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Raji, A.N., Kuku, O.R., Ojo, S.S., Hunvu, M.S.

DESIGN DEVELOPMENT AND PERFORMANCE EVALUATION OF WASTE PLASTIC SHREDDER

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Abstract: *The conservation of energy and sustaining clean environment had been a focus for attention. Waste plastics releases hazardous substances into the environment. Plastic shredding machine had played considerable role in the waste plastic recycling process towards solving the problem associated with plastic waste and the harvesting of the much energy that the waste plastic could provide for human need. In this paper, a 50 kg processing shredding machine for waste plastics was designed and fabricated. The drive mechanism for the machine combined the belt and gear drives to avoid the deficiency associated with the common single belt drive shredders. The data obtained from the design analysis of the shredder machine was used to fabricate the machine for improve energy utilization of the prime mover through optimizing the design parameters of the drive mechanisms. Performance evaluation of the machine indicates that the machine efficiency is between 90-96 % for the HDPE, PVC and the PET waste plastic.*

Key words: *Plastic, shredder, shaft, frame, cutting blade, belt drive, gear drive.*

Razvoj dizajna i ocena performansi drobilice za otpad. *Fokus ovog rada je na očuvanju energije i održavanju čiste životne sredine. Otpadna plastika izbacuje opasne materije u životnu sredinu. Mašina za drobljenje plastike ima značajnu ulogu u procesu recikliranja otpadne plastike u cilju rešavanja problema vezanog za plastični otpad i uštedu velike količine energije koju otpadna plastika može da obezbedi za ljudske potrebe. U ovom radu je dizajnirana i izrađena mašina za drobljenje od 50 kg za otpadnu plastiku. Pogonski mehanizam mašine kombinuje pogonske trake i zupčanike kako bi se izbegao nedostatak koji je povezan sa uobičajenim drobilicama sa jednim remenom. Podaci dobijeni konstrukcijskom analizom mašine za drobljenje korišćeni su za izradu mašine za poboljšanje iskorišćenja energije primarnog pokretača kroz optimizaciju konstrukcijskih parametara pogonskih mehanizama. Procena performansi mašine pokazuje da je efikasnost mašine između 90-96% za HDPE, PVC i PET otpadnu plastiku.*

Ključne reči: *Plastika, drobilica, osovina, ram, testera, remen, pogon zupčanika.*

1. INTRODUCTION

Plastic waste is damaging to the environment and its removal should be a major concern which can be done by recycling. In recent time the hip of non-biodegradable waste plastic is becoming challenging especially in the developing economy like Nigeria. Current disposal methods of the waste plastics especially as landfills had created serious environmental concern which is threatening human health and safety [1]. Pollution resulting from accumulation of the plastic waste especially in the water ways and oceans had been a source of concerns. Although much energy is consumed during the production and manufacture of plastic, the energy value for the plastic manufacture at the end lifecycle is hardly reclaimed. The plastic waste is often used as landfill which more occupies useful spaces. These energies in some plastic products could be reclaimed through recycling. Since plastic products are petroleum based, the rising cost of petroleum as raw material for production and manufacture of plastic could make the consideration for recycling of the plastic waste a profitable and sustainable venture.

Management of waste plastic for recycling involves six basic stages; this includes the plastic collection, sorting, washing, shredding, melting, and pelletizing. The collection procedure in most developing countries presently is done manually by drop-off centers and buy-back centers but the mechanization of the other stages of the recycling process had received considerable research efforts in the past years. The different stages of the recycling process had received considerable attention [2]. The sorting process is the separation of the waste plastic according to their types. The sorting machine designed for this purpose are as discussed in [3, 4], the washing process [5, 6], the melting process [7] and the material pelletizing. The shredder seems to be the major focus of researchers [8-18].

Design of a plastic recycling machine which combined the principle of conveying and heating to effect shredding and melting of the plastic was however attempted [19], this machine was observed only suitable for domestic plastics of smaller units. Although optimization attempt was done for the heating process, the conveying unit and extrusion for efficient output need be thoroughly analyzed. The desired to package shredded waste plastic for foreign export as may be required for foreign exchange earnings should encourage stand alone shredding operation for such waste plastic management.

Plastic shredding is the process of reducing the waste plastic to flakes for further processing. The development of shredding machine for plastic waste management can therefore not be overemphasized.

Shiri et al [20] developed a combined washing and shredding machine. The machine is built of single chamber for the washing and shredding process. The cutting unit of the machine is an assemblage of the fix and rotary blades mechanism. This design consists of only a belt drive for the operation of the rotary blade shaft. A similar machine combining the washing and shredding process of recycling the plastic was specifically designed for PET bottles in Okunola et al [21]. The machine incorporates cutting blades arranged in auger screw manner. The machine was observed to perform at over 90% operating efficiency. Ravi [22] emphasized on improving the performance of the shredding machine by optimizing the design of the cutter blades. The modified cutter blade was design to have two cutting edges as against the conventional multiple cutting edges. The two cutting edges blade was observed to perform effectively with reduced operation time as discussed in the study. Tegegne et al [23] develop electrically driven dual shafted-multi bladed shredding machine. The cutting angle of the cutter blades and blade spacing and cutting speed were considered essential variables considered in the design.

The concept of plastic shredder had over the years emphasized on the need for efficient cutting unit of the machine [17, 18, 22]. The cutting unit of the shredder consists of fixed and rotary cutting blades which have been the concept admitted by most designers as the state of the art knowledge for improving the performance of the machine and very few of the designers do a performance evaluation to verify this claims. However the possible loss of efficient interrelations for the drive mechanisms had been overlooked as a possible determinant for improving the efficiency of the machine and other similar mechanical systems. Most of the design of the shredding machine for small scale operation is characterized by low reliability; hence the major focus should be on the drive mechanism for optimum shredding operation. This paper discuss the complete design of the plastic shredder with emphasize on the optimum design of the drive unit configuration.

2. MATERIALS AND METHODS

2.1 Design concept

The design concept of the machine is shown in Figure 1. The machine consists of five major subassemblies. The machine frame which comprises the machine stand, feeder unit of the hopper and the cutting unit housing, the cutting unit which comprises the cutting blades and the shaft, the drive mechanism which is the combination of the v-belt drive and the gear mesh drives, and the prime mover. The prime mover supplies the required power for the operation of the machine. The power from the prime mover is transmitted via the belt to the driven pulley shaft. The driven pulley drives a helical gear carrying the positive shaft on which a first set of the cutting tool is mounted. The helical gear meshes with a second helical gear carrying the negative shaft on which the second set of the cutting tool is mounted. The first set of the cutting tool rotates in the clockwise direction against the second set rotating in the counterclockwise direction as viewed from the left hand side for the cutting process.

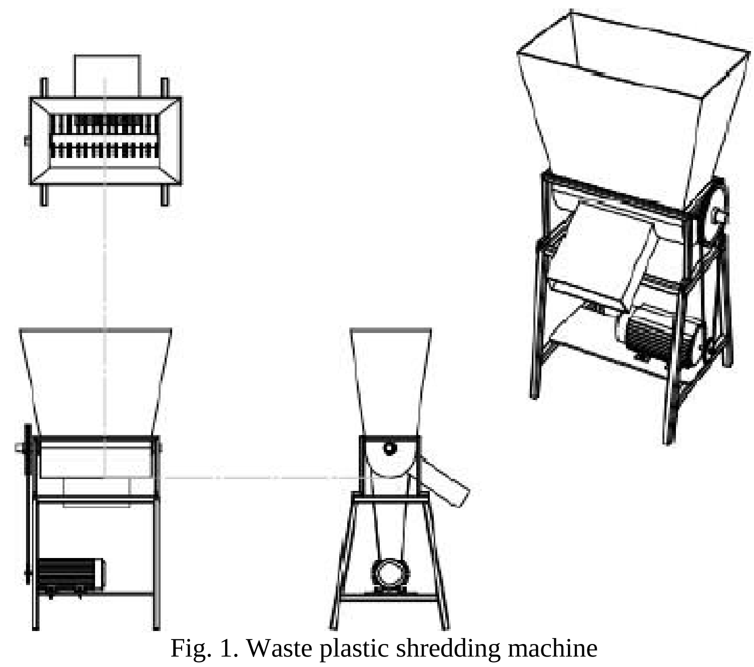

Fig. 1. Waste plastic shredding machine

2.2 Design Analysis

The design analysis involves the design of the feeder unit, the cutting unit, the drive mechanism, and the frame structure.

The belt drive design: The drive mechanisms include the v-belt drive and the helical gear drive as shown in Figure 2. The v-belt is selected for the design to provide possible better combination of the traction, speed of rotation, the bearing load, and the belt service life. The belt drive is design according to the operating condition of Table 1.

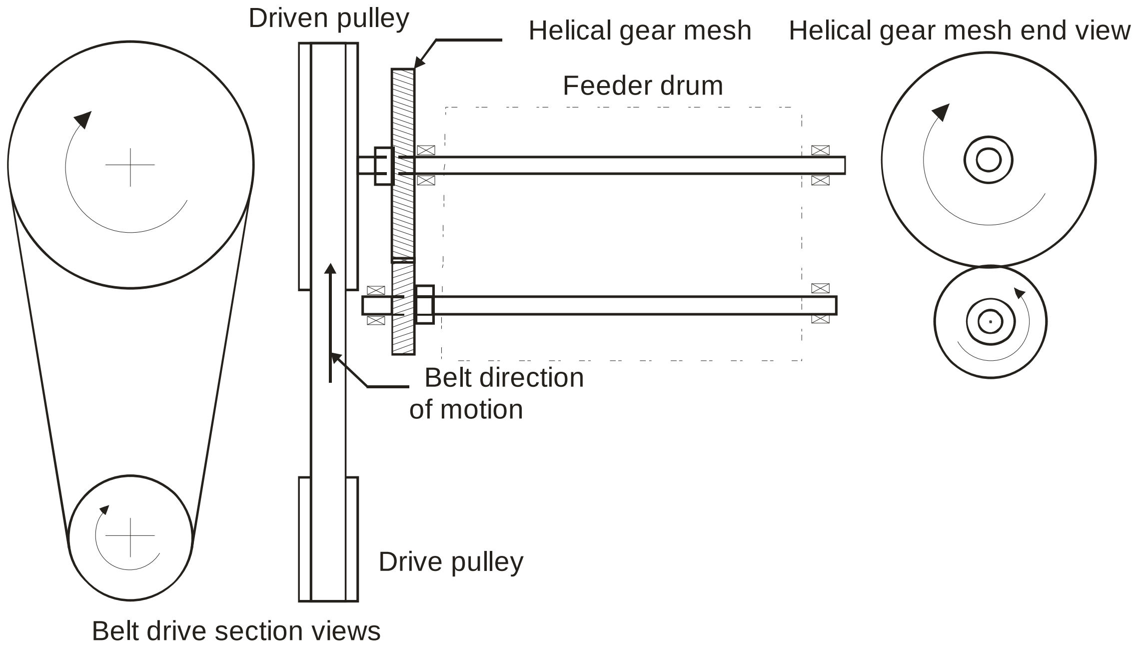

Fig. 2. Drive mechanism

Design specification	
Hours/ day duty	10
Power rating of prime mover, P_n	3 h.p
Rotational speed of prime mover	1440 rev/min
Rotational speed of driven shaft	980 rev/min
Service factor, Ks	1.3
Sheave center distance, C	1400 mm

Table 1. Operating conditions

Belt selection: The effective operation of the belt drive could depend upon the frictional force between the belt and the pulley, and the elasticity of the belt. This is required for short inter pulley distance as is required for this design.
The velocity ratio of the drive assuming negligible slip and creep effect is obtained as in equation (1).

$$Speed\ ratio = \frac{n_i}{n_o} \quad (1)$$

n_i is the rotational speed of the driving sheave, and n_o is the rotational speed of the driven sheave. The design power could be obtained as expressed in equation (2).

$$Design\ power, P_d = K_s.P_n \quad (2)$$

The equations (1) and (2) are combined with the manufacturers chat to select the narrow profile A-section (SPA) wedge belt for the design. The results are obtained as tabulated in Table 4 and Table 5.
In order to avoid energy waste during operation of the machine, there is need to avoid excessive friction. The belt is pre-loaded with tension T_o to avoid slippage of the belt on the pulleys. The value of the preload could be obtained as expressed in equation (3).

$$2T_o = T_p + T_h \quad (3)$$

T_p and T_h are the pull and hold force on the belt respectively representing the tight and slack side belt tension which is obtained equations (4a) and (5).

Equation (4) described the belt friction forces between the belt and the pulley surface. This friction is responsible for the difference in tight side and the slack side tensions of the belt. The frictional force increases with the amount of wrap on the surface of the pulley and is described by the belt Euler equation (4a).

$$\frac{T_p}{T_h} = \exp\left(\frac{\mu\theta}{Sin\frac{\beta}{2}}\right) \quad (4a)$$

θ is the belt wrap angle on the driving pulley, ❨ is the coefficient of friction between the belt and the pulleys, and β is the pulley groove angle. The belt wrap angle is obtained from equation (4).

$$\theta = \pi - 2\,Sin^{-1}\frac{D-d}{2C} \quad (4b)$$

D and d are the pitch diameters of the driving and driven sheaves respectively.

The power delivered to the gear drive of the machine is a function of the belt tensions as obtained from equation (5a) as in [24].

$$P_d = (T_p - T_h).v \quad (5a)$$

v is the belt velocity obtained as expressed in equation (6).

$$v = \frac{\pi n_i}{60}.d \quad (5b)$$

The resultant of the pull and hold forces, F_R, is the turning force producing the required torque for the operation of the positive cutting-tool shaft. The resultant force is obtained as defined in equation (6) [25, 26].

$$F_R = \left(T_p^2 + T_h^2 - 2T_pT_hCos\theta\right)^{1/2} \quad (6)$$

The transmission torque is thus obtained as expressed in equation (7).

$$M_t = F_R.\frac{d}{2} \quad (7)$$

Gear selection: The gear drive suggested for the machine is the spur gear mesh. The Lewis equation (8a) is used for the selection of the spur gear for the operation. The operation condition of the spur gear is as given in Table 2.

$$\sigma = \frac{W_t}{K_vF.m.Y} \quad (8a)$$

Specification for the spur gear design	
Material for pinion and gear	Carburized hardened steel
Permissible bending stress, σ	144.1 MPa
Rotational Speed of pinion and gear, n_o	980 rev./min.
Power transmitted, Pd	2.91 kW
Gear ratio	1:1
Number of teeth on pinion and gear, N	22
Module, m	1.5
Pressure angle, ϕ	20^o
Lewis form factor, Y	0.41883

Table 2. Operating condition for shredder spur gear

The face width of the gear is obtained from equation (8a) as follows in equation (8b);

$$F = \frac{W_t}{K_v.\sigma.m.Y} \quad (8b)$$

The transmitted load $W_t$is obtained as expressed in equation (9).

$$W_t = \frac{Power\ transmitted, P_d}{pitch\ line\ velocity, v_p} \quad (9)$$

The pitch line velocity is obtained as expressed in equation (10)

$$v_p = \frac{\pi n_o}{60}.d_p \quad (10)$$

d_p is the pitch diameter of the gear which could be determined from equation (11)

$$d_p = m.N \quad (11)$$

The dynamic factor, K_v is determined from equation (12)

$$K_v = \frac{6}{(6+v_p)} \quad (12)$$

The design values obtained from equations (8) – (12) as detailed in Table 7 could be used to select the appropriate pinion and gear parameters for the design as presented in Table 8.

The shaft design: The shaft design include specifying the shaft dimensions for strength and possible fluctuating load integrity considering the shaft bearing supports, the mounted components and the shaft dynamic. The shaft layout is as shown in Figure 3

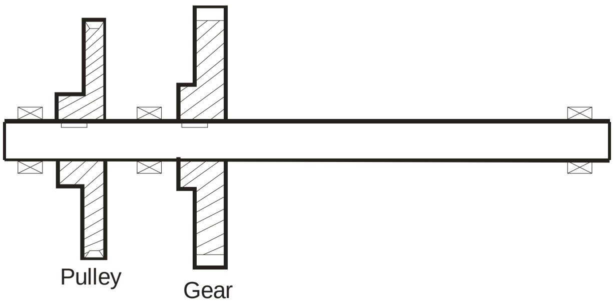

Fig. 3. Shaft layout

The shaft consists of stepped sections to accommodate the bearing mount, the gears, and the sheaves. Keys are provided to assemble the gears on the shafts. The shaft is designed according to the ASME code for ductile material expressed in equation (13),

$$d^3 = \frac{16}{\pi \tau_{all}} \sqrt{(k_m M)^2 + (k_t T)^2} \quad (13)$$

k_m is the bending factor accounting for shock and k_t is the torsion factors accounting for fatigue in the machine. τ_{all} is the material yield strength, M and T are the shaft bending moment torsion load respectively. The shaft design is base on the specification as given in Table 3.

Parameters	
Design load	50 kg
Rotational speed of shaft	980 rev/min
Power transmitted, Pd	2.91 kW
Bending factor for shock, km	2
Torsion factor for fatigue, kt	1.5
Allowable Stress, τ_{all}	40 Mpa

Table 8. Design specification

The cutter blade design: The $3\frac{3}{8}$ *inches* circular saw blade with PV-form teeth and made of solid alloy steel as shown in Figure 4 was adopted for the design. The blades were mounted and rigidly fixed on the positive and negative drive shafts spaced 10 mm on both shafts. The arrangements of the blades are as shown in Figure 4b

The machine frame: The grinding machine elements are supported on the frames. The frame design includes the gear mesh housing, the cutting tool enclosure, the hopper and the machine support framework. The frame design was considered for rigidity, size and weight. The frames were fabricated from mild steel plates of 2.5 mm thickness and the 38 x 38 mm angle iron..

The angle iron support beam was design to resist bending by limiting the deflection due to the loading from the machine elements using the model expressed in equation (14) assuming that the support beam is simply supported. The frame stand is assumed as a column and designed against buckling to ensure that the length of each stand do not exceed L_c as expressed in equation (15).

$$\delta < \frac{FL^3}{48EI_{yy}} \quad (14)$$

$$L_c = \pi \sqrt{\frac{EI_{xx}}{F}} \quad (15)$$

Where F is the force exerted by the machine elements, L is the length of the beam frame, L_c, E is the Young's modulus for mild steel, and I_{xx} , I_{yy} are the second moment of area for the beam and column stand respectively.

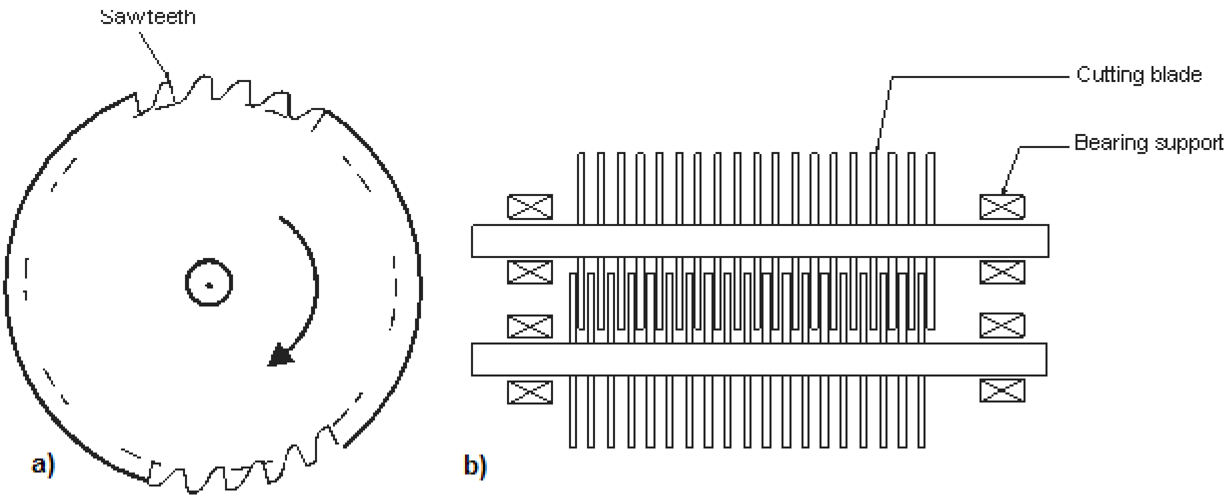

Fig. 4. Schematic of the cutting blade and arrangement on shafts (a) Cutting blade, (b) Blades arrangement

2.3 Assembly

The machine hopper was welded on the cutting unit housing. The cutting blades and shaft assembly were placed in the cutting unit housing and supported on bearings which were bolted on the machine stands. The machine stand was fabricated from 40 x 40 mm angle iron and joined with arc welding. A plate is welded below the support to carry the the prime mover. The prime mover is connected to the driven pulley using the v-belt as selected. Consideration should be given to the periodic lubrication of the meshing gears to avoid wearing of the gear tooth and noise produced from the meshing gears when in operation.

3. PERFORMANCE EVALUATION

The results obtained from the design process are presented in Table 4. The SPA wedge belt configuration is as given in Table 5 and the sheave bore size is obtained as in Table 6. The parameters as obtained were used for the fabrication of the machine and performance analysis of the machine carried out.

SPA wedge belt selection results		
Speed ratio	1.47	
Allowable power per belt	2.45 kW	
Pitch diameter of sheave	Driving	90 mm
	Driven	132 mm
Belt length, Lp	3150 mm	
Number of belt required	2	

Table 4. Belt selection results

	Top width	Height	Angle (^{o})
SPA	13 mm	10 mm	38

Table 5. SPA belt configuration for the design

	Bore No.	Max bore dia.	Outside dia.
Sheave bore size	1610	42 mm	96 mm

Table 6. Sheave selection

Design values for selected gears	
Addendum, a	1.2
Dedendum, b	1.5
pitch circle diameter of gear	33 mm
pitch line velocity, v_p	1.693 m/s
Transmitted load, W_t	1719 N
Dynamic factor, K_v	0.78
Face width, F	25 mm

Table 7. Pinion and gear properties for the shredder

	Parameters
Outer diameter	48 mm
Boss diameter	35 mm
Bore diameter	15 mm

Table 8. Selected gear dimensions

The test of the machine is done to analyze its shredding performance. Four categories of the waste plastics were shredded; these include the low density polyethylene (LDPE), high density polyethylene (HDPE), Polyvinyl chloride (PVC) and the polyethylene terephthalate. (PET). Selected quantities of the waste plastic materials were shredded and the quantity of pellets output by weight and sizes between 2 – 4 mm as required for an extruder were measured. Three trials were performed for each material. The result is as shown in Table 9.

The machine was observed to have low efficiency for the LDPE. This may be due to the poor flexural strength and flexural modulus of the LDPE. The machine performance for HDPE, PVC and PET is satisfactorily above 90%. This may be considered fairly efficiently for a medium scale production process of the shredding machine. The machine performance was further evaluated at three speed level of the prime mover. The result is as shown in Table 10.

Test Material	Input Quantity (kg)	Quantity of pellets (kg)	Mean Value (kg)	Efficiency (%)
LDPE	37.5	20	22.5	60
		22.5		
		25		
HDPE	50	44.5	46.17	92.34
		46		
		48		
PVC	50	47	47.23	94.46
		47.8		
		46.9		
PET	52.5	50	48.67	92.7
		48		
		48		

Table 9. Machine performance result

	Machine efficiency %			
Motor Speed (rpm)	LDPE	HDPE	PVC	PET
950	63.45	90.95	89.6	95.8
1200	60.9	92.85	95	92.7
1420	60	92.34	94.46	92.7

Table 10. Efficiency comparison for machine under varying motor speed

The result shows that the machine performance improved at lower speed of operation for the LDPE and the PET materials. The speed of operation of the machine could be specified for the type of waste plastic desired to be shredded. The PET plastic could be shredded efficiently at a speed of 950 rpm compared with the PVC and the HDPE with higher efficiency at 1200 rpm. The variation in the performances of the machine at different speed of operation could be attributed to the excusive disparities in the mechanical properties of the plastic materials.

4. CONCLUSION

The plastic shredding machine is a need for plastic waste management. The plastic shredding machine was designed and fabricated. The typical requirement for the design is the machine rigidity, strength, stability and safety of operation. The machine was designed to accommodate an average of 50 kg waste plastic for processing. The performance evaluation of the machine shows that the machine is more effective for shredding of the HDPE, PVC and PET waste plastics. However at a speed of 950 rpm the machine could be use for the shredding of LDPE. The shredder machine could be used for medium scale waste plastic recycling plant where such size of pellet between 2 – 4 mm would be required for processing by an extruder. The machine is readily available and affordable for small and medium scale waste plastic processing plant.

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Authors: **Nurudeen A. Raji** (Associate Professor)
Rafiu O. Kuku (Lecturer)
Seun S. Ojo (Research Student)
Sejero M. Hunvu (Research Stdent)
Mechanical Engineering Department, Lagos State University, Nigeria
E-mail: nurudeen.raji@lasu.edu.ng