of 150 mm was selected, to meet the desired goal of a maximum power requirement of 100 W (Hopf, 1950).

Figure 2 shows the design of the stone with straight 6 mm deep grooves on the surface which were implemented according to the recommendations of Hensel (1995). The basic materials for the millstones are a solution of magnesium chloride ($MgCl_2$) in water with a density of 1.26 g/cm^3, magnesium oxide (MgO) and corundum, which were mixed together in a ratio of 2:3:10.

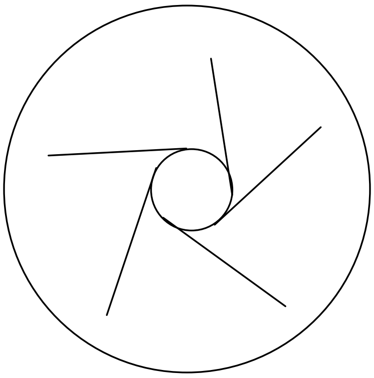

Figure 2. Fixed millstone with grooves and an opening (eye) at the centre of the millstone for directing the grain to the grinding zone.

The mass was poured in a form and dried for about 12 hours. Then it was removed from the form and hardened for at least two weeks at room temperature. Finally the surface was hammered with a sharp edged hammer to increase the roughness of the grinding zone. A standard 12 V/85 W DC-motor with an efficiency of about 80 % was selected for the drive. The motor was directly coupled to a gearbox with a speed transmission ratio of 13.5:1 and a transmission efficiency of about 90 %. The motor was connected to a battery buffered PV-system consisting of two 50 Wp PV-panels, a battery with 85 Ah and a battery control unit.
For the milling tests, kernels of barley, maize, sorghum and wheat were used, since these grains are widely grown in Africa for human consumption. To obtain a defined kernel size, the grain was sieved before milling. Broken grains were excluded. The kernel sizes of barley ranged from 2.8 to 4.0 mm, for maize from 6.3 to 8.0 mm, for sorghum from 1.4 to 2.0 mm and for wheat from 2.8 to 4.0 mm. To investigate the influence of the moisture content on the energy demand, the grains were conditioned before milling so as to contain a moisture content of 10 to 23 %, which was conducted in steps of 2 to 3 %. Directly before each milling test the moisture content of the grain was measured gravimetrically by drying a 10 g sample in an oven at 105° C for 24 hours.

The feed rate, the millstone gap and the speed of operation were varied to investigate their effect on the power and torque requirement. During the experiments the feed rates of barley, maize, sorghum and wheat were varied between 1.5 to 8 kg/h, 2 to 8 kg/h, 1.5 to 13 kg/h and 1 to 7 kg/h, respectively, with an accuracy of ± 5 %. The influence of the millstone gap on the power requirement and the particle size of the milled product was analysed for values of 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm. After finding the minimum rotational speed of the mill without blocking in a series of pre-tests, the rotational speed was varied between 70, 140, 210 and 280 rpm.

During experimentation all relevant process parameters of the mill such as voltage and current (Voltmeter/Amperemeter, Agilent Technologies, 94970A), torque (Torquemeter, Staiger-Mohilo, 0-50 Nm, +/- 0,2 %), temperature (Thermocouple, Heraeus, Cu-CuNi, +/- 1 K) and solar radiation (Pyranometer, Kipp & Zonen, CM 11, 0-2000 W/m², +/- 0,6 %) were continuously monitored by a computer assisted data acquisition unit (Agilent Technologies, 94970A). In addition, manual measurements of particle size distribution, feed rate (Digital balance, Satorius, 0-2000g, +/- 0,01g), and millstone gap were conducted and recorded. The particle size analysis was carried out according to the ASAE Standard, (ASAE, 1997).

3. RESULTS AND DISCUSSION

Since power and torque available from the PV-powered drive of the mill are generally limited, an increase in the opposing torque lead to a reduction in speed of the millstone. If the opposing torque due to the milling process is higher than the motor torque for a certain period of time, the mill locks. In this case the grain has to be removed from the milling zone before the mill can be restarted again. Short peaks of the torque which are higher than the motor torque did not cause the motor to lock due to the moment of inertia of the millstone that acts as a flywheel, thus providing a certain amount of kinetic energy. A characteristic course of the torque of the investigated stone mill is shown in figure 3**.**

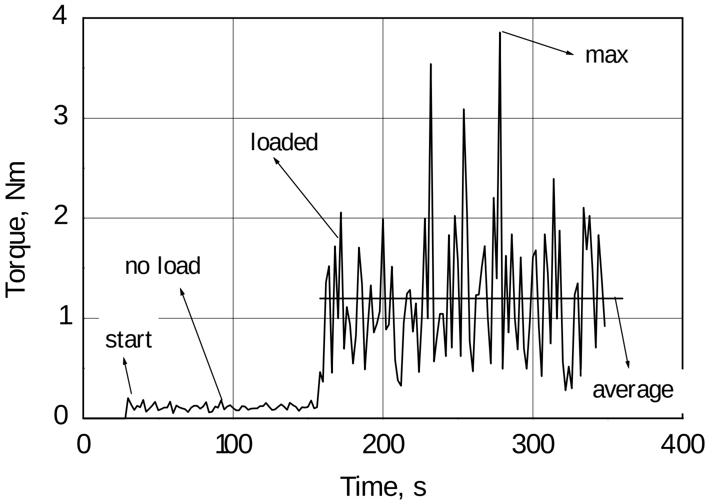

Figure 3. Characteristic torque curve of the PV powered stone mill (grain type: maize; feed rate: 2 kg/h, millstone gap: 1.0 mm, rotational speed: 210 rpm).

The height of the torque mainly depends on the loading conditions. When starting the mill, only the friction between the millstones, the friction of the bearings and the resistance of the air are influencing the torque. During the milling process both the average value and the amplitude of the peaks were much higher. This was caused by the variation in the orientation of the grain kernels in the grinding zone, the non-uniformity of the feed rate as well as the different size and brittleness of the kernels. Under the given conditions an average torque of 1.2 Nm was measured, while the torque peaks did vary between 0.3 and 3.8 Nm. Since the torque peaks occurred for only short periods of 2 to 4 seconds, the general operation was not adversely affected, since the kinetic energy of the rotating millstones was sufficient to overcome the peaks.

Figure 4 shows the effect of different rotational speeds on the amplitude of the torque curve. It can be seen that as the speed of rotation is increased the amplitude of the torque curve decreases, thus reducing the risk of blocking. Hence milling maize at a rotational speed of 70 rpm and a feed rate of 2 kg/h with a millstone gap of 1.5 mm was not possible. The mill did block after a period of 85 s. Increasing the rotational speed to 140 rpm reduced the peak torque by about 25 % and allowed an operation of the mill without blocking. At 280 rpm the peak load decreased from a maximum original value of 3.6 Nm at 70 rpm to 0.9 Nm.

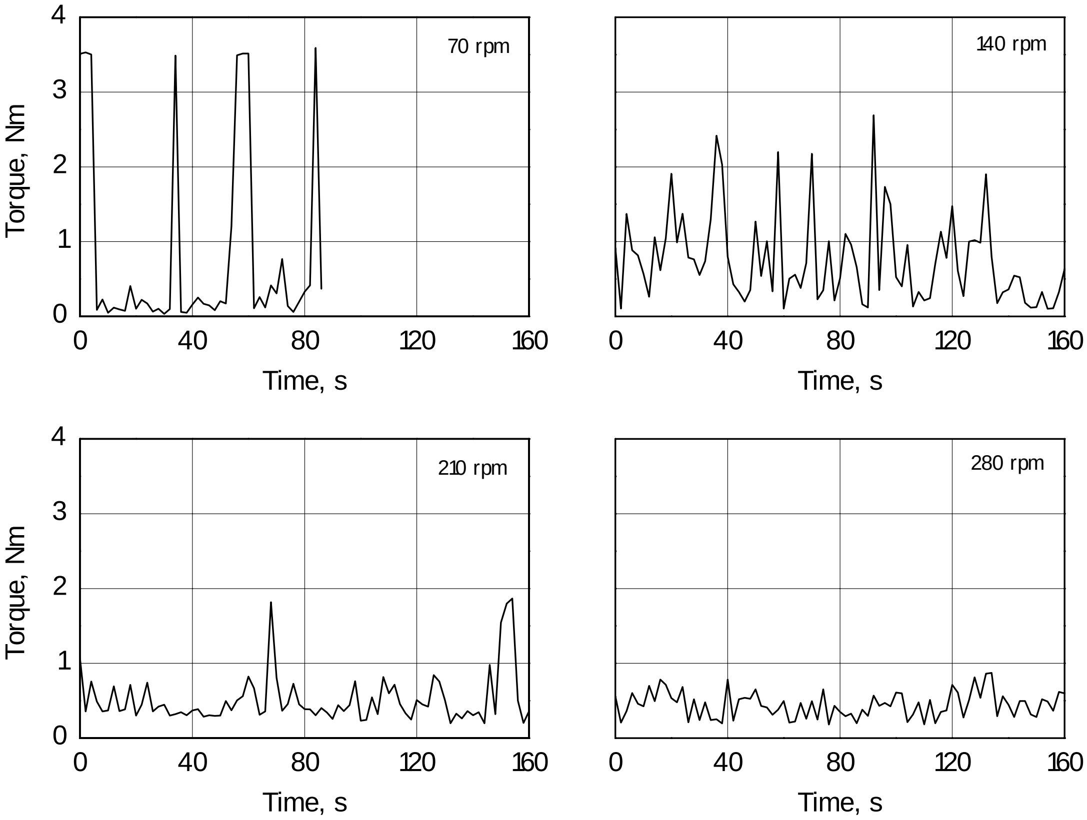

Figure 4. Effect of rotational speed on the characteristic torque curve of the PV powered stone mill (grain type: maize; millstone gap: 1.5 mm; feed rate: 2 kg/h).

Figure 5 shows the power requirement and the average torque at different rotational speeds. As the speed of rotation increases the power requirement also increases, while conversely the torque decreases. Considering the results shown in figure 4 a rotational speed between 200 and 300 rpm seems the most suitable to provide both a smooth operation and a low power requirement to drive the mill. The influence of the millstone gap on the average torque was also measured. By increasing the gap between the millstones from 0.5 to 1.0 mm the average torque was reduced by up to 50 %. However, the results also show that the influence of the millstone gap was lower for higher speeds of rotation of the millstone.

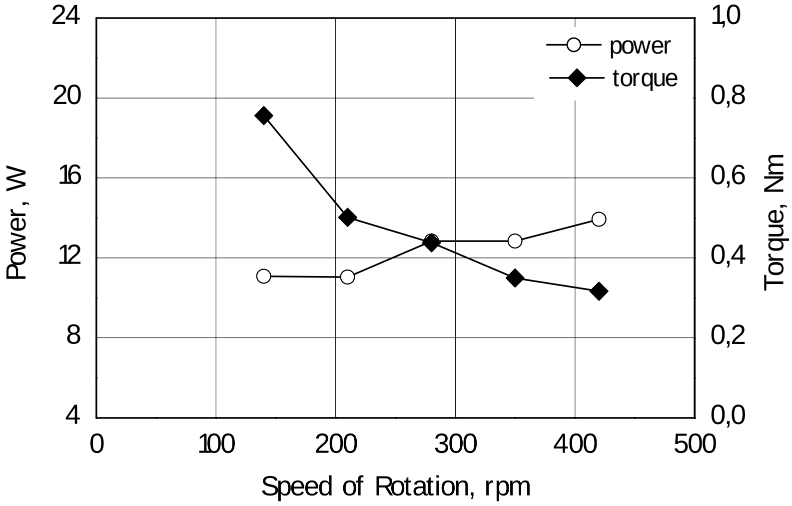

Figure 5. Effect of the rotational speed on the average torque and power for milling with the PV powered stone mill (grain type: maize; millstone gap: 1.5 mm; feed rate: 2 kg/h).

Figure 6 shows the influence of the millstone gap and the type of grain (maize, barley) on the power requirement. When the gap between the millstones is decreased, the maximum power requirement is increased.

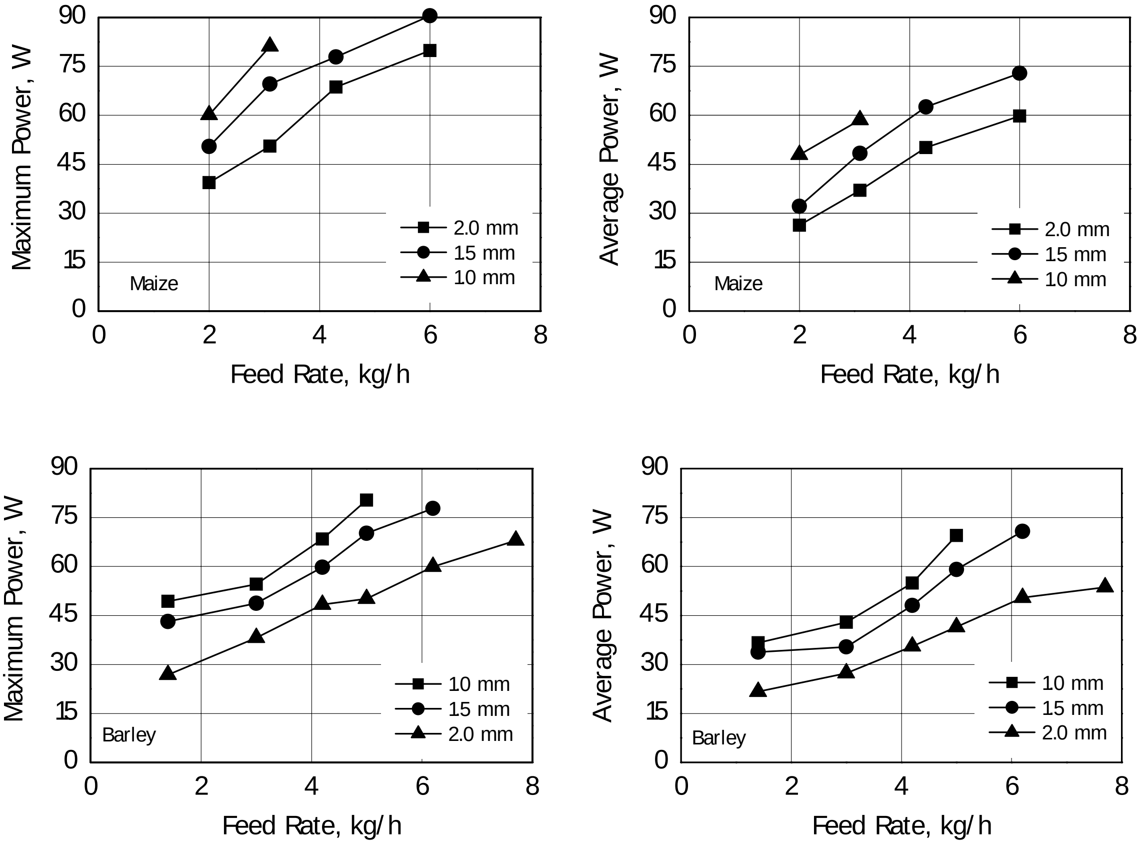

Figure 6. Maximum and average power required for maize and barley milling with the PV powered stone mill at different feed rates and millstone gaps.

Generally the highest power was required for milling maize, followed by wheat and barley. At feed-rates of up to 4 kg/h for maize and 6 kg/h for barley the maximum power required was still below the anticipated power of 100 W.

The maximum power recorded during the milling process is relevant for the dimensioning of the motor and the circuit breaker. However, the knowledge of the average power is required to calculate the total amount of energy required for a given bulk of grain. For example, milling barley at a feed rate 5 kg/h with a millstone gap of 1.5 mm requires a minimum power of the drive of 70 W to avoid blocking. However, per hour of operation only 60 Wh of electrical energy are consumed, figure 7.

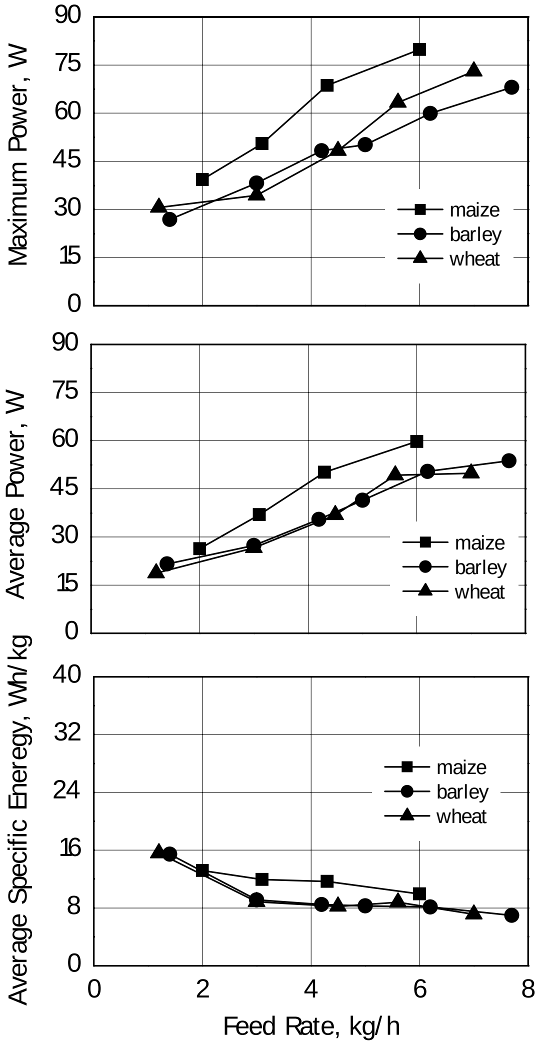

Figure 7. Maximum power, average power and average specific energy required during maize, barley and wheat milling at different feed rates with a millstone gap of 2.0 mm.

For all the grain being investigated the average specific energy required during the milling process decreases as the feed rate increases. Further more, the results presented in figures 6 and 7 show that the specific energy requirement is reduced as the millstone gap is increased.

The comparison between the different types of grains shows that the maximum and the average power as well as the specific energy requirement is highest for milling of maize (at all feed rates). This may be due to the larger kernels of maize compared to the other analysed grains.

In order to reduce the maximum power requirement, a two stage milling process was investigated, the first stage using a 2.0 mm gap and the second using a 1.0 mm gap. Compared to a single stage process using a 1.0 mm gap, the two stage maize milling process reduced the maximum power requirement from 60 to 40 W at a feed rate of 2 kg/h and from 85 to 50 W at a feed rate of 3 kg/h as shown in figure 8. Furthermore the two stage milling process increased the proportion of fine particles < 0.5 mm from about 25 to 50 %. At the same time the amplitude of the torque curve was reduced resulting in a smoother overall operation of the mill.

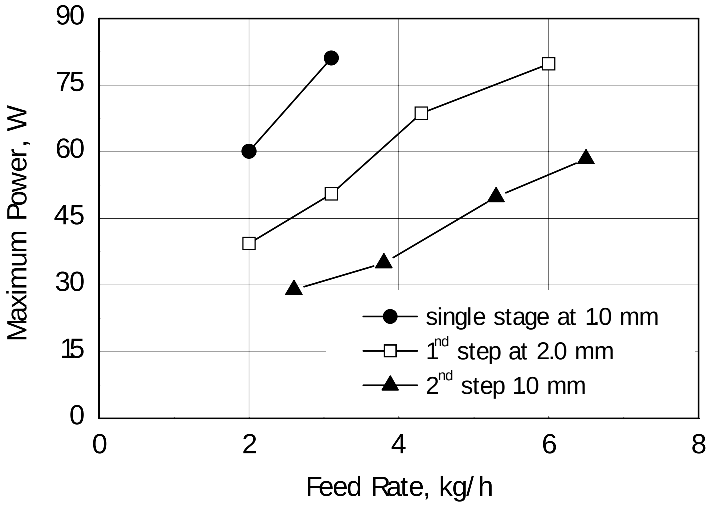

Figure 8. Effect of two and single stage milling on the maximum power requirement during milling with the PV powered stone mill (type of grain: maize, millstone gap: 1.0 and 2.0/1.0 mm).

To evaluate the fineness of the flour a sieve analysis was carried out. Samples obtained from the new mill have been compared to hand milled samples from Zambia and flour obtained from a large scale industrial mill, figure 9. For the Zambian maize flour classified as “fine” by the local consumers, more than 50 % of the particles were smaller than 1.0 mm and about 5 % were able to pass through a 0.5 mm sieve. For the maize flour classified as “coarse” more than 20 % of the flour was coarser than 1.5 mm. All samples produced by the new mill, being it under a millstone gap of either 1.0 or 1.5 mm or by a two stage milling process were generally finer than those milled by hand. However, even with two stage milling only 50 % of the particles of the maize flour were smaller than 0.5 mm.

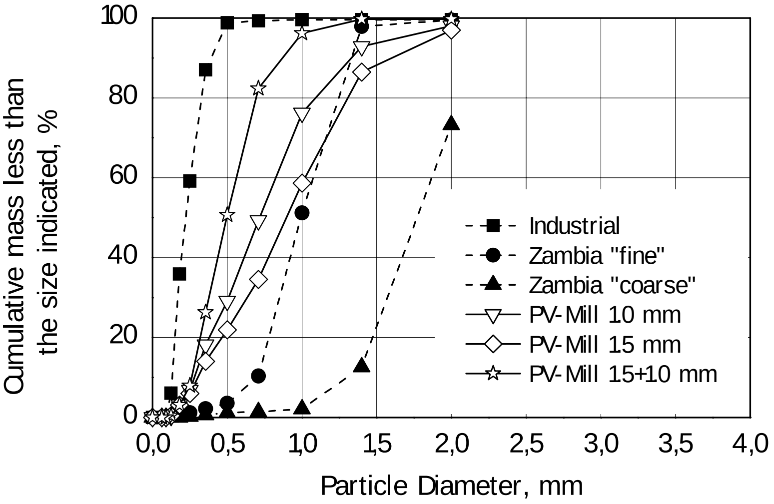

Figure 9. Comparison between the particle size distribution of maize milled locally in Zambia and that milled by the new PV powered stone mill with different gaps and at different milling stages.

Figure 10 shows the influence of the moisture content on the power requirement. Increasing the moisture content of maize from 10 % to 23 % w.b. by conditioning, reduced the maximum power requirement for milling from 70 to 29 W at a feed rate of 3 kg/h and from 78 to 39 W at 4.3 kg/h. This corresponds to a reduction by 58 and 50 %, respectively. However, if the water activity of the kernels is raised to values higher than 70 % the risk of deterioration is increasing fast. Under the given temperature conditions this critical value corresponds to a moisture content of 12 to 14 % w.b. Nevertheless, increasing the storage moisture content from 10 to 14 % w.b. can reduce the maximum power requirement by about 30 to 40 %. Since the produced flour is normally consumed within a couple of days, this does not necessarily imply any negative effects on quality.

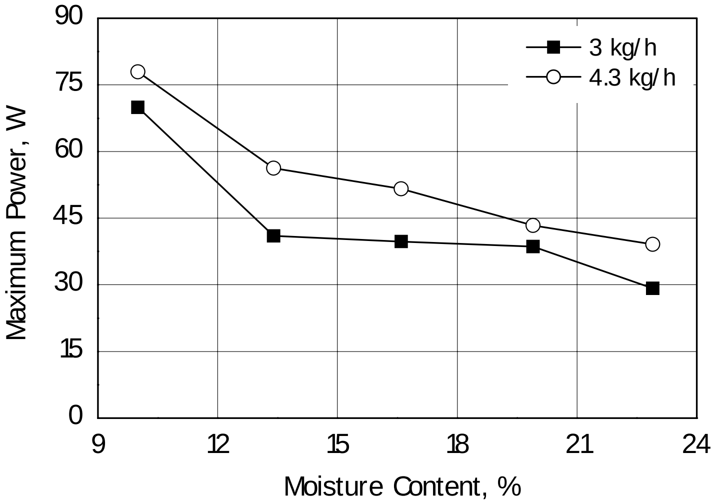

Figure 10. Maximum power required during maize milling with different moisture contents for two feed rates and a millstone gap of 1.5 mm.

4. CONCLUSION

The newly constructed mill proved to be suitable for milling barley, maize, sorghum and wheat at feed rates of 2 to 8 kg/h if connected to a PV-generator with 100 Wp and a battery with a capacity of 85 Ah. The quality of the produced flour in terms of fineness was better than hand-milled samples from Zambia which were rated as very good by local consumers. Increasing the gap reduced both the power and the specific energy requirement whereas increasing the feed rate increased the power requirement and reduced the specific energy consumption. Moreover increasing the gap also increased the proportion of coarse flour. Therefore, a compromise has to be made between the specific energy requirement and the required consistency of the flour. However, a higher proportion of fine flour without increasing the specific energy requirement could be produced by operating the mill in a two stage process with a millstone gap of 2 mm in the first step and 1 mm in the second step. Conditioning of the grain from its storage moisture content of 10 % to about 14 % reduced the maximum power requirement by about 25 W while the specific energy requirement was reduced to 7-15 Wh/kg. This is increasing the milling capacity considerably and improving the smooth operation of the mill. However, by conditioning the grain the total amount of work involved during the milling process will be increased.

Generally the maximum power requirement of 25 to 90 W at an average specific power consumption of 10-25 Wh/kg allows to operate the mill for up to 8 hours at a solar radiation of 6 kWh/m²d. This corresponds to a daily milling capacity of about 60 kg of flour under optimum conditions. Under poor milling conditions and a solar radiation of 4 kWh/m²d at least 16 kg per day can be milled. Even when considering a conservative estimate it should be possible to produce enough flour for 10 to 15 African families.

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