Modeling of Tangential Teff Threshing and Separation System

Kebrebeal Addisu Belay[1], Dereje Engida Woldemichael[1]
[1]College of Electrical and Mechanical Engineering
Addis Ababa Science and Technology University
Addis Ababa, Ethiopia

Abstract - **Teff is a small size cereal that has its origin in Ethiopia. It is the major cereal grown on about 3million hectares annually which equates to 27% of the land. Seventy percent of the workforce in the country relies on small-scale agriculture, among this Teff accounts for about a quarter of the total cereal production and it is alone grown by 6.2 million farmers. This makes it the major staple food grain for over 50 million Ethiopian people. In terms of crop production, it stands third (after maize and wheat) by 18.57% coverage of the crop production which equals to 29.9 million quintals. But due to the traditional methods employed to harvest, the country did not get the most out of it. From the ploughing stage to the threshing process, harvesting is done using conventional techniques. Threshing is done using animals (livestock) walking on it or beating the plant on the ground. This process is primitive, inefficient, unhygienic and time consuming. There is 12% to 25% of Teff postharvest losses using this techniques. Due to this one of the biggest challenges facing the agricultural sector in Ethiopia right now is meeting the growing demand for Teff to feed its increasing population. To challenge the primitive way of Teff harvesting, modern technologies need to be employed and that is why this paper focuses on the design and validation of a tangential Teff threshing and separation system. By keeping the size variances similar, the design of Teff tangential threshing and separation system is validated in comparison with a published research. The threshing rate parameter, the threshing efficiency and the separation efficiency are the major threshing performance indices that are selected for validation. The validation was done at a threshing drum speed of 27m/s, threshing drum diameter of 0.48m, threshing drum length of 0.83m, wet basis Teff moisture content of 12%, Teff MOG bulk density of 35kg/m^3 and MOG throughput (feed rate) of 0.13kg/s. The result showed, 5.4% error in the threshing rate parameter and 1.23% error in the threshing efficiency while 1.17% error in the separation efficiency at a drum speed of 1200rpm and feed rate of 275kg/s.**

Keywords—Teff, Teff threshing machine, Tangential Threshing

1. INTRODUCTION

Teff (Eragrostis tef) is an ancient tropical cereal that has its center of origin and diversity in the northern Ethiopian highlands from where it is believed to have been domesticated [1]. In Ethiopia, seventy percent of the workforce relies on small-scale agriculture, among this Teff accounts for about a quarter of the total cereal production and it is alone grown by 6.2 million farmers [2], [3]. This makes it the major staple food grain for over 50 million Ethiopian people. It is indigenous to the country and is a part of the culture, tradition, and food security of the people [4], [5].

Teff is a minor cereal crop worldwide though it is spread in South Africa, Kenya, USA, Brazil, Canada, Australia and small areas in Japan [6], [7]. Whereas in Ethiopia, it is a major food grain, mainly used to make Injera, a traditional fermented pancake. In fact it is the foremost crop that it is grown on about 3million hectares annually [8], which equates to 27% of the land. It is Ethiopia's most significant crop not only by area planted but also by the value of production and it is the second largest cash crop (after coffee), generating almost 500 million USD income per year for local farmers [9]. In terms of crop production, it stands third (after maize and wheat) by 18.57% coverage of the crop production which equals to 29.9 million quintals [5]. Its Production in Ethiopia experienced an average growth of 11.28% per year between 2004 and 2011 and shows no sign of slowing [9]. The price of Teff tripled in 5 years to 855.8 birr per quintal in 2010 and it tripled again in 9 years to 2400 birr per quintal in 2018 and now it ranges from 4000 – 5000 birr.

Teff is possibly the smallest cereal grain with an average length of 1.17mm and average width of 0.61mm. Thousand grain weighs around 0.14g [10]. It is made of 77.6% carbohydrate, 12.9% protein and the rest constitutes minerals, fat, fiber and ash [11]. Other than the fact that very little knowledge is known about its nutritional composition and health benefits, the technological limitations in processing Teff is the main reason for its consumption not to wide spread globally as it is used in its center of origin. However, Kaleab baye [1] noted that, over the past decade, the recognition that Teff is gluten-free has spurred global research interest. Health benefits like it reduces iron deficiency, celiac disease and it prevents and control diabetes are the other reasons that prompted the researchers. Among the various varieties of Teff grain, Quncho is regarded as the variety with greater yield per unit of field and easily adaptable which helps in sustaining food security [12], [13].

With this amount of fascinating facts and figures, Teff farming is still done using traditional methods. For this widely used cereal, from the ploughing stage to the threshing process, harvesting is done using conventional methods which dated back when Teff was first introduced to the country. For sickling, extensive man power is used and threshing is done using animals (livestock) walking on it or beating the plant on the ground.

Traditional method of threshing are very slow, gives low output, the cost of operation is high and there is a huge loss of grains because of rodents, birds, insects, wind, and untimely rain and fire hazards [3], [5], [8], [9]. [14]Threshing operation and its subsequent loss followed is among points requiring proper attention and that generally accounts about 6% cereal crops loss in Ethiopia. According to the African Postharvest Losses Information System, postharvest losses for Teff were estimated to be 12.3% which is really a big number. More than 12 quintal out of 100 is a loss which can feed a mid-sized family for 2-3 years. Other literatures studied that the threshing and other subsequent losses ranges from 12% to 25% [15]–[18]. This kind of fact is devastating for a country trying to reach food security. One way to tackle this kind of issue is to employ technology based agriculture one of which is using threshing systems.

Modern Teff harvesting technologies will help to transform the arduous, unsanitary and inefficient harvesting process in to a new level. To get the most out of Teff, an increase in productivity is required apart from the household consumption. This way it is possible to feed the emerging grain processing industries resulted from the change in lifestyle and the recently burgeoning global Teff market which will boost the economy directly or indirectly. From achieving food security to substituting imported foods, it has a lot to contribute to the growing economy of the country.

Other than the economical aspect, using modern technologies like Teff Threshing systems has its own social impacts which can be pronged in three. Creating more prosperous communities, more education opportunities, and healthier grain production. Firstly, the Teff Thresher boosts Teff production, increasing agricultural prosperity and self-sustainability and reducing poverty. The product will also spur the formation of local micro businesses that sell the machines or provide services for other farmers. Secondly, it will prevent children from being removed from school during harvest periods. And thirdly, it will produce a safer, more hygienic grain, improving the health of a majority of the population in Ethiopia

2. MATERIALS AND METHODS

A Teff thresher is a machine that will thresh or detach grains out of the straw mat and sends the threshed Teff grain to the cleaning system for further cleaning and separation while the rest of MOG is flowed to the exit. So the main purpose of the machine is to detach, separate and clean Teff grains from the straw mat. In this way we can understand that the machine has different systems to form a complete threshing machine. The feeding system, the threshing system, the separation system and the cleaning system are all the major systems that comprises a Teff threshing machine. This paper focuses on the design and validation of a Teff threshing and separation system.

2.1 Design Considerations

The threshing machine is based on a tangential flow threshing system. It incorporates a tangential feeding system, a tangential threshing unit, a tangential separation unit, an extra straw walker separation system and a grain conveying system. First, Teff material is fed to the feeding system manually. Then, a threshing unit consist of active elements like rasp bar mounted on a threshing drum are rotated to drug Teff materials tangentially towards the threshing space. In the threshing space due to the friction and impact of active elements such as rasp bar and concave bar shown in figure 2.1, Teff grain is detached from the straw mat and flows to the cleaning unit through the concave openings.

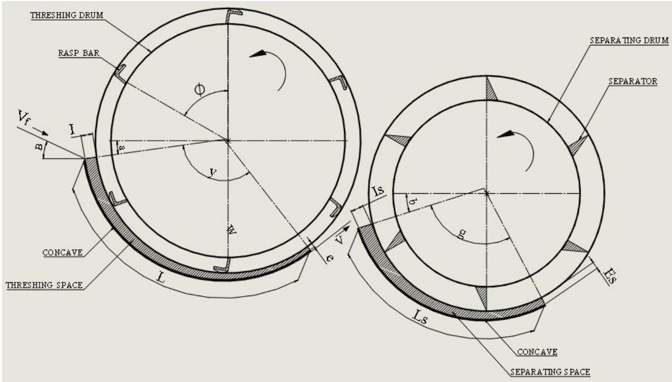

Figure 2.1 Tangential threshing system

The concave will be designed in such a way to facilitate a tangential and smooth flow of materials towards the subsequent unit. While the portion of detached grains flows to the cleaning shoe, the rest of material move towards the separation unit for separation of grains and straw mat.

2.2 Working Principle

First an operator feeds Teff straw and MOG to the hopper leading the feed material to flow to the threshing unit. The threshing system contains a threshing drum, a rasp bar and a concave. When the feed material flows through the threshing space (the space between the lower tip of the rasp bar on the threshing drum and the upper tip of the concave) at a specific feeding velocity, the rotating threshing drum with mounted rasp bar detaches Teff grains. This is due to the friction and impact of the rasp bar and concave grate that wraps the drum underneath at a specific angle. The threshing space or concave clearance has a relatively wider space at the inlet of the material than at the exit. This increases the threshing action and results somehow a compressed straw mat to flow to the next stage. The detached grain will then pass through the concave opening while unseparated grain and the rest of the MOG flows to the separation unit.

The separation unit has two separation systems, a separator and a straw walker. In the separator, there is a rotating separation drum with mounted bucket like structures across the edges and a separation concave. The separation drum separates detached Teff grains that are segregated in the straw mat (MOG) which came from the threshing unit. Since the separator and concave has a similar structure and arrangement with the threshing unit, it serves as additional threshing mechanism for the unthreshed crop material that flows through this unit. After the Teff grains are separated and detached, it passes through the separation concave openings while the MOG (straw mat) is delivered to the last separation stage, the straw walkers. The straw walker serves as another separation unit where the last bit of Teff grain gets separated limiting the probability of detached and unseparated grains to exit the machine as a discharge.

The straw walker unit contains three independent straw walkers or shakers which are positioned along the length of the threshing drum length. Each straw walker is constructed from a sheet metal sidewalls of saw tooth profile (to push the straw to the rear side) and steps of screens. The walkers or shakers are mounted on a crank axle on the front and end sides at different angle. The screens on the shakers are inclined at a certain angle (10^o – 22^o) to form a series of cascades. When the crank rotates, each straw walker reciprocates at different phase in a way when one moves up the other moves down. This motion intensifies the separation action while forcing the MOG to the rear side. The separated Teff grain will pass through the screens to the straw walker sieve and then to the cleaning unit while the MOG flows to the rear and discharged at the exit.

The cleaning unit is the last stage of operation before Teff grains are conveyed to the storage. It comprises an oscillating grain pan, two stage of cleaning sieve mounted one above the other, a straw walker sieve and a radial flow fan that blows current of air from the bottom to the upward and rear direction of the sieves. The function of the cleaning unit is to separate free Teff grains from grain chaff and straw mixture, to forward cleaned grains to the auger and discharging MOG fragments to the ground due to the action of the fan and the reciprocating motion of the cleaning unit crank.

Teff grains, chaffs, small straws and MOG fragments separated from the threshing unit, the separator and the straw walker are delivered to the oscillating grain pan and the straw walker sieve through the threshing concave, separator concave and straw walker screens respectively. Then, as the result of the winnowing action of the grain pan, the straw walker sieve and the simultaneous effect of the fan, primary grain cleaning occurs since there is a space for Teff materials before reaching the top sieve from the grain pan and straw walker sieve.

Secondary grain cleaning happens due to the combination of the oscillatory motion of the top sieve and gravitational force while air is blown from the bottom. Finally Teff grain flows to the bottom sieve through the openings of the top sieve for further and deep cleaning. Again from the force generated from the vibratory motion of the bottom sieve and gravity, the final cleaning occurs and the cleaned grain flows to an inclined sheet surface where it is conveyed to the feeding auger which feeds to the storage while the rest of the material is discharged to the exit.

2.3 mathimatical modeling of Teff threshing performance indices

For the modeling of the systems, the following parameters were considered.

- Teff material to be processed is homogeneous and uniformly distributed
- Threshing unit is feed with constant feed rate and amount
- Effective Teff threshing starts at the entrance of the threshing zone
- Material to be threshed moves continuously in the threshing space
- Mass of the material is continuously distributed in the threshing space

Threshing performance evaluates the working conditions of the threshing system using various indices like MOG feed rate, percentage of threshed, unthreshed, separated and unseparated grain, grain damage, cleaning efficiency, specific power consumption and output capacity. Since this paper focuses on threshing and separation system of a Teff thresher, the threshing and separation performance indices are discussed below. To analyze Teff threshing performance indices, consider the physical properties of Teff grain and chaff in the following table.

Table 2-1: Physical properties of Teff grain [19]

Moisture content (Wet basis)	Thousand grain mass (TGM) (gram)	Grain density (Kg/m^3)	Average diameter (mm)	Terminal velocity (m/s)	Drag coefficient (C_d)
11.94%	0.292	1361.8	0.74	3.24	0.76
15.1%	0.320	1358.2	0.76	-	-
21.1%	0.361	1314.9	0.86	-	-
24.2%	0.392	1283.7	0.87	-	-
27.1%	0.421	1252.9	0.88	4.04	0.66

Table 2-2: Physical properties of Teff chaff [19]

Straw length (mm)	Node free		Middle node		End node	
	Mass (gram)	Diameter (mm)	Mass (gram)	Diameter (mm)	Mass (gram)	Diameter (mm)
6	0.029	1.630	0.032	1.760	0.032	1.810
8	0.034	1.870	0.060	1.712	0.061	1.720
10	0.058	1.670	0.064	1.880	0.063	1.830

2.3.1 MOG Feed Rate

The threshing space between the threshing drum and the threshing concave as shown in figure 2.1 has a capacity of consuming more Teff straws based on the designed intake volume of the machine.

MOG feed rate or throughput is calculated considering Teff straw and grain weight, feeding velocity, concave clearance and threshing drum width and speed. Teff has different varieties across the country and their straw or the plant height ranges between 450mm to 900mm. The Teff threshing machine should be designed to process the highest straw height.

From table 3.6, the maximum value of the straw diameter in all cases is 1.88mm. This means the threshing drum along the length of the threshing drum can house specified number of straws if the straw lay one next to another in a series. But this should consider the space needed so that no clogging occurs. Therefore the mass of MOG throughput Q_M is expressed as;

$$Q_M = Ws + Wg \tag{2.1}$$

$$Q_M = (Ts \times Sw) + (Ts \times Tg \times Gw) \tag{2.2}$$

$$Q_M = (0.64Ts) + (0.00032Ts.Tg) \tag{2.3}$$

Where, Ws - Total weight of straw
Wg - Total weight of grain
Ts - Total number of straws
Sw - Individual weight of highest straw (gram)
Tg - Total number of grain in each straw

Gw - Individual grain weight

Now the material throughput or MOG feed rate Q_P can be determined based on the above equations. The MOG throughput is the product of the total mass of the MOG throughput Q_M and the number of rounds of total straw N processed per unit time. Therefore, Q_P becomes

$$Q_P = Q_M \times N \tag{2.4}$$

Where, N – number of rounds of total straw processed per unit time (s^{-1})

2.3.2 Percentage of threshed and separated Teff grain in the threshing drum

The detachment of grains or generally a threshing system is described in terms of probabilistic laws as an exponentially distribution function. The probability density function pdf of an exponential distribution function determines the probability of the grain to detach from the ear/straw considering variables like the concave length and threshing rate parameter [20], [21]. For the threshing and separation unit analysis discussed in the following paragraphs, refer to Figure 2.1 to identify the terms used.

The pdf expresses the probability of grains to be detached or the percentage of threshed grain $G_T(x)$ along the concave length [22], [23]. It is mathematically expressed as,

$$G_T(x) = 1 - e^{-\lambda x} \tag{2.5}$$

Where, x – threshing space/current position of straw inside the Concave length (m)

λ – threshing rate parameter (m^{-1})

To determine the value of $G_T(x)$, the corresponding value of the threshing rate parameter λ is required. According to Miu petre [22], λ is a function of MOG bulk density, threshing drum speed, exit concave clearance, MOG throughput, Wet basis MOG moisture content, optimum working MOG throughput, Wet basis maximum MOG moisture content, threshing drum peripheral speed, Optimum working threshing drum peripheral speed. The functions of threshing rate parameter λ is mathematically expressed as,

$$\lambda = K_T \sqrt{\frac{\rho Vc\delta e}{Qp\sqrt{U}}}\, e^{\left(\frac{Qp}{Q} + \frac{U}{UM} - \frac{Vc}{V}\right)} \tag{2.6}$$

Where, K_T Coefficient that depends on crop type

ρ MOG bulk density (kg/m^3)

Vc Threshing drum peripheral speed (m/s)

δe Exit concave clearance (m)

Q_P MOG throughput (kg/s)

U Wet basis MOG moisture content (%)

Q Optimum working MOG throughput (kg/s)

U_M Wet basis max MOG moisture content (%)

V optimum threshing drum peripheral speed (m/s)

Wet basis maximum MOG moisture content U_M represents the wet basis moisture content that results minimum grain damage at the MOG throughput Q_P. Optimum working threshing drum speed V corresponds to the maximum threshing drum peripheral speed that result higher grain separation. In this case **V** will be same as **Vc** since it is the only selected working drum speed and let **U_M** be 12% since it is the ideal working moisture content for minimum grain damage and using data studied by Geta Kidanemariam [24], the MOG bulk density of Teff straw ρ is 35 kg/m^3 at a moisture content of 15.1%.

Therefore, the threshing rate parameter λ becomes

$$\lambda = K_T \sqrt{\frac{35xVc.\delta e}{Qpx\sqrt{15.1}}}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12} - \frac{Vc}{V}\right)} \tag{2.7}$$

Therefore, the probability of threshed grain $G_T(x)$ as a function of concave length x becomes

$$G_T(x) = 1 - e^{-\left(K_T \sqrt{\frac{35xVc.\delta e}{Qpx\sqrt{15.1}}}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12} - \frac{Vc}{V}\right)}\right)x} \tag{2.8}$$

At the beginning of the inlet concave clearance where x = 0, the probability of threshed grain $G_T(x = 0)$ is 0 since there is no material in the threshing space to be threshed. However, at the end of the concave length (exit), the probability of threshed grain $G_T(x = L)$ becomes,

$$G_T(x = L) = 1 - e^{-\left(K_T \sqrt{\frac{35xVc.\delta e}{Qpx\sqrt{15.1}}}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12} - \frac{Vc}{V}\right)}\right).L} \tag{2.9}$$

The percentage of unthreshed grain $G_R(x)$ becomes,

$$G_R(x) = e^{-\lambda x} = e^{-\left(K_T \sqrt{\frac{35xVc.\delta e}{Qpx\sqrt{15.1}}}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12} - \frac{Vc}{V}\right)}\right)x} \tag{2.10}$$

At the end of the threshing space where x = L, the percentage of unthreshed grain $G_R(x)$ becomes the threshing loss T_L in the threshing unit.

$$T_L = G_R(x{=}L) = e^{-\left(K_T \sqrt{\frac{35xVc.\delta e}{Qpx\sqrt{15.1}}}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12} - \frac{Vc}{V}\right)}\right)x} \tag{2.11}$$

Based on Miu petre's studies [22], the fraction of separable and segregated grain $G_S(x)$, which is the amount of grain that are threshed but segregated in the straw mat that needs separation in the threshing space is given as:

$$G_S(x) = \frac{\beta}{\lambda - \beta}\left(e^{-\beta x} - e^{-\lambda x}\right) \tag{2.12}$$

Where, β is separating rate parameter (m^{-1}) which describes the rate of grain separation along the threshing and separation space. The value of β is determined as

$$\beta = K_S \sqrt{\frac{VcU\sqrt{Qp}}{\sqrt{\rho}\, e^{\left(\frac{Qp}{Q} + \frac{U}{Um}\right)}}} \tag{2.13}$$

Where, K_S coefficient that depends on crop type

U_m Wet basis minimum MOG moisture content (%)

U_m represents the wet basis minimum moisture content that results minimum grain damage at the MOG throughput of Q_P. Therefore, the separating rate parameter β becomes,

$$\beta = K_S \sqrt{\frac{VcU\sqrt{Qp}}{\sqrt{35}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12}\right)}}} \tag{2.14}$$

Thus, the fraction of separable and segregated grain $G_S(x)$ can now be determined as,

$$G_S(x) = \frac{KS\sqrt{\frac{VcU\sqrt{Qp}}{\sqrt{35}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12}\right)}}}}{\lambda - KS\sqrt{\frac{VcU\sqrt{Qp}}{\sqrt{35}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12}\right)}}}}\left(e^{-KS\sqrt{\frac{VcU\sqrt{Qp}}{\sqrt{35}\, e^{\left(\frac{Qp}{Q} + \frac{15.1}{12}\right)}}}x} - e^{-\lambda x}\right) \tag{2.15}$$

At the end of the threshing space where x becomes the thresher concave length L, the fraction of separable and segregated grain $G_S(x)$ becomes the thresher (threshing drum) separation loss S_L.

$$S_L = G_S(x{=}L) \tag{2.16}$$

The percentage of grain separation T_S at the end of the threshing space becomes

$$T_S = 1 - G_S(x{=}L) \tag{2.17}$$

2.3.3 Percentage of threshed and separated Teff grain in the separation drum

As mentioned earlier, Teff materials enters the separation system after processed in the threshing drum. In the separator, unthreshed and threshed but segregated Teff grains are separated. The probability of grains to be detached in the separator $G_{TS}(X_S)$ along the separation space (separator concave length) X_S is given as

$$G_{TS}(L_S) = 1- e^{-\lambda Xs} \quad (2.18)$$

At the end of the separation space where X_S becomes the separator concave length L_S, the probability of grains to be detached $G_{TS}(L_S)$ becomes

$$G_{TS}(Xs=L_S) = 1- e^{-\lambda Ls} \quad (2.19)$$

At the end of the separation space, the percentage of unthreshed grain becomes the separator threshing loss ST_L.

$$ST_L = 1 - G_{TS}(L_S) = e^{-\lambda Ls} \quad (2.20)$$

The fraction of separable and segregated grain $G_{SS}(X_S)$, which is the amount of grain that are threshed but not separated instead segregated in the straw mat that needs separation in the straw walker is

$$G_{SS}(X_S) = \frac{\beta}{\lambda-\beta}\left(e^{-\beta Xs} - e^{-\lambda Xs}\right) \quad (2.21)$$

At the end of the separation space, the fraction of separable and segregated grain $G_{SS}(X_S)$ becomes the separation loss SS_L.

$$SS_L = G_{SS}(X_S=L_S) = \frac{\beta}{\lambda-\beta}\left(e^{-\beta Ls} - e^{-\lambda Ls}\right) \quad (2.22)$$

So the percentage of separated grain at the end of the separating space S_S is

$$S_S = 1 - G_{SS}(L_S) \quad (2.23)$$

2.3.4 Percentage of separated Teff grain in the straw walker

The straw walker is the last unit of separation. In this unit the last bit of unseparated Teff grain is separated before it is discharged in the rear. According to Miu petre [22], the fraction of remaining grains $G_W(y)$ as the function of the current position y along the length of the straw walker (L_W) that still exist with the straw mat is expressed as:

$$G_W(y) = (Vt+Vs)\left\{1 - \frac{1}{b}\left[a\left(1-e^{-by}\right) - b\left(1-e^{-ay}\right)\right]\right\} \quad (2.24)$$

Where, Vt Total threshing loss
Vs Total separation loss
a The specific rate of grain segregation (m^{-1})
b The specific rate of grain separation through the screen (m^{-1})

The values of a and b for most of the crops as published by Miu petre [25] are determined to be a = 1.9–4.54 and b = 0.9–2.26 m^{-1} for variety of crops.

At the end of the straw walker length when y becomes the length of the straw walker L_W, the fraction of remaining grains $G_W(y)$ becomes the straw walker separation loss W_L.

$$W_L = (Vt+Vs)\left\{1 - \frac{1}{b}\left[a\left(1-e^{-bLW}\right) - b\left(1-e^{-aLW}\right)\right]\right\} \quad (2.25)$$

2.4 Analysis of Threshing performance indices

Bearing in mind efficiency, affordability, simplicity and portability, the mathematical models are simulated and analyzed which resulted the following variables which are considered to define the threshing performance indices which consequently will fix the geometrical model of the Teff threshing and separation systems.

- Crop material feeding velocity V_f to the threshing drum is 0.9m/s
- Threshing drum diameter is 450mm
- Threshing drum speed is 450 rpm
- Threshing drum length is 700mm
- Number of rasp bar is 6
- Separating drum diameter is 400mm
- Separating drum speed is 400rpm
- Separating drum length is 700mm
- Threshing drum concave wrap angle is 120°
- Threshing drum concave length is 490mm
- Threshing drum concave inlet and exit clearance are 20mm and 10mm respectively
- Separating drum concave inlet and exit clearance are 22mm and 12mm respectively
- Separating drum concave wrap angle is 100°
- Separating drum concave length is 490mm
- Threshing and separation drum concave rod diameter is 3mm
- Threshing and separation drum concave bar thickness is 5mm
- Threshing and separation drum concave bar depth is 50mm
- Threshing and separation drum concave length is 700mm
- There are three number of shakers (individual straw walker) of width 235mm each and length 1500mm
- Straw walker crank shaft rotation is 200rpm

2.4.1 MOG Feed Rate

According to the listed parameters above and equations discussed in section 2.3.1, the MOG feed rate for the designed machine is calculated as follows.

From table 3.6, the maximum value of the straw diameter in all cases is 1.88mm. This means the threshing drum along its 700mm length can house 372 number of straws if it lay one next to another in a series. But considering the space needed so that no clogging occurs, let's assume the straw diameter to be 3mm which will result 230 number of straws. On the other hand, the concave inlet clearance is 20mm, which means it can hold 5 number of straws considering 3mm of straw diameter. Therefore multiplying 230 by 6, the threshing space can house a total number of 1150 straws (straw with grain) at a time.

As Teff crop height is taken to be 900mm and the feeding velocity is defined to be 0.9 m/s, the threshing drum receives 1150 individual Teff straw every second. Though the concave wraps the threshing drum at an angle of 120°, let's consider the threshing drum discharges the straws every half revolution (180^0) to the next zone which is the separation drum assuming the slippage between the crop material and the rasp bars. This means the first round of feed materials will stay in the threshing drum for only half of the revolution. From researches, each straw of Teff holds minimum of 500 number of Teff grains. With this data and values from Table 2-1 and 2-2, the mass of MOG throughput Q_M is expressed as follow.

$$Q_M = (Ts \times Sw) + (Ts \times Tg \times Gw) \quad (2.26)$$

$$Ts = 1150, \quad Tg = 500 \quad (2.27)$$

$$Sw = 9 \times 0.064 = 0.576 \quad (2.28)$$

$$Gw = 0.320/1000 = 0.00032 \quad (2.29)$$

Substituting equation 2.27-2.29 into equation 2.26, the total mass of MOG throughput Q_M becomes

$$Q_M = Ws + Wg = 846.4 \text{ gram} = 0.846 \text{ kg} \quad (2.30)$$

The MOG throughput is the product of the total mass of the MOG throughput Q_M and the number of rounds of total straw N processed per unit time. In this case since the feeding velocity is

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0.9 m/s and Teff straw height is 0.9m, one round of 1150 number of straws will be processed every second.
Therefore, Q_P becomes

$$Q_P = Q_M \times N \quad (2.31)$$

$$Q_P = 0.846 \times 1 = 0.846 \text{ kg/s} = 3 \text{ ton/hr} \quad (2.32)$$

Considering affordability and design simplicity, manual feeding of Teff material is chosen at a feeding velocity of 0.9 m/s. This value can be changed to a higher value to match the threshing drum peripheral speed (10.6 m/s) so that larger amount of MOG is processed. If the feeding velocity is increased to 2.7 m/s, the mass of MOG throughput increases drastically to 2.54 kg/s or 9.1 ton/hr since the number of rounds of straw processed per unit time increases to 3. This requires a powered feeding mechanism like screw or conveyer method though it will increase the cost of the machine questioning the machine's affordability to the majority of farmers.

Out of 0.846 kg/s of Q_P, Teff grain comprises 0.184 kg. Thus, without considering the separation and cleaning losses and assuming ideal threshing, the machine has an ideal threshed Teff grain output of 0.184 kg/s or 662.4 kg/hr.

2.4.2 Percentage of threshed and separated Teff grain in the threshing drum

According to section 2.3.2, the percentage of threshed and separated Teff grain in the threshing drum is as follows.

$$\lambda = K_T \sqrt{\frac{\rho V c \delta e}{Qp\sqrt{U}}}\, e^{\left(\frac{Qp}{Q} + \frac{U}{UM} - \frac{Vc}{V}\right)}$$

If it is considered that the threshing space will be filled with exactly the straw diameter assuming 2mm though the maximum diameter is 1.88mm from Table 2-2, the space will be filled with 350 number of straws along the length of the threshing drum (700mm).

Figure 2.2 Threshing and separation unit

Multiplying 350 number straws with 8 assuming the inlet concave clearance space (20mm) holds 8 number of straws, the optimum number of straws would be 2800. Using equation 2.26 – 2.29 results an Optimum working MOG throughput **Q** of 2.05 kg/s, but due to extra factors like human operator incapability and slippage between straws and rasp bar, consider an optimum throughput of 0.53kg/s. Since the designed Teff thresher is manually fed, the MOG throughput or feed rate is dependent on the operator. So consider minimum feed rate of 0.14 kg/s to be realistic and analyze worst case scenario.

Therefore, except K_T all the other variables are known to determine the threshing rate parameter λ.

$$\lambda = K_T \sqrt{\frac{35 \times 10.6 \times 10 \times 10^{-3}}{0.14 \times \sqrt{15.1}}}\, e^{\left(\frac{0.14}{0.53} + \frac{15.1}{12} - \frac{10.6}{10.6}\right)} \quad (2.33)$$

$$\lambda = 4.4 K_T \quad (2.34)$$

Because λ is proportional to threshing losses, let's take the value of K_T to be 1.08 assuming 8% increase to analyze the threshing efficiency in worst case scenario. Thus, λ becomes 4.75 m^{-1}. Now all the values to determine the probability of threshed grain $G_T(x)$ as a function of concave length x are known.

$$G_T(x) = 1 - e^{-\lambda x} = 1 - e^{-4.75x} \quad (2.35)$$

At the end of the concave length (exit), the probability of threshed grain $G_T(x = L = 490\text{mm})$ becomes,

$$G_T(x = L) = 1 - e^{-4.75L} = 0.902 = 90.25\% \quad (2.36)$$

The percentage of unthreshed grain $G_R(x)$ becomes,

$$G_R(x) = e^{-\lambda x} = e^{-4.75x} \quad (2.37)$$

At the end of the threshing space where x = L, the percentage of unthreshed grain $G_R(x)$ becomes the threshing loss T_L in the threshing unit.

$$T_L = G_R(x{=}L) = e^{-4.75 \times 0.49} = 0.0975 = 9.75\% \quad (2.38)$$

Separating rate parameter β (m^{-1}) which describes the rate of grain separation along the threshing and separation space is determined as

$$\beta = K_S \sqrt{\frac{10.6 \times 15.1\sqrt{0.846}}{\sqrt{783}\, e^{\left(\frac{0.846}{2.052} + \frac{15.1}{15.1}\right)}}} = 1.133\, K_S \quad (2.39)$$

Let's assume the value of K_S to be 0.7. Since the separating rate parameter β is directly proportional to the separation process, reducing the value of β will increase the safety factor of the outcome. So β becomes 1.04. Thus, the fraction of separable and segregated grain $G_S(x)$ can now be determined as,

$$G_S(x) = \frac{1.04}{4.75 - 1.04}\left(e^{-1.04X} - e^{-4.75X}\right) \quad (2.40)$$

The thresher (threshing drum) separation loss S_L becomes:

$$S_L = G_S(x{=}L) = 14.12\% \quad (2.41)$$

Therefore, the fraction of separable and segregated grain which is the amount of grains that are threshed but segregated in the straw mat that needs separation in the separator is 14.1%. Thus, the percentage of grain separation T_S at the end of the threshing space becomes

$$T_S = 1 - G_S(x{=}L) = 85.88\% \quad (2.42)$$

In the threshing drum (threshing space), 90.25% of Teff grains are threshed (grains are detached) and out of the 90.25% threshed grains, 85.88% of Teff grains are separated (passed through the threshing concave openings). However, the threshing losses which are the remaining 9.75% of the MOG throughput and 14.12% of threshed but segregated grains are forced to flow to the next unit, separation drum, for further threshing and separation.

2.4.3 Percentage of threshed and separated Teff grain in the separation drum

As discussed in section 2.3.4, the probability of grains to be detached in the separator $G_{TS}(X_S)$ along the separation space (separator concave length) X_S is given in equation 2.18. Thus, at the end of the separation space, the probability of grains to be detached $G_{TS}(L_S)$ becomes

$$G_{TS}(X_S{=}L_S) = 1 - e^{-4.75L_S} = 84.32\% \quad (2.43)$$

At the end of the separation space, the separator threshing loss ST_L becomes,

$$ST_L = 1 - G_{TS}(L_S) = e^{-\lambda L_S} = 15.68\% \quad (2.44)$$

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At the end of the separation space, the fraction of separable and segregated grain $G_{SS}(X_S)$ becomes the separation loss SS_L.

$$SS_L = G_{SS}(X_S=L_S) = \frac{\beta}{\lambda-\beta}\left(e^{-\beta Ls} - e^{-\lambda Ls}\right) = 14.31\% \quad (2.45)$$

So the percentage of separated grain at the end of the separating space S_S is

$$S_S = 1 - G_{SS}(L_S) = 85.69\% \quad (2.46)$$

Thus, in the separator, from the remaining unthreshed and unseparated Teff grains that came from the threshing drum, 84.32% are threshed (Teff grains are detached) and 85.69% are separated. The remaining 15.68% unthreshed Teff grain and 14.31% unseparated Teff grain are send to the last unit of separator, the straw walker.

2.4.4 Percentage of separated Teff grain in the straw walker

There are three shakers that constitutes the straw walker along the length of the separation drum. The length of each shaker (individual straw walker) is 1500mm and width 235mm.

From equation 2.24, total threshing loss Vt is the total remaining unthrshed grain that enters the straw walker. There is 90.25% of threshed grain in the threshing drum and 85.88% of threshed grain in the separator. Which means out of the 9.75% threshing loss in the threshing drum, 84.32% which is 8.22% of Teff grains are recovered in the separating drum. Therefore, the total threshing loss Vt is 1.53% (100-90.25-8.22). With the same procedure, the total separation loss Vs which is the total remaining unseparated Teff grain that enters the straw walker is 2.03% (100-85.88-12.09). Take a=1.9 and b=0.9 since this values result the highest losses which will help to analyze the worst circumstances.

So the fraction of remaining grains $G_W(y)$ that still exist with the straw mat at the end of the straw walker length L_W is

$$G_W(y=L_W) = (0.0153 + 0.0203)\left\{1 - \frac{1}{0.9}\left[1.9\left(1 - e^{-0.9y}\right) - 0.9\left(1 - e^{-1.9y}\right)\right]\right\} \quad (2.47)$$

Thus, the straw walker separation loss W_L becomes,

$$W_L = G_W(y=L_W) = 1.89\% \quad (2.48)$$

Therefore, the percentage of separated grain at the end of the straw walker S_W is 98.11%. This implies 98.11% of the separation losses are recovered (Teff grains are separated) in the straw walker.

2.4.5 Model Based Threshing and Separation efficiency

The threshing and separation efficiency is one of the major performance indices that indicates the Teff thresher performance to thresh and separate Teff MOG throughput. This efficiencies are determined from the performance indices analyzed earlier. The threshing efficiency is defined as the ability of the machine to detach Teff grains from the MOG throughput whereas, the separation efficiency is the machine's capability to separate Teff grains that were threshed but segregated in the straw mat. This tasks are done by the actions of the threshing drum, the separation drum and the straw walker in a continuous MOG flow.

Threshing efficiency is calculated from the individual threshing capacities in the threshing and separation units. The probability of threshed grain in the threshing and separation unit is 90.25% and 84.32% respectively as indicated in equation 2.36 and 2.43. This means 84.32% of the threshing drum threshing loss (9.75%) is rethreshed in the separator. Therefore, the overall model based threshing efficiency $\boldsymbol{\varepsilon_t}$ of the Teff threshing machine becomes:

$$\boldsymbol{\varepsilon_t} = G_T(L) + G_{TS}(L_S)xT_L \quad (2.49)$$

$$\boldsymbol{\varepsilon_t} = 90.25\% + 0.8432x9.75\% = 98.47\% \quad (2.50)$$

In the separation process, other than the threshing drum, the separation drum and the straw walkers are involved. Out of 90.25% threshed Teff grains in the threshing drum, 85.88% got separated from the straw mat and move to the cleaning system through the threshing concave openings. The remaining 14.12% flows to the separation drum. As discussed in equation 2.42, 85.88% of the threshing drum separation loss (14.12%) is recovered and passed through the separation concave openings. Out of the 14.31% separation drum separation loss, 98.11% are reseparated in the straw walker. So the overall model based separation efficiency $\boldsymbol{\varepsilon_s}$ becomes:

$$\boldsymbol{\varepsilon_s} = T_S + S_S x S_L + S_W(SS_L x S_L) \quad (2.51)$$

$$\boldsymbol{\varepsilon_s} = 99.96\% \quad (2.52)$$

Thus, only 1.53% of Teff grains from the MOG throughput are not threshed and from the 98.47% of threshed Teff grains, 99.96% of the grains are separated through the concave and screen openings and passed to the cleaning unit.

2.5 Geometrical modeling

Complete model of the Teff threshing machine is shown in the figure 2.6. To make the threshing, separation and cleaning systems visible, some parts of the machine housing is hidden.

2.5.1 Power consumption

The total power consumption for the Teff threshing machine can be identified after determining the power requirement of the threshing, separation and cleaning units. Since this paper focuses only on the threshing and separation systems, the power analysis will focus only in the two.

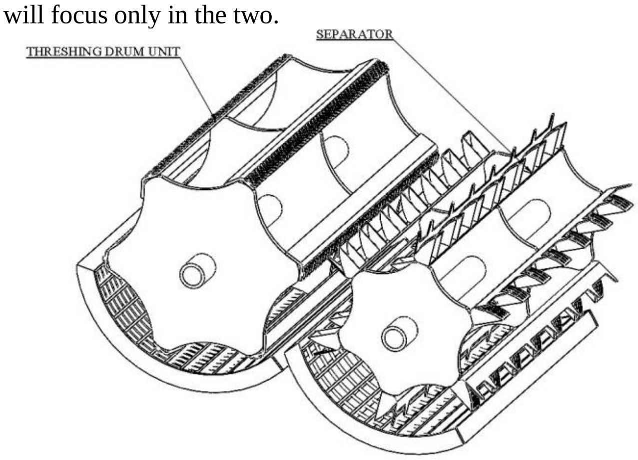

Figure 2.3 Threshing drum unit and separator

Threshing Unit

According to O.J Olaoye [26], the power P_T required to drive the threshing drum is

$$P_T = \frac{2\pi N}{60}\frac{M_d}{75}\left(g + \frac{Vc^2}{D}\right) \quad (2.53)$$

Where,
- N — Drum speed (rpm)
- M_d — Mass of threshing drum (kg)
- g — Gravitational acceleration (ms^{-2})
- D — Threshing drum diameter (m)
- Vc — Drum peripheral velocity (m/s)

Substituting N = 450rpm, M_d = 39.16kg, g = 9.81ms^{-2}, D = 0.45 and Vc = 10.6m/s in equation 3.58 results,

$$P_T = 6.39 \text{ kw} \quad (2.54)$$

Power per throughput of MOG P_G required to detach grains from their panicle is calculated according to C.O.Osueke [27] and it is expressed as:

$$P_G = Ke\,[\frac{Vc\ Qp^2}{\rho_g\ C^2}] \qquad (2.55)$$

Where, Ke Grain size characteristics constant
Qp MOG feed rate (kg/s)
ρ_g Grain bulk density (kg/m^3)
C Average concave clearance (m)

Substituting Vc = 10.6m/s, Qp = 0.846kg/s, ρ_g = 1340 kg/m^3 and C = 14mm into equation 3.60, the Power P_G required to detach Teff grains becomes

$$P_G = 28.88Ke\ w \qquad (2.56)$$

Considering the values of other grains, take the grain size characteristics constant Ke to be 0.20. This results

$$P_G = 5.77w \qquad (2.57)$$

This implies the Teff threshing machine will consume 6.82kw to thresh ton of MOG throughput. The total power consumption P becomes the summation of P_G and P_T.

$$P = P_G + P_T = 6.395\ kw \qquad (2.58)$$

Separation Unit

The power P_S required to drive the separation drum is

$$P_S = \frac{2\pi Ns}{60}\frac{M_S}{75}\,(g + \frac{Vs^2}{Ds}) \qquad (2.59)$$

Where, Ns Separation drum speed (rpm)
M_S Mass of separation drum (kg)
Ds Separation drum diameter (m)
Vs Separation drum peripheral velocity (m/s)

Substituting Ns = 400rpm, M_S = 26.07kg, g = 9.81ms^{-2}, Ds = 0.4 and Vs = 8.37m/s in equation 3.64 results,

$$P_S = 2.69\ kw \qquad (2.60)$$

Power per throughput of MOG P_{GS} required to detach grains from their panicle is

$$P_{GS} = Ke\,[\frac{Vs\ Qp^2}{\rho_g\ Cs^2}] \qquad (2.61)$$

Where, Cs Separation concave average clearance (m)

Substituting Vc = 8.37m/s, Qp = 0.846kg/s, ρ_g = 1340 kg/m^3, Ke = 0.2 and C = 16mm into equation 3.66, the Power P_{GS} required to detach Teff grains becomes

$$P_{GS} = 3.5\ w \qquad (2.62)$$

Therefore, the total power P_{TS} required to drive the separation unit is

$$P_{TS} = P_S + P_{GS} = 2.7\ kw \qquad (2.63)$$

Straw walker unit

The power consumption of the straw walker P_W can be determined as

$$P_W = \frac{2\pi Nw\ Tw}{60} \qquad (2.64)$$

Where, Nw Straw walker speed (rpm)
Tw Torque (Nm)

The torque is calculated from the weight on the straw walker W_W and the crank radius Rc. Ww is the mass of the straw walker M_W and the mass of the straw fragments and MOG materials received from the separator. Assuming maximum load of MOG on the straw walker which is mass of the material throughput Q_M, W_W becomes

$$W_W = Q_M.g + M_W.g \qquad (2.65)$$

$$W_W = 8.3 + 495.4 = 503.7\ N \qquad (2.66)$$

The crank radius Rc is 45mm.

Hence the torque Tw becomes

$$Tw = Ww \times Rc = 22.66\ Nm \qquad (2.67)$$

Therefore, the power consumption P_W to drive the straw walker results

$$P_W = 474.7\ w = 0.47\ kw \qquad (2.68)$$

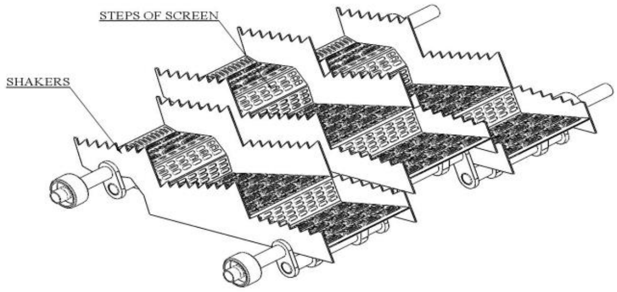

Figure 2.4 straw walker separation unit

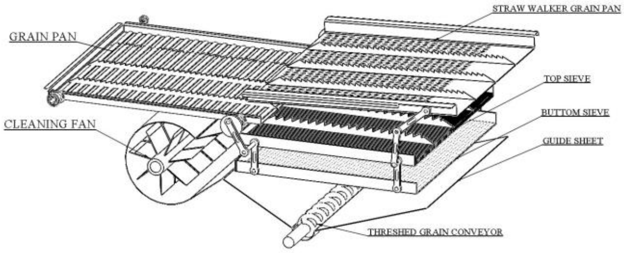

Figure 2.5 cleaning unit

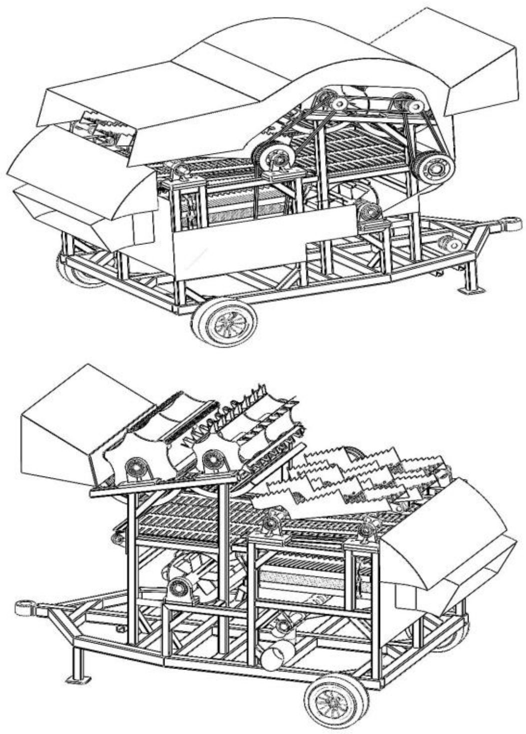

Figure 2.6 Tangential Teff threshing machine

3. RESULT AND DISCUSSION

3.1 Validation of Designed Threshing and separation systems

The designed Teff threshing and separation sytem is evaluated and validated in comparison with a developed Teff thresher designed by Geta Kidanemariam [24]. Evaluation of threshing performance indices of the newly designed system is done in comparisons with Geta kidanemariam's [24] design, a

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PHD thesis submitted to Addis Ababa university and a paper published by International Journal of Engineering.Vol.17 no3, May 2019. He evaluated and compared his design with another existing thresher (Bahir Dar modified SG-2000 thresher).

As far as concerned with the validation, in order to eliminate different results due to size variance, the size of major components of the threshing units are kept similar with Geta kidanemariam's design. The threshing rate parameter λ, the threshing efficiency and the separation efficiency are among the major threshing performance indices that are selected to compare with Geta Kidanemariam's design for validation.

For validation purpose, the following threshing drum and Teff crop physical parameters are changed to new values which are exactly the same with Geta kidanemariam's design so that comparison is done on similar basis.

- Threshing drum speed (peripheral velocity) Vc = 27m/s
- Threshing drum diameter D = 480mm
- Wet basis Moisture content of Teff U = 12%
- MOG (Teff straw) bulk density ρ = 35 kg/m^3
- Threshing drum length L_D = 830mm
- MOG throughput (feed rate) Q_P = 0.13kg/s

The above Independent parameters are taken from Geta Kidanemariam's design which are kept similar for both designs that are going to determine the threshing performance indices listed in the above paragraph. If the values of this performance indices according to the newly designed model are similar with Geta Kidanemariams model or the error is within 15%, then this research will be validated. But if the error exceeds more than 15%, the newly designed model needs to be analyzed again till the error is below 15%. In the following sections, major threshing performance indices are compared with Geta Kidanemariam's design.

3.1.1 Threshing rate parameter $\boldsymbol{\lambda}$

Threshing rate parameter is one of the major factors that determines the performance indices of any thresher. Geta Kidanemariam [24] uses a model proposed by simonyan et al. [28] to determine the threshing rate parameter λ_G to be 3.49 m^{-1}.

For the newly designed Teff threshing and separation system, the threshing rate parameter λ is determined based on the models proposed by [22], [29]–[31]. So from equation 2.6, the threshing rate parameter λ is,

$$\lambda = K_T\sqrt{\frac{\rho Vc\delta e}{Qp\sqrt{U}}}\, e^{\left(\frac{Qp}{Q}+\frac{U}{UM}-\frac{Vc}{V}\right)} \qquad (3.1)$$

Substituting exactly same parameters defined from Geta Kidanemariam's design discussed in section 3.1, i.e, ρ = 35 kg/m^3, Vc = 27m/s, U = 12%, Q_P = 0.13kg/s and take δe = 8mm, Q = 0.53kg/s, U_M = 21%, V = 27m/s and K_T = 1.08, the threshing rate parameter λ becomes,

$$\lambda = K_T\sqrt{\frac{35x27x8x10^{-3}}{0.13x\sqrt{12}}}\, e^{\left(\frac{0.13}{0.53}+\frac{12}{21}-\frac{27}{27}\right)} \qquad (3.2)$$

$$\lambda = 3.68$$

To validate the result, let's determine the error E between the two studies. Error E becomes,

$$E = E = \frac{\lambda - \lambda_G}{\lambda_G}\, x\, 100\% \qquad (3.3)$$

$$E = \frac{3.68 - 3.49}{3.49}\, x\, 100\% = 5.4\%$$

Therefore, the validation for the threshing rate parameter λ is a good agreement.

3.1.2 Threshing Efficiency

Based on Geta Kidanemariam's design, the threshing drum efficiency E_G at threshing drum speed of 27m/s, feed rate of 0.13kg/s, threshing drum diameter of 480mm and Teff moisture content of 12% is determined to be 82.5% [24]. With exact parameters, the threshing drum efficiency for the newly designed Teff threshing and separation system is as follows.

From section 2.3.2 and equation 2.5, the threshing drum efficiency $G_T(x)$ which is the percentage of threshed Teff grain along the threshing space length x is,

$$G_T(x) = 1 - e^{-\lambda x}$$

Substituting the value of threshing rate parameter λ calculated from equation 3.2 and taking the value of the threshing space (concave) length from the design considerations as 0.49m, the threshing drum efficiency $G_T(x = 0.49)$ becomes,

$$G_T(x = 0.49) = 1 - e^{-3.68*0.49} = 83.52\%$$

Error E between the two studies becomes,

$$E = E = \frac{G_T - E_G}{E_G}\ x\ 100\% \qquad (3.4)$$

$$E = \frac{83.52-82.5}{82.5}\ x\ 100\% = 1.23\%$$

With the above result, the threshing drum efficiency is validated with good terms.

3.1.3 Separation Efficiency

According to Geta Kidanemariam's design, the separation efficiency is evaluated at different configurations of feed rate and drum speed. His design considers threshing drum speeds of 1200 rpm, 1000 rpm and 900 rpm. For MOG throughput (feed rate) a value of 400kg/hr, 325kg/hr and 275kg/hr is selected and the moisture content is kept constant at 12% [24]. With combinations of this variables, the separation efficiency is analyzed. So using the exact values and configurations, below is the separation efficiency analysis for the newly designed Teff threshing and separation system. If Error between the two designs is below 15%, then the validation process will be on good agreement. The combinations of the independent variables is as follows.

Table 3-1: Drum speed and feed rate combinations for evaluating separation efficiency [24]

Test	Drum speed (rpm)	Feed rate (kg/s)	S_{GK} (%)
1	1200	275	89.12
2	1200	325	94.35
3	1200	400	91.9
4	1000	275	95.62
5	1000	325	93.75
6	1000	400	92.5
7	900	275	94.5
8	900	325	92.45
9	900	400	94.98

S_{GK}: Separation efficiency of Geta Kidanemariam's design

Test 1 (1200rpm and 275kg/s)

From equation 2.23, the separation efficiency S_S in the separation drum which is the percentage of the separated grain in the separation space is expressed as,

$$S_S = G_{SS}(X_S{=}L_S) = \left(1 - \frac{\beta}{\lambda - \beta}\left(e^{-\beta L_S} - e^{-\lambda L}\right)\right) \times 100\% \qquad (3.5)$$

Where, L_S Length of separation concave length, 0.49m
L Length of the Threshing concave length, 0.6m
β Separation rate parameter
λ Threshing rate parameter

To determine the separation efficiency at a separation drum speed of 1200rpm and feed rate of 275kg/s, the value of λ and β needs to be defined at the specified drum speed, feed rate and Teff moisture content.

From equation 2.6, λ becomes,

$$\lambda = 1.08\sqrt{\frac{35x30.15x8x10^{-3}}{0.0.0764x\sqrt{12}}}\, e^{\left(\frac{0.0764}{0.53}+\frac{12}{21}-\frac{30.15}{30.15}\right)} \qquad (3.6)$$

$\lambda = 4.59$

From equation 2.13, β becomes,

$$\beta = 0.8\sqrt{\frac{30.15x12x\sqrt{0.0764}}{\sqrt{35}\, e^{\left(\frac{0.0764}{0.53}+\frac{12}{21}\right)}}} \qquad (3.7)$$

$\beta = 2.3$

The separation efficiency S_S becomes,

$$S_S = \left(1 - \frac{2.3}{4.59 - 2.3}\left(e^{-2.3x0.65} - e^{-4.59x0.49}\right)\right) x\ 100\% \qquad (3.8)$$

$S_S = 88.07\%$

The error E for separation efficiency between the to studies at drum speed of 1200rpm and feed rate of 275kg/s becomes,

$$E = \frac{88.07-89.12}{89.12}\ x\ 100\% = 1.17\% \qquad (3.9)$$

Doing the same procedure for all the other 8 tests, the separation efficiency and the error becomes as follows.

Table 3-2: Separation efficiency and error at various drum speed and feed rates

Test	Drum speed (rpm)	Feed rate (kg/s)	S_{GK} (%)	S_S (%)	Error (%)
1	1200	275	89.12	88.07	1.17
2	1200	325	94.35	88.56	6.13
3	1200	400	91.9	89.79	2.29
4	1000	275	95.62	87.24	8.76
5	1000	325	93.75	87.77	6.37
6	1000	400	92.5	89.12	3.65
7	900	275	94.5	86.81	8.13
8	900	325	92.45	87.38	5.48
9	900	400	94.98	88.78	6.52

S_S: Separation efficiency of newly designed Teff thresher

So from all the nine tests for validation, the maximum error is found to be 8.76% at the minimum drum speed and feed rate of all the configurations and the minimum error is found to be 1.17% at the maximum drum speed and minimum feed rate of the variables. With an average error of 4.9%, it can be stated that the new Teff thresher design is validated with good agreement.

3.2 Effects of threshing parameters

To deliver a high performance threshing machine, the effects of different threshing parameters like threshing and separation drum speed, drum diameter, concave clearance, concave length, material throughput or feed rate and grain moisture content has to be study on the effects of the performance indices. In the following sections, this parameters and their effect on the threshing performance indices is analyzed. The graphs below are generated by analyzing the relation between the resulted equations of the corresponding indices in the above sections.

3.2.1 Effect of Teff threshing drum speed Vc on threshing rate parameter $\boldsymbol{\lambda}$

The threshing rate parameter is one of the major parameter that determines the threshing performance and it is affected by many factors. One of which is the threshing drum speed. The threshing rate parameter and the threshing drum speed has an inverse relation at a constant exit concave clearance and Teff moisture content. As shown in the graph below, when the threshing drum speed decreases, the threshing rate parameter increases and vice versa.

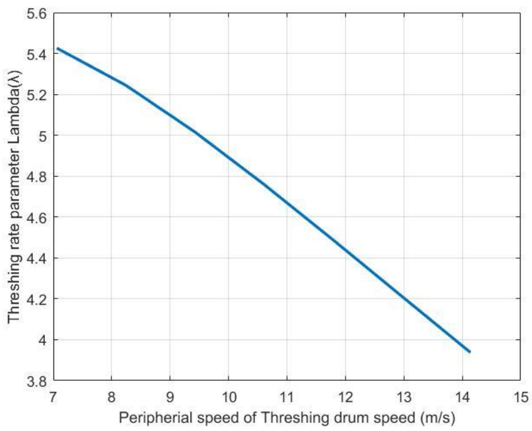

Figure 3.1 Effect of threshing drum speed on threshing rate parameter λ

As shown in the figure, the inverse relation is due to the fact that, when the threshing drum speed decreases, Teff materials will have more time to stay in in the threshing space. This will increase the rate of grain detachment from the straw mat which basically is the threshing rate parameter λ. Although, if the threshing drum speed is increased, then the time to stay in the threshing space will decrease which will result faster movement of materials without complete threshing which then will reduce the threshing rate parameter λ in a relation shown in the graph.

When Vc is increased from 300rpm (7.06 m/s) to 350rpm (8.24m/s) λ is reduced by 3.4% from 5.43 m^{-1} to 5.24 m^{-1}. When Vc is increased from 400rpm (9.42m/s) to 500rpm (11.78m/s), λ is decreased by 10.37% from 5.02 m^{-1} to 4.49 m^{-1}. The following table shows the value of λ at different values of threshing drum speed with in the range 300rpm to 600rpm.

3.2.2 Effect of exit Concave clearance on the threshing rate parameter $\boldsymbol{\lambda}$

The exit concave clearance is crucial to the threshing performance indices. Directly or indirectly, all the threshing performance indices are dependent on the exit concave clearance. If the exit clearance is zero, no material will flow to the subsequent unit leading no work at all. And if clearance is very wide, all the straw mat will flow out without adequate grain detachment resulting low performance indices. This effect on the threshing rate parameter at a constant threshing drum speed and moisture content is well described in the figure below.

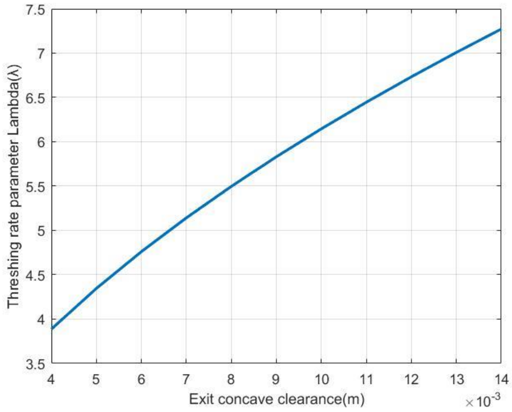

Figure 3.2 Effect of exit concave clearance δe on threshing rate parameter λ

As shown in the figure, there is an exponential relation between threshing rate parameter and exit concave clearance. When the clearance is wider, because there will be more material flow, the rate of grain detachment increases until it reaches a maximum. When the exit clearance is reduced, since there will not be more material flow, the rate of Teff grain detachment or the threshing rate parameter is reduced significantly.

When δe is increased from 4mm to 6mm, λ increases by 19.7% from 3.89 m^{-1} to 4.35 m^{-1}. The value of λ at various values of exit concave clearance is shown in the table below.

3.2.3 Effect of Current Concave Position on the Probability of Threshed Teff Grain

In the above section, the current concave position and the probability of threshed grain at a constant moisture content, threshing drum speed and MOG throughput is related as;

$$G_T(x) = 1- e^{-\lambda x} = 1 - e^{-4.75x}$$

Figure 3.3 below shows the relation between the probability of threshed grain and the current position of the concave length or threshing space length. At the beginning of the threshing space length, the probability of threshed grain is zero since no material enters the threshing space yet. The maximum probability of threshed grain is found at the end of the threshing space length where the materials exit the threshing unit.

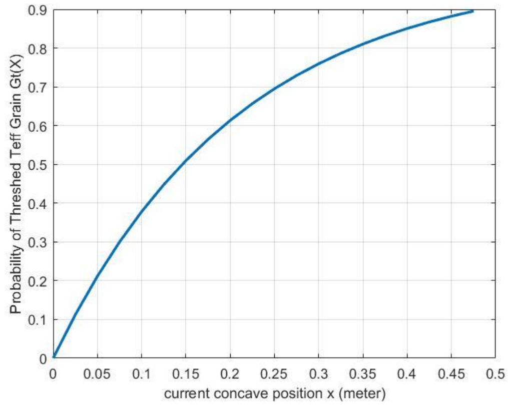

Figure 3.3 Effect of Current Concave Position on the Probability of Threshed Teff Grain

At the middle of the threshing space length, that is when Teff materials travel 50% of the threshing space length, 69.5% of Teff grains from the input amount are threshed. It can be shown that the longer the concave length (threshing space length), the higher the probability of Teff grain detachment. The following table shows, the percentage of threshed grain at different concave positions.

The comparison between the probability of threshed and unthreshed Teff grain along the threshing space length is shown in the figure below.

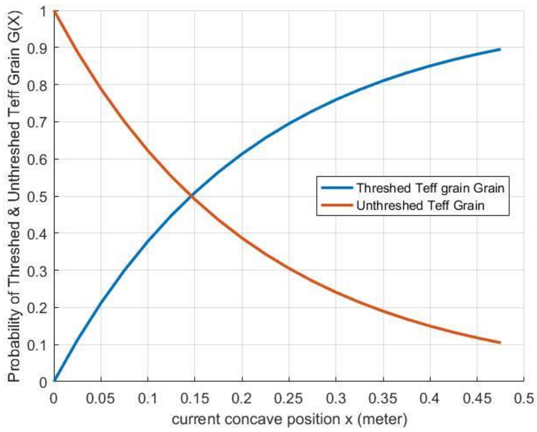

Figure 3.4 threshed and unthreshed Teff grain along the threshing space length

As shown in the figure, at the beginning of the threshing space length, the probability of unthreshed Teff grain is 100% since there is no material yet. But this value reduces along the threshing space length and it gets its threshing loss 9.25% at the end of the concave length where Teff material exits the threshing unit.

3.2.4 Effects of MOG throughput (Feed rate) on Threshing Efficiency

The effect of feed rate on the threshing efficiency in the threshing drum is described in the figure 4.5 below. When the feed rate is increased from 0.14kg/s to 0.26kg/s, the threshing efficiency drops by 2.2% from 90.28% to 88.29%. This is because the sudden increase in feed rate will clog the threshing space limiting the flow of crop materials. In this case, some portion of the crop will be segregated in the straw mat which will remain undetached from the straw. When the feed rate reaches 0.5kg/s, the threshing efficiency in the threshing drum increases by 3.2% from 88.29% to 91.22%. This is due to the fact that after few revolutions of the threshing drum, the clogged straw will leave the threshing space allowing more impact on the straw mat.

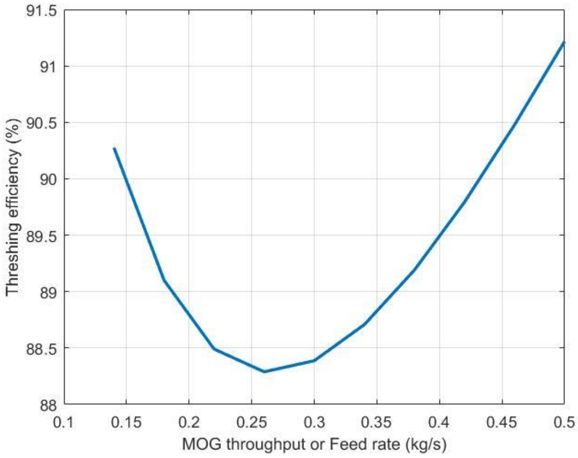

Figure 3.5 Effect of feed rate on threshing rate parameter

The effect of feed rate at constant drum speed on the threshing rate parameter lambda and threshing efficiency is shown in figure 3.6. As it can be shown, the change in the threshing rate parameter due to feed rate has a small impact in the threshing efficiency.

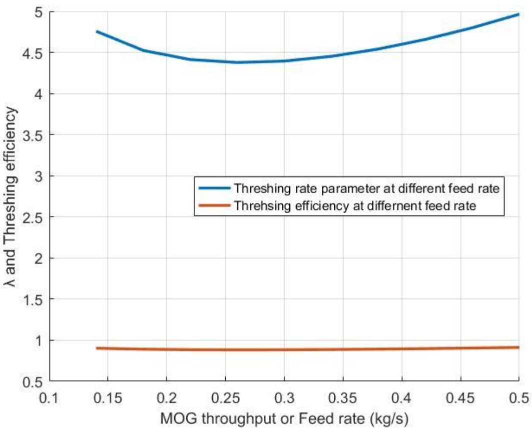

Figure 3.6 Effect of MOG feed rate on threshing rate parameter and threshing efficiency

3.2.5 Effects of MOG throughput (Feed rate) on Separation Efficiency

The Effect of MOG throughput on separation rate parameter and separation efficiency is shown in Figure 3.7. Due to the same reason as the threshing efficiency, the straw clogging due to feed rate will reduce the efficiency at first, but after drum develops continuous inertia, the clog will break which in turn increases the separation efficiency. In general, the separation efficiency increases by 0.8% when the feed rate is increased from 0.14kg/s to 0.5kg/s.

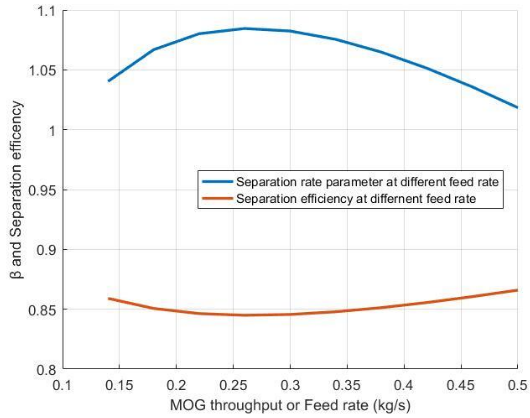

Figure 3.7 Effect of MOG throughput on separation rate parameter and separation efficiency

3.2.6 Relations of Separation Efficiency Separation loss over the concave length

The separation efficiency has a maximum value at the beginning of the concave and reduces to a certain value at the end of the separation space as shown in figure 3.8. On the other hand the separation loss is zero at the concave inlet and it reaches the maximum value at the concave exit. This is due to the fact that at the concave inlet, there is no material inlet yet, hence there is no separation loss. But as the separation space advances to the concave exit, the separation loss increases to its maximum value 14.12% as shown in figure 3.9.

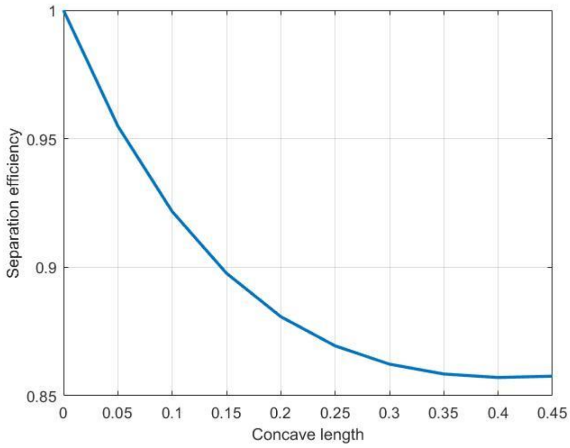

Figure 3.8 Relations of Separation Efficiency over the concave length

At the concave inlet, since there is no material inlet, unseparated grain is zero. Which means the separation efficiency is 100%. But as the concave length advances, unseparated grain will increase while the separation efficiency is decreased. At the end of the concave the separation efficiency reaches 85.76%. At 45% of the concave length, the separation efficiency is 88.08%. So the separation efficiency drops 2.6% after half of the concave length.

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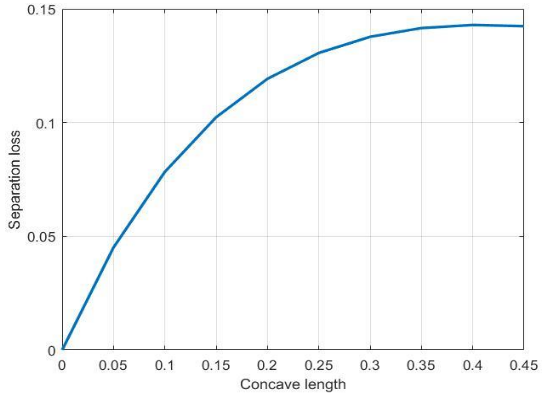

Figure 3.9 Relations of separation loss over the concave length

At the middle of the concave length, that is when the straw mat advances 0.225m, the separation loss is 12.49%. So in the remaining half of the concave length, the separation loss increases only 1.63% to reach 14.12%. To compare the separation efficiency and the separation loss, their relation over the concave length is shown in Figure 3.10.

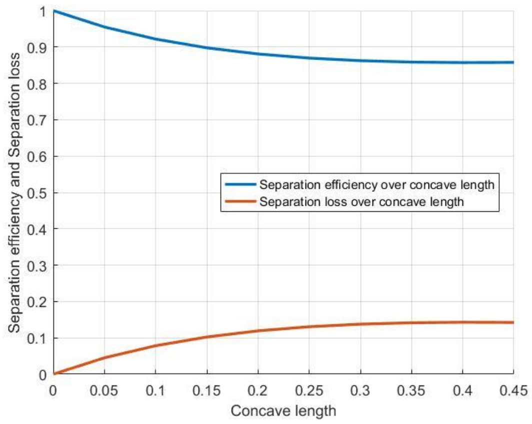

Figure 3.10 Relations of separation efficiency and loss over concave length

3.2.7 Effects of Drum speed on Separation Efficiency

The effect of Drum speed is proportional to the Separation Efficiency. Increasing the drum speed will increase the separation efficiency at the cost of grain damage. Because over a certain drum speed, the impact of separation drum will be high resulting a grain damage. As shown in Figure 3.11, when drum peripheral speed is increased from 10.6m/s to 21.2m/s, the separation efficiency increases by 2% from 85.9% to 87.42%.

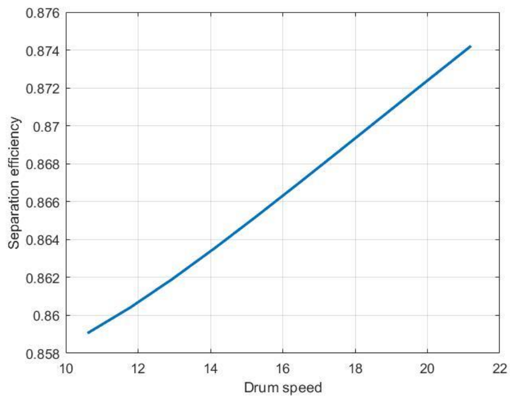

Figure 3.11 Effects of Drum speed on Separation Efficiency

3.2.7 Power consumption

The Effect of Drum speed on Drum power consumption is shown in figure 3.12. The relations shows, an increase in drum speed from the input power source will increase the power requirement. When the drum speed is increased from 450rpm to 650rpm, the power consumption increases by 6.28% from 6.38kw to 17.2kW.

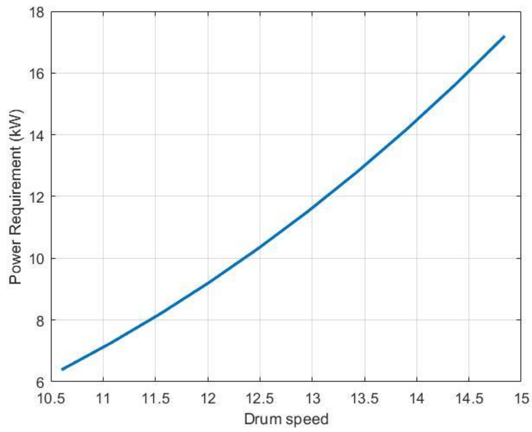

Figure 3.12 Effect of Drum speed on Drum power consumption

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion and Recommendation

From this research work, the following conclusions were drawn.

- The MOG feed rate, the threshing efficiency, separation efficiency in the threshing drum, separation drum and in the straw walker is determined.
- The performance of the threshing unit is validated with a thresher designed and prototyped by Geta kidanemariam which is based on another model and the result shows the maximum and minimum separation efficiency error between the two studies were 8.76% and 1.17% respectively. Hence, all the performance indices mathematical functions were validated with experimental data obtained from Geta Kidanemariam's design.
- The evaluation was analyzed with various configurations of threshing drum speed and MOG feed rates. The drum speed used was 900rpm, 1000rpm and 1200rpm whereas the MOG feed rate used was 275kg/s, 325 kg/s and 400 kg/s.
- The error generated between the two studies on the threshing rate parameter was determined to be 5.4%.
- The designed model illustrates the relations of threshing parameters like drum speed, MOG feed rate, moisture content, concave clearance and concave length with performance indices.
- The percentage of threshed grain in the threshing drum and in the separation drum is 90.25 and 84.32% respectively. The percentage of separated grain in the threshing space, separation space and straw walker is 85.88%, 85.69 and 98.11% respectively.
- The above performance indices at different sections of the machine defines the Teff threshing machine's overall threshing efficiency to be 98.47% and the overall separation efficiency to be 99.96%.

- Any related research in the future should consider the value of portability and the countries land scape for agricultural activities so that the end users can move from field to field easily.
- When designing or using a Teff thresher, the appropriate moisture content of the Teff should be noted. High moisture content will increase difficulties during MOG flow and very law moisture content will increase grain damage.
- The inlet and exit concave clearances are crucial during designing and operation of the machine.

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