Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: P. O. Babalola *et al* 2019 *J. Phys.: Conf. Ser.* **1378** 022091

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Performance Evaluation of a Centrifugal Pump with different Impeller Materials

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Abstract. Many factors affect the performance characteristics of a pump. One of these is the impeller material. This paper is on the effect of impeller material on the operating characteristics of a centrifugal pump. The impeller materials used were cast iron, bronze and zinc. Cost, pumping efficiency, pressure head and power consumption are the factors that were taken into consideration. The results from the test, showed that the impeller made of zinc material was found to be more efficient (48.24%) and required the most power (3.38bhp). The zinc impeller was the least expensive to manufacture and pumped better head. The zinc impeller however failed at (very) high pump speed due to the fact that its strength could not match up with the pump speed. The cast iron impeller on the other hand, required the least power (0.86bhp) to run but pumped the least head (6.25m) and was more efficient (46.35%) than the bronze impeller; this was majorly due to cavitation and friction losses. The bronze impeller pump was the least efficient (38.79%), the most expensive to manufacture but pumped more head (8.50m) than the cast iron impeller and required more power (2.32bhp) than the cast iron impeller.

Key words: Centrifugal pump, impeller, cast iron, bronze, zinc, flow rate, efficiency

1. Introduction

A pump is an equipment for transforming mechanical energy to hydraulic energy [1]. Pumps are classified as dynamic and positive displacement pumps. Examples of dynamic pumps are cantilever, jet, turbine, axial flow, mixed flow and radial. The last three are known as centrifugal pumps. Typical examples for positive displacement pumps are gear, screw, vane, plunger, diaphragm and piston. This paper is on radial centrifugal type of pump. A centrifugal pump transports fluid by converting rotational kinetic energy to hydrodynamic energy of fluid flow. The force which is exerted by a body moving in a circular path is referred to as centrifugal force and hence it is used to designate this type of pump.

The fluid is attracted to the centrifugal pump at extreme speed close to the midpoint of the rotating impeller and it is forced against the enclosure by the vanes. The developed centrifugal pressure forces the fluid through an outlet in the casing. The speed of the fluid reduces simultaneously with increase in pressure due to piecemeal widening of the outlet in a spiral fashion. Hence, centrifugal pumps are capable of generating unceasing flow of fluid at high pressure; the pressure can be increased further by interconnecting many impellers together in one system. Some applications of centrifugal pumps are water supply, transfer, disposal of sewage, irrigation, flood control, power station cooling system, dewatering and swimming pool systems [1]. Centrifugal pumps can also be utilized as gas compressors in central air conditioning system.

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Journal of Physics: Conference Series **1378** (2019) 022091 doi:10.1088/1742-6596/1378/2/022091

Due to the ever-increasing demand for greater pumping efficiency, pump designers and manufacturers alike have been set on the edge to seek out new and better ways of increasing the performance characteristics of pumps.

Many factors affect centrifugal pump performance; specific speed, cavitation, Net Positive Suction Value (NPSV), flow rate, static pressure head, dynamic pressure head, power et cetera. The relationship between these factors has been studied by many investigators [1-6]. Another factor that affects the performance of a centrifugal pump is the type of impeller material used.

Nomenclature:

NPSV- Net Positive Suction Value
NPSH - Net Positive Suction Head
NPSHA- Net positive suction head available
NPSHR- Net Positive Suction Head Required
h_a=Atmospheric pressure in mts. absolute.
h_{vap} = Vapour pressure of liquid in mts. absolute.
h_s = Total suction head in mts. (-sign for suction lift, + sign for suction head).
P_g: Brake power (W)
GPM: Flow rate in Gallons Per Minute
$S.G_m$: Specific Gravity of impeller material
H_f : Total head in feet
H_m: Total head (m)
η : Efficiency of the electric motor
η_p : Pump efficiency
P_c: Water power (kW)
Q: Flow rate (m^3/s)
γ: Density of the water (kg/m^3)

The aim of this paper is to ascertain the effect of impeller materials on the performance of centrifugal pump and thus determine the most efficient material for centrifugal pump impellers. Materials in consideration for this report include cast zinc, cast iron and cast bronze.

2. Performance parameters of centrifugal pump

The performance of centrifugal pump depends largely on the performance of the impeller and so we would be examining the performance parameters of the impeller (pump) upon which this research is based.

2.1 Flow rate

The flow rate also called the discharge rate is the volume of liquid per unit time which the pump can discharge or which flows in the pump. The common units for flow rate are gallons per minute (gpm), liters per minute (l/min) or cubic meters per second (m^3/sec).

2.2 Head

The head of a pump is an indication of the pressure delivered to the liquid during flow through the pump by the impeller. It is the pressure difference between the suction and discharge sides of the pump. Head can also be defined as the net work done on a unit weight of water by the pump impeller. The pressure and head of a pump are two separate ways of expressing the same value. Usually, the head is expressed in feet (ft) or meters (m) while pressure is expressed in psi (pounds per in^2) in English units or kilopascals (kPa) in metric units. To attain a pressure of 1 psi, a column of 2.31 ft in height is required.

2.3 Net positive suction head

It must be understood that it is impossible for a fluid to be sucked by a pump. The fluid must be at the suction aperture of the pump. In pumps taking fluid from a tank opened to atmosphere, it is the atmospheric pressure that pushes the fluid into the pump. Net Positive Suction Head (NPSH) is used to express this suction condition of the pump. NPSH is the **head** that is responsible for the water that moves into the eye of the impeller and is the least **suction** pressure needed to prevent cavitation. Local decrease of the static pressure to the vapor pressure of the liquid may result in vaporization of the liquid and cavitation. The blade loading, loss within the impeller, impeller inlet velocity and inlet passage loss are responsible for the drop in internal pressure. In order to avoid a significant decrease of impeller pressure rise, the addition of these pressure drops should not be greater than the difference between static pressure and vapor pressure, the equivalent head is referred to as the 'Net Positive Suction Head' or NPSH.

$$NPSH = h_a - h_{vap} + h_s \qquad (1)$$

Where
h_a = Atmospheric pressure (absolute mts.)
h_{vap} = Vapour pressure of liquid (absolute mts.)
h_s = Total suction head in mts. (-sign applies to suction lift, + sign applies to suction head).

Net Positive Suction Head (NPSH) has two values, available NPSH and required NPSH. Net positive suction head available (NPSHA) is the aggregate suction head in meter or feet of liquid absolute, at the suction eye and referred to datum, minus the vapour pressure of the liquid in feet absolute [7]. On the other hand, net positive suction head required (NPSHR) is the suction pressure needed by the pump for safe and unfailing process. To avoid cavitation, the NPSHA and/or pressure at the inlet of the impeller, P_{in} must be greater than NPSHR.

3. Methodology

Wooden patterns were used to produce sand moulds for the impeller and the pump casing. All impellers were cast using oil-fired tilting furnace [8-10] at the foundry workshop of Mechanical Engineering, Covenant University. The following materials were used for the same design of the impeller; cast iron, bronze and zinc. The melts were then poured into sand moulds for solidification. Solidified parts were machined with Warco (Model GH-1440A) lathe (Figures 1 and 2) and milling machine to obtain required tolerance and cut out keyways respectively. The pump setup is shown in Figure 3.

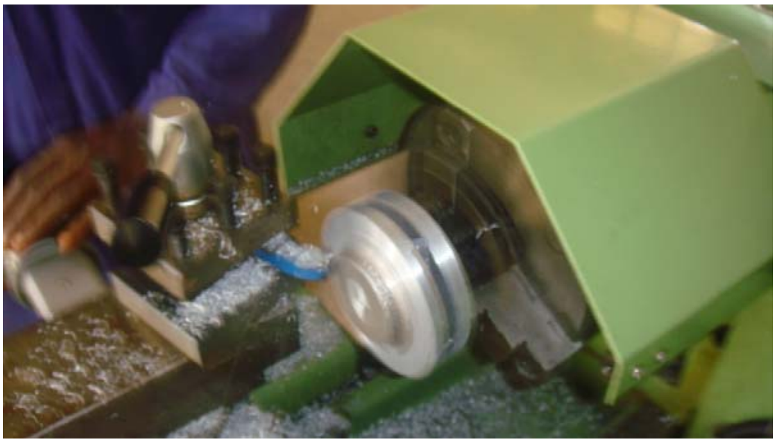

Figure 1: Impeller undergoing machining operation on the lathe machine

Figure 2: Finished Impeller

Figure 3: View of the assembled centrifugal pump

3.1 Cast iron

Cast iron has hitherto been the most extensively used material for the manufacture of pump impellers. Cast iron, however is notorious for its poor corrosion resistant property. Cast iron is a generic term that applies to high carbon-iron alloys containing silicon. These irons are extremely hard and brittle. Cast iron has a specific gravity of 7.3.

3.2 Bronze

Bronze is made from copper having tin as the major alloying element. Some industrial usage are pump impellers, water pump bushings, liquid fuel pump bushings, pump fixtures, bearings, fittings, et cetera. Machinability of bronze is above average and it could be joined using soldering and brazing techniques hence coated metal arc, gas shielded arc and oxyacetylene arc processes are not recommended for joining bronze. Bronze has a specific gravity of 8.3.

3.3 Zinc

Zinc also is known as spelter in non-scientific context. It is a metal with the symbol 'Zn' and atomic number of 30. It is brittle and hard at most temperatures aside between 100 and 150 °C when it is malleable. When temperature is higher than 210 °C, zinc lost its malleability and again becomes brittle for easy pulverization by beating. Zinc melting and boiling points are 419.44 °C and 907 °C respectively. Zinc has a specific gravity of 7.135.

Although centrifugal pumps can be selected from rating charts, performance curves give a much clearer picture of the characteristics at a given speed. Various forms of curves were generated from actual test data with a specific impeller diameter and constant speed. The measured and calculated values for flow rate, brake power, pump pressure, water power and total pump efficiency are summarized in Tables 1, 2 and 3.

Brake power of the electric motor was calculated by equation 2 below:

$$P_g = \left(GPM \times H_f \times S.G_m\right) / (3960 \times \eta) \qquad (2)$$

Where;
P_g: Brake power (W)
GPM: Flow rate in Gallons Per Minute
$S.G_m$: Specific Gravity of impeller material
H_f: Total head in feet
η : Efficiency of the electric motor

Water power was calculated using equation 3 [11] below;

$$P_c = (Q \times H_m \times \gamma \times 0.735) / 75 \qquad (3)$$

P_c: Water power (kW)

Q: Flow rate (m^3/s)
H_m: Total head (m)
γ: Density of the water (1,000 kg/m^3 at +26 ºC)

Pump efficiency was calculated using equation 4 [5] below;

$$\eta_p = {N_c}/{N_g} \qquad (4)$$

η_p is Pump efficiency
P_c is water power (kW)
P_g is brake power (kW)

Table 1: Maximum and minimum flow rate, total head and brake power for cast iron impeller

Flow rate (m^3/hr)*10^{-2}	Total head(m)	Brake Power (hp)	Water power (hp)
0	6.25	0.75	0
19	5.00	0.82	12.67
30	3.00	0.86	12.00

Table 2: Maximum and minimum flow rate, total head and brake power for the bronze impeller

Flow rate (m^3/hr)*10^{-2}	Total head(m)	Brake Power (hp)	Water power (hp)
0	8.5	1.900	0
30	7.0	2.165	28
45	5.0	2.320	30

Table 3: Maximum and minimum flow rate, total head and brake power for zinc impeller

Flow rate (m^3/hr)*10^{-2}	Total head(m)	Brake Power (hp)	Water power (hp)
0	12.0	2.500	0.00
42	9.1	3.169	50.96
55	6.5	3.388	47.67

Water at a temperature of +26 ºC was used in the experiments. Vaporization pressure (kPa), density (kg/m^3) and viscosity (m^2/s) of the water were determined, using table data, which are 0.0083 kPa, 1,000 kg/m^3 and 17.8m^2/s, respectively [12]. The centrifugal pump (electrical motor) speeds are 2500rpm while the available power in pump driver is 1hp (0.75 kW).

Manufacturing costs of the impellers, including casting and labor cost (Table 4) were calculated for bronze, zinc and cast iron (all closed type) impellers for a pump production of one unit each.

Table 4: Production cost for impellers (₦)

	Bronze impeller	Cast iron impeller	Zinc impeller
Casting	11,000	8,000	6,000
Labour	4,000	4,000	4,000
Total	15,000	12,000	10,000

All impellers were cast using the same designed mold.

Table 5: Maximum and minimum flow rate, pressure and head for each impeller

Bronze	Flowrate (m^3/h)	Pressure (mH_20)	Head (m)
Maximum	0.4500	5.0000	0.6140
Minimum	0.0000	8.4500	1.0370
Cast iron	**Flowrate (m^3/h)**	**Pressure (mH_20)**	**Head (m)**
Maximum	0.3014	3.0000	0.4110
Minimum	0.0000	6.2500	0.8570
Zinc	**Flowrate (m^3/h)**	**Pressure (mH_20)**	**Head (m)**
Maximum	0.5569	6.5000	0.9110
Minimum	0.0000	12.0000	1.6830

4. Results and Discussion

The pump characteristics, both maximum and minimum values for flow rate, pressure and head for each impeller are shown in Table 5 with the summarized results in Table 6.

Table 6: Summarized results for centrifugal pump characteristics

Impeller Type	Brake Power (hp)	Total head (m)	Flow rate (m^3/hr)*10^{-2}	Overall efficiency (%)
Cast Iron	0.860	6.25	30	46.35
Bronze	2.320	8.50	48	38.79
Zinc	3.388	12.00	65	48.24

The pump with the zinc impeller was the most efficient (48.24%) and it required the highest power (3.38hp). The cast iron impeller pumped the least head but however required the least power and was more efficient than the bronze impeller. Graphs representing pump characteristics with different impeller materials are shown in Figure 4, Figure 5 and Figure 6 below.

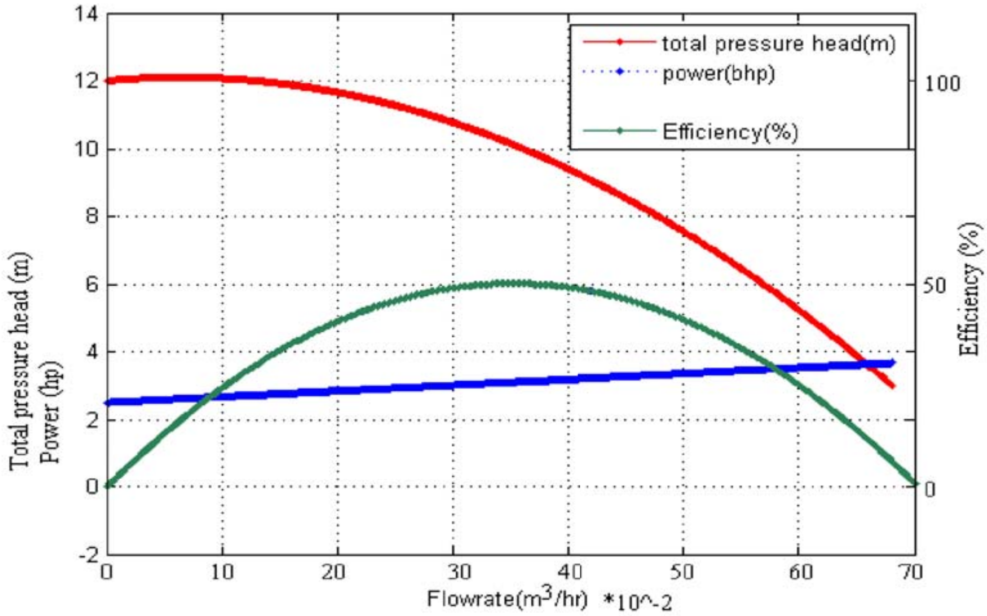

Figure 4: Pump characteristics of the zinc impeller

The zinc impeller was the least expensive to manufacture and pumped better head. The zinc impeller however failed at (very) high pump speed due to the fact that its strength could not match up with the pump speed.

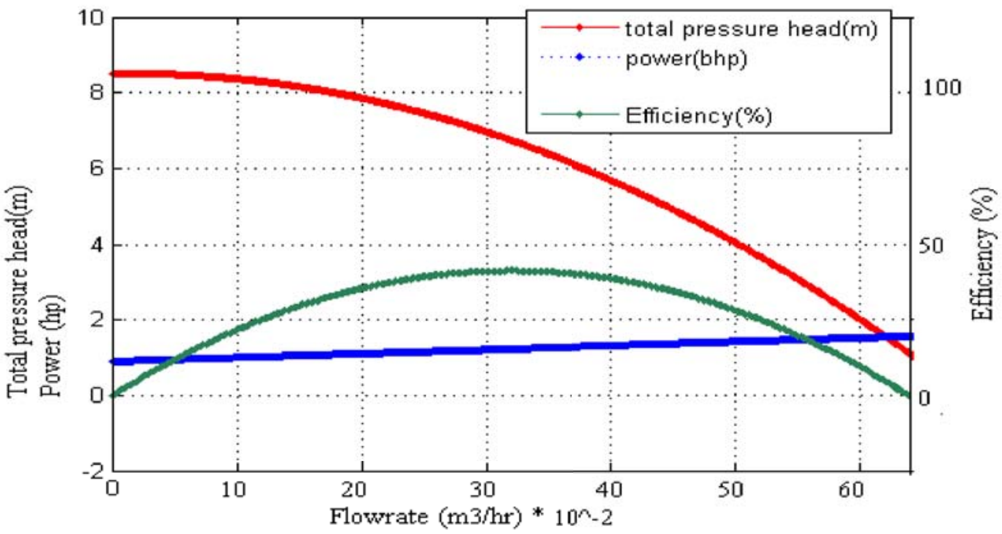

Figure 5: Pump Characteristics of the bronze impeller

The bronze impeller pump was the least efficient (38.79%), the most expensive to manufacture but pumped more head (8.50m) than the cast iron impeller and required more power (2.32hp) than the cast iron impeller. The impeller made of zinc was found to be more efficient (48.24%) with a power requirement of 3.38bhp.

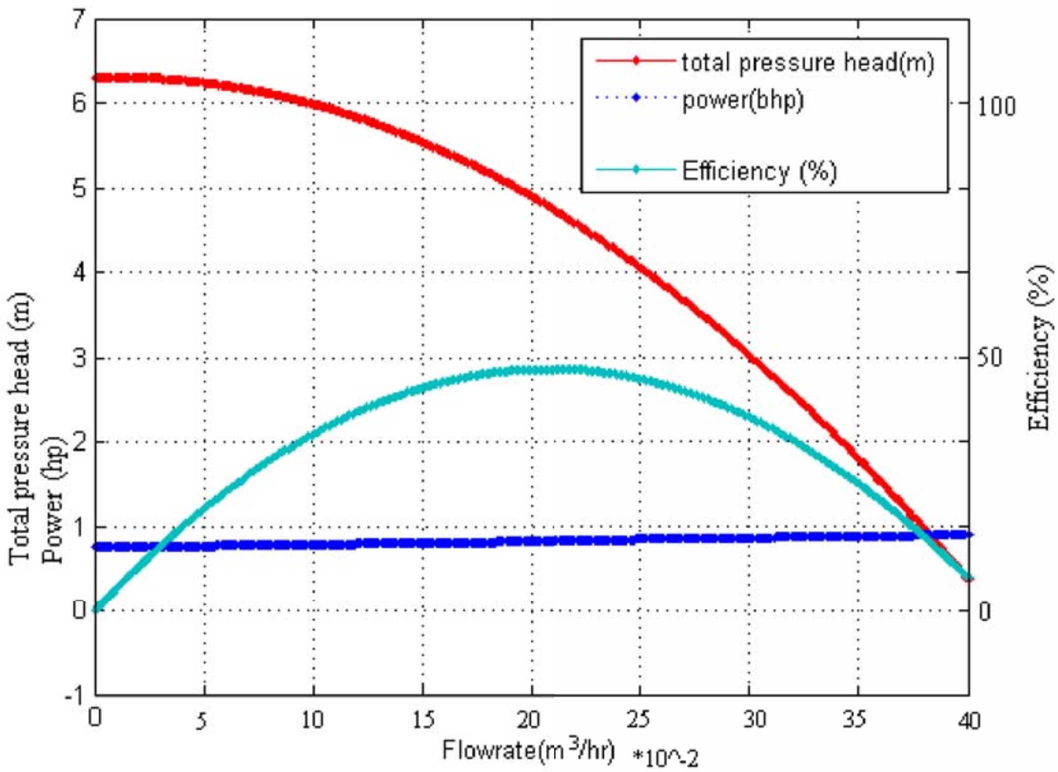

Figure 6: Pump characteristics of cast iron impeller

The cast iron impeller, on the other hand, required the least power (0.86hp) to run but pumped the least head (6.25m) and was more efficient (46.35%) than the bronze impeller; this may be due to cavitation and friction losses.

5. Conclusion and Recommendation

The following conclusions were drawn from this work:

1. Zinc was observed to be the most efficient impeller material with greater pump head and flow rate than the cast iron impeller and the bronze impeller.

2. Depending on pumping system requirement, zinc impeller is only recommended for low-speed pump speed requirements (say with the pump speed of less than 2850rpm). This is because the zinc impeller failed at very high pump speed due to the fact that the strength of the material could not withstand high speed.
3. For pumping systems with high pump speed requirements, the bronze impeller is recommended because it has greater strength of material compared to zinc.
4. Cast iron impeller was just the least performed impeller as it produced a flow rate and pressure head less than those of the bronze impeller and the zinc impeller. Initiation of corrosion was also observed in cast iron impeller.
5. From the graphs above, the zinc impeller pump required more power to pump than the bronze impeller, and the cast iron impeller required the least power to pump.
6. The bronze impeller was the most expensive to manufacture while the cast iron impeller was more expensive to manufacture than the zinc impeller.

From the results, it was observed that two of the three impeller materials stand out; zinc impeller and the cast iron impeller. The bronze impeller performed poorest; being the least efficient, most expensive and requiring more power than the cast iron impeller. Zinc impeller is therefore recommended for lower pump speed requirements due to the following two reasons:

a. zinc impeller performed best, being the most efficient of the three impellers and the least expensive to manufacture.
b. zinc impeller is recommended for low pump speeds (below 2800rpm) because it failed after 3 hours of the test because it could not withstand the torque of the shaft (2850rpm).

For higher pump speeds, an impeller made of cast iron is recommended for the following reasons;

a. The cast iron impeller required the least power to pump and had the next best efficiency rating (46.35%) to the zinc impeller, better than the bronze impeller (38.79%).
b. Cast iron as a material is stronger than zinc and so can withstand higher pump speed (above 2850rpm).

c. For cast iron to be used as impeller material, it might have to be coated with less corrosive material.

Funding: Special appreciation to Covenant University (CU) and Covenant University Centre for Research, Innovation and Discovery (CUCRID) Ota, Nigeria for funding this work.

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