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RESEARCH ARTICLE OPEN ACCESS

DYNAMIC AND HYDRAULIC PERFORMANCE OF A PERIPHERAL PUMP IMPELLER MADE OF PINEAPPLE FIBER REINFORCED BIOCOMPOSITE MATERIAL

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ABSTRACT

Pumps are machines used at industrial and domestic level for the transport of incompressible fluids, the impeller being one of its main components that directly affects its performance; usually this element is manufactured in metallic materials, but there are not enough studies on its manufacture with new materials such as biocomposites reinforced with natural fibers. For this reason, this paper presents the results of the dynamic characterization and hydraulic performance of a peripheral pump impeller made of a biocomposite material reinforced with natural pineapple fibers. The biocomposite was prepared by the hand lay-up technique using a polyester resin with pineapple fibers in random distribution. A morphological and mechanical characterization of the fabricated material was carried out to evaluate the adhesion of the fiber with the matrix and to obtain the maximum tensile stress. Experimental modal analysis according to ISO 7626-2 and ISO 7626-5 standards was used to study the dynamic behavior. The hydraulic evaluation of the impeller was carried out by obtaining the pump characteristic curves using an academic-commercial test bench. The results were compared with those of a conventional metallic impeller, and lower natural frequencies were obtained in the pineapple biocomposite material. In terms of hydraulic performance, the head, power and efficiency were lower for the pineapple biocomposite impeller

I. INTRODUCTION

Pumps are machines that convert mechanical energy into hydraulic energy of incompressible fluids and are used in both domestic and large-scale industrial applications [1].

The impeller is one of the most important elements of a hydraulic pump, and its shape, size and material directly affect its performance and efficiency [2].

The knowledge of the dynamic behavior of a pump impeller is essential for a reliable design, where the phenomenon of resonance does not occur, since during the operation of the pump it is subjected to the vibrations of the mechanical system and the disturbances of the unsteady flow [3].

Resonance is a phenomenon that occurs when one of the natural frequencies (frequency at which a body tends to vibrate once excited) of the impeller is close to an external forced frequency, such as the speed of the pump's electric motor, where intense levels of vibration are generated that can affect the normal operation of the machine [4].

The technique for identifying the natural frequencies of a body is known as modal analysis. This technique is critical to ensuring the proper and safe operation of components such as the impeller. Modal analysis makes it possible to identify the frequencies at which the impeller naturally vibrates and the modal shapes associated with those frequencies [5].

The study of dynamic effects in rotating machines, such as pumps, is becoming increasingly important due to the increase in power and speed of these devices [6], as an example, [7] performed a dynamic analysis by measuring the vibrations of a metallic impeller induced by a periodically unsteady flow in a single vane pump, obtaining the radial deflections of the impeller. Similarly, [8] measured the dynamic response of the metallic impeller of a 497.7 MW vertical pump and obtained its main natural frequencies and modal shapes.

The material used to manufacture the impellers is another important aspect as it has a direct impact on the cost, corrosion resistance, mechanical and dynamic properties of the pumps [9].

Most of the pump systems reported in the literature use traditional metallic materials in their impellers [10],[11], however, one of the current trends is the replacement by composite materials, since they can optimize the systems based on the reduction of pump weight and increased productivity, accompanied by good thermal and corrosion resistance, using faster manufacturing processes and with less material waste [12].

Natural fiber-reinforced composites are defined as materials obtained by bonding natural fibers obtained from stems, leaves, or seeds of various plant species by mechanical or chemical methods and combined with a biodegradable or synthetic matrix [13]. Their flexibility in processing, lower environmental impact and low cost make them very attractive to industry [14].

One of the fibers used in this type of materials is pineapple fiber, which is native to Brazil, but is currently cultivated in all continents, with Asia (Thailand, Philippines, Indonesia, India and China), America (Costa Rica and Brazil) and Africa (Nigeria and South Africa) being the main producers [15].

Several composite materials have been prepared with pineapple fibers [16-18], and their properties have been shown to be mainly influenced by matrix-fiber adhesion, fiber orientation, matrix type, and fiber length [19]. However, the use of these biomaterials in hydraulic industrial applications has not been demonstrated. This study presents the results of the dynamic characterization through experimental modal analysis and hydraulic behavior, obtaining the performance curves of a peripheral pump impeller made of biocomposite material reinforced with natural pineapple fiber.

II. MATERIALS AND METHODS

II.1 MATERIALS

Randomly arranged short pineapple fibers supplied by the Fibrense Foundation, Santander, Colombia, were used to reinforce the impeller.

The pineapple fibers had an average length of 1.76 ± 0.53 mm and a diameter of 9.53 ± 1.29 µm, as observed in Figure 1, obtained by SEM electron microscopy.

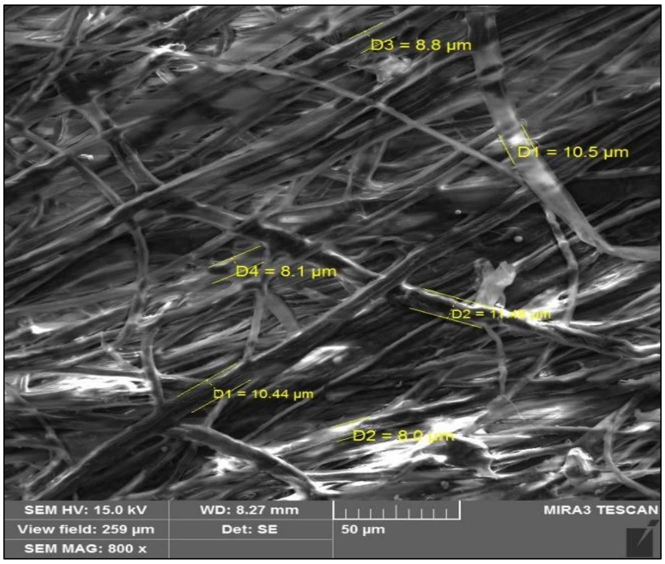

Figure 1: Micrograph of pineapple fibers in random. configuration.
Source: Authors, (2024).

The weight of each layer of pineapple fiber used to make the impeller was 0.0233 g/cm2.

A pre-accelerated polyester resin catalyzed with 2% by weight of methyl ethyl ketone peroxide (MEK peroxide) was used as the matrix of the biocomposite material. These materials were purchased from Ingequímicas, Bucaramanga, Santander, Colombia.

II.2 MECHANICAL CHARACTERIZATION

Tensile testing was performed in accordance with ASTM D3039/D3039M using an MTS universal machine, model C43.104, with a capacity of 10 KN. The test was performed at a speed of 2 mm/min and a temperature of 20°C ± 3°C.

For this purpose, five specimens of pineapple fiber biocomposite material were fabricated using the hand lay-up technique. The specimens were cured for 24 hours at room temperature.

The specimens had a pineapple fiber content of 45.3 ± 0.5% with respect to the weight of the biocomposite and a geometry of 25 cm long, 2.5 cm wide and 3 mm thick as required by the normative. Figure 2 shows the tensile test performed.

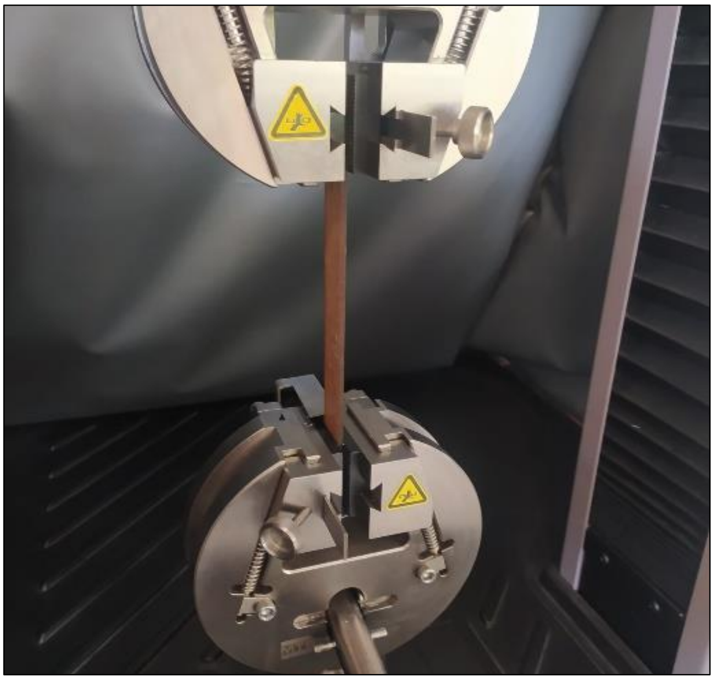

Figure 2: Tensile Test.
Source: Authors, (2024).

The mechanical results presented are the average of those obtained in the five test specimens.

II.3 MORPHOLOGICAL CHARACTERIZATION

Scanning electron microscopy was performed using a Tescan microscope, model MIRA 3 FEG-SEM, equipped with a secondary electron detector, model A65c SED, to analyze the adhesion of the pineapple fiber to the polymer matrix in the fabricated impeller.

Images were obtained between 100X and 500X and at an electron accelerating voltage of less than 10 KV. The use of an electron accelerating voltage below 10 kV was strategically chosen to minimize electron penetration and improve surface image contrast. This approach is particularly important when analyzing biodegradable composites such as pineapple fiber, where the structural integrity of the fiber and its interaction with the polymer matrix are sensitive to high voltages.

The analyzed biocomposite material extracted from the tensile test specimens was coated with a small layer of gold using a sputtering model 108 auto/SE Cressington brand in order to improve the electrical conductivity and to be able to apply the characterization technique.

II.4 IMPELLER FABRICATION

The impeller was manufactured using the "hand lay-up" process, a method in which the reinforcing layers, specifically pineapple fibers, are manually placed on a mold and then impregnated with resin. This technique was chosen because it allows precise control over the orientation and distribution of the fibers within the mold, a critical feature for parts with complex geometries such as the impeller. This precise fiber alignment is essential because it maximizes the strength and mechanical efficiency of the component, ensuring optimal performance under demanding operating conditions.

First, a conventional metal peristaltic pump impeller was molded in silicone to serve as a base for the biocomposite impeller. Figure 3 shows the mold used in the process.

Figure 3: Impeller mold.
Source: Authors, (2024).

The different layers of pineapple fiber were cut with the geometry of the impeller using a laser cutting machine, stacking 40 layers of natural fiber inside the mold, corresponding to 45.2% by weight of the biocomposite, after impregnation with polyester resin.

The material was cured for one day at room temperature, with an additional pressure of 100 psi applied to the biocomposite material inside the mold using a hydraulic cylinder to improve compaction.

Once the impeller was removed from the mold, the excess was removed using a Mototool polishing tool.

Figure 4 shows the fabricated impeller and the conventional bronze impeller used to make the mold. The latter was also used to compare the dynamic and hydraulic behavior of the pineapple impeller.

Figure 4: Fabricated impeller and conventional impeller.
Source: Authors, (2024).

II.5 DYNAMIC VIBRATION TEST

The dynamic vibration test was carried out with experimental modal analysis, obtaining frequency response (FRF) measurements according to ISO 7626-2 and ISO 7626-5. The purpose of the test was to determine the differences between the natural frequencies of the conventional metal impeller and the pineapple fiber impeller, and to determine if the pineapple fiber impeller could resonate at the pump's operating speed.

Two experimental configurations were created to evaluate the impeller, one reproducing its axial arrangement as the fluid would enter the pump, and the other measuring the response on the blades.

For the axial evaluation, excitation was applied using an electrodynamic shaker from The Modal Shop with a sinusoidal sweep covering a frequency range from 5 Hz to 3200 Hz. The excitation force was recorded with a PCB force sensor, reference 208C02, while the acceleration response was recorded with a PCB brand accelerometer, reference 352C68. Figure 5 shows the axial test setup.

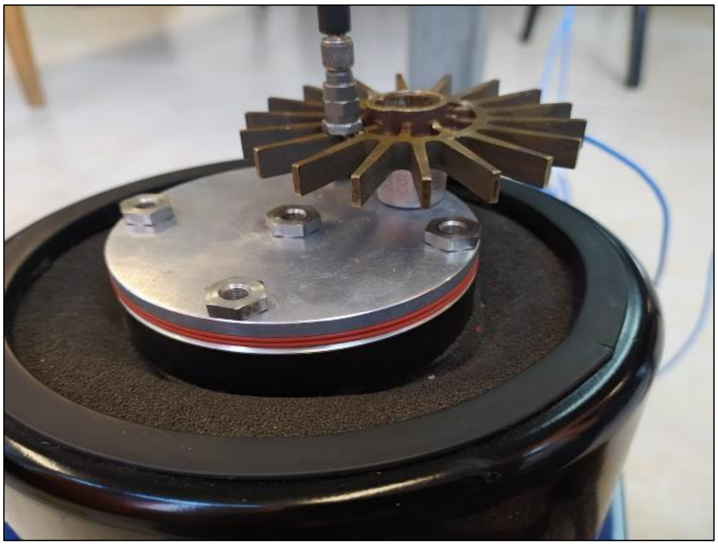

Figure 5: Axial dynamic vibration test.
Source: Authors, (2024).

A PCB accelerometer with reference number 352C68, placed on the blade itself, was used to evaluate the blade. Excitation was provided by an impact hammer from reference PCB 086C01 striking the blade. The use of the hammer was chosen for this test due to space limitations that prevented other forms of excitation. The impeller was suspended on elastic elements to simulate free motion conditions. Figure 6 shows the setup used to evaluate the dynamic response of the blades.

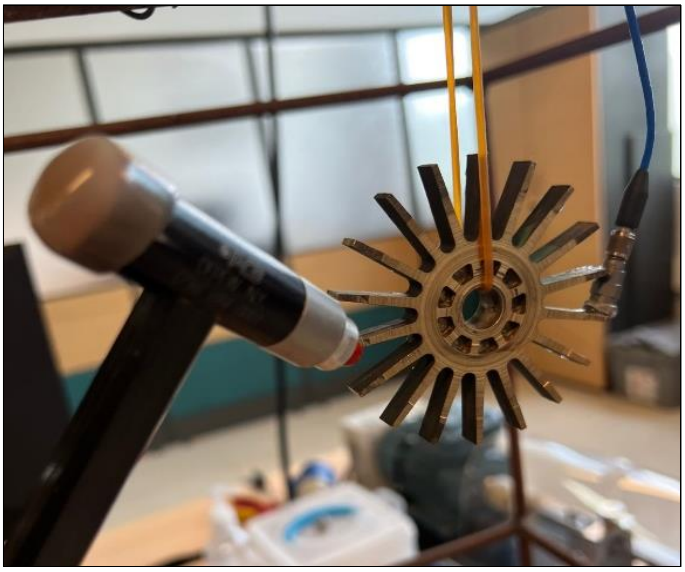

Figure 6: Dynamic vibration test on blades.
Source: Authors, (2024).

In both configurations, the acceleration response was recorded at 5 points evenly distributed over the impeller surface and blades.

II.6 PUMP CHARACTERISTICS CURVES.

The manufactured impeller was evaluated when mounted on a peripheral pump with a maximum flow of 8 l/min and a maximum head of 12 m (meters of water column). The results were compared with the original pump impeller using the Edibon PBOC multipump test bench. Figure 7 shows the test bench used.

Figure 7: Pump bench.
Source: Authors, (2024).

A capacitive level sensor was used to measure the water flow and two pressure gauges, one on the suction side and the other on the discharge side of the pump. This allowed the pump head to be determined at an operating speed of 2000 rpm according to Equation 1.

$$h_b = \frac{P2-P1}{\gamma} + Z \qquad (1)$$

Where P2 is the discharge pressure, P1 is the suction pressure, γ is the specific gravity of the water, and Z is the head difference between the pump suction and discharge.

The hydraulic power was obtained using Equation 2.

$$P_h = h_b Q\gamma \qquad (2)$$

Where Hb is the manometric head of the pump, Q is the flow rate, and γ is the specific gravity of the water.

The pump efficiency was determined using Equation 3.

$$n\% = \frac{P_h}{P_f} = \frac{h_b Q\gamma}{\omega T} \qquad (3)$$

Where Ph is the hydraulic power, Pf is the mechanical power, ω is the shaft angular velocity and T is the torque.

III. RESULTS AND DISCUSSIONS

III.1 MECHANICAL CHARACTERIZATION

Figure 8 shows the stress-strain curve corresponding to the pineapple fiber reinforced biocomposite material. This material exhibits a behavior characterized by a non-linear relationship between the applied stress and the resulting strain.

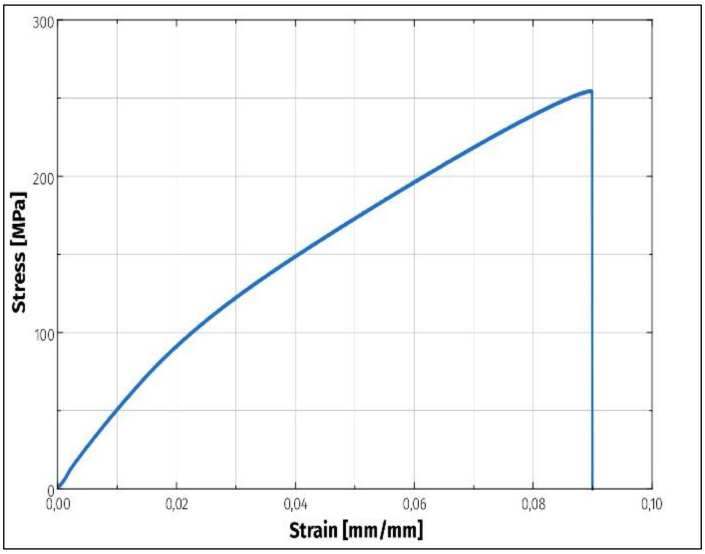

Figure 8: Stress-strain curve.
Source: Authors, (2024).

The maximum tensile stress recorded was 254.4 ± 7.32 MPa, while the Young's modulus was 5.04 ± 1.01 GPa. These results are consistent with the mechanical results reported by [20] in their review of pineapple fiber composites.

It is important to note that the tensile stress is closely related to several factors, such as the amount and orientation of the fibers, the interfacial adhesion between the fiber and the matrix, as well as the manufacturing method used [21].

III.2 MORPHOLOGICAL CHARACTERIZATION

Figures 9 and 10 show the micrographs of the biocomposite at different magnifications. The presence of gaps between the fiber components and the matrix can be observed, indicating low adhesion. This phenomenon is attributed to the hydrophobic nature of the matrix and the hydrophilic properties of the fibers [22].

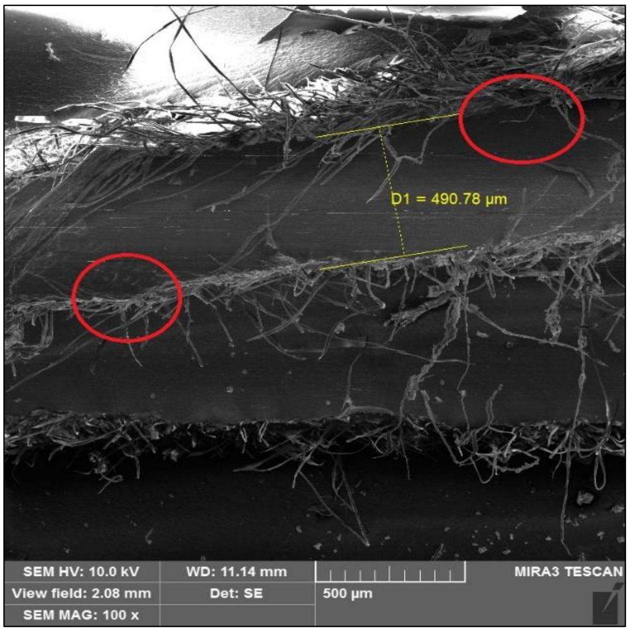

Figure 9: 100X biomaterial micrograph.
Source: Authors, (2024).

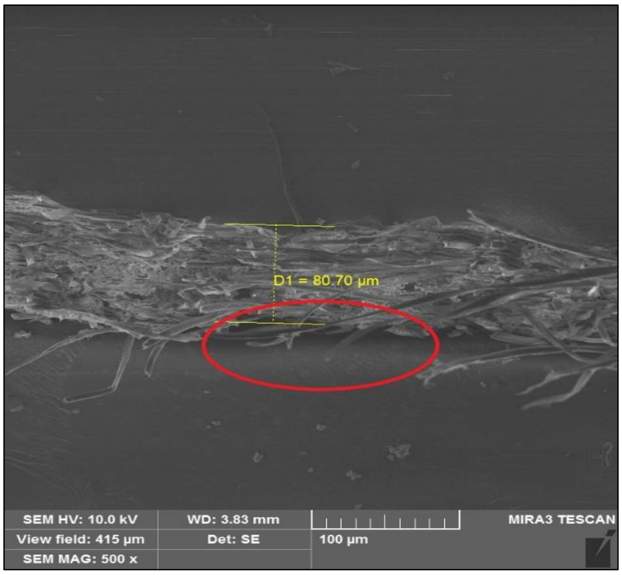

Figure 10: 500X Biomaterial Micrograph.
Source: Authors, (2024).

This low adhesion affected the mechanical and dynamic properties of the biocomposite due to the low load transfer between the resin and the fiber.

III.3 DYNAMIC VIBRATION TEST

The natural frequencies of the biocomposite impeller and the conventional metal impeller, both in the axial configuration and in the blade evaluation, were identified by means of the peaks in the frequency response function (FRF) obtained from the experimental modal analysis (see Figures 11 and 12).

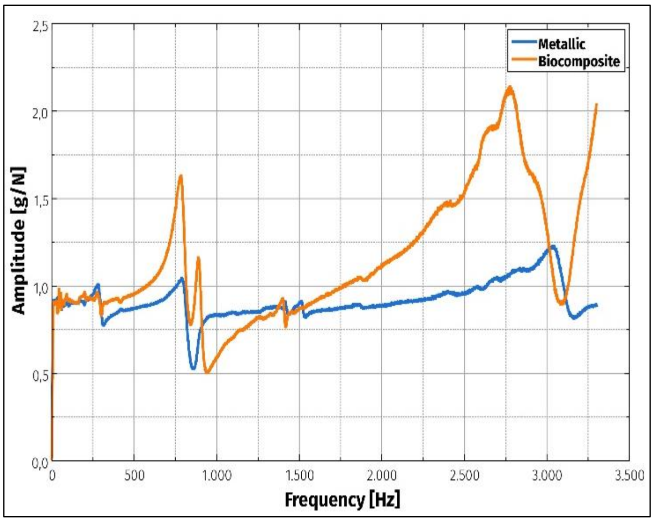

Figure 11: FRF axial configuration.
Source: Authors, (2024).

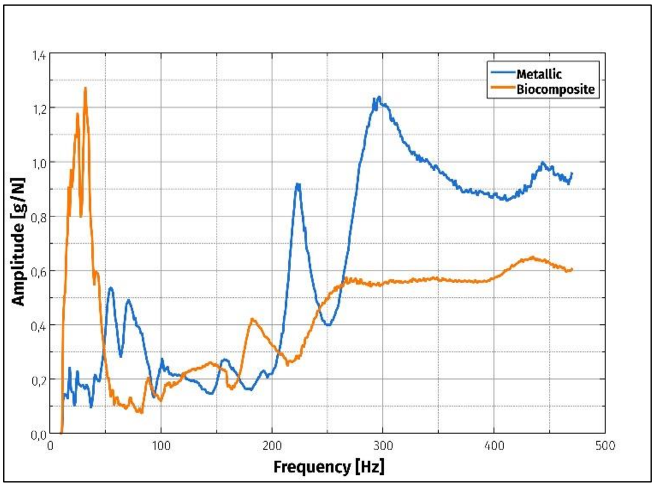

Figure 12: FRF blade configuration.
Source: Authors, (2024).

As can be seen in Figures 11 and 12, the curves of the biocomposite and the metallic material have a similar structure. This is due to the fact that the dynamic behavior of a part is largely related to its geometry [23], being the same for both impellers.

However, as far as the natural frequencies are concerned, lower values were obtained in the biocomposite material than in the metallic one, as can be seen in Table 1.

Table 1: Natural frequencies of materials.

Configuration	Modes	Natural frequency [Hz]	
		Biocomposite	Metallic
Axial	Mode 1	280 ± 2.5	284 ± 3.7
	Mode 2	782 ± 5.2	797 ± 2.1
	Mode 3	1401 ± 14.2	1518 ± 8.7
	Mode 4	2777 ± 22.1	3053 ± 12.1
Blade	Mode 1	25 ± 4.6	55 ± 2.1
	Mode 2	32 ± 5.1	73 ± 3.1
	Mode 3	181 ± 7.8	224 ± 5.7
	Mode 4	256 ± 9.1	295 ± 8.1

Source: Authors, (2024).

The observed difference is attributed to the stiffness, which is lower in natural fiber reinforced composites than in metals, as reported by Pickering et al. [24] and supported by the experimental data obtained in section III.1. This property has a direct effect on the natural frequencies of the material, as pointed out by [25], since stiffness affects the ability of the body to resist deformation under load. Lower stiffness allows for greater flexibility and ease of deformation of the body, resulting in a reduction in natural frequencies. The values obtained for the natural frequency of the blades in the biocomposite material are very close to the operating frequency of the pump (2000 rpm, 33.3 Hz), which can cause resonance in the blades. This phenomenon can have adverse effects on the operation and structural integrity of the pump, including excessive vibration, premature wear, and even catastrophic failure.

III.4 PUMP CHARACTERISTICS CURVES.

Figure 13 shows the variation of pump head versus flow rate for both types of impellers, which show a linear decreasing behavior. The slopes of the material curves are practically identical, which is due to the similar design and geometry of the impellers.

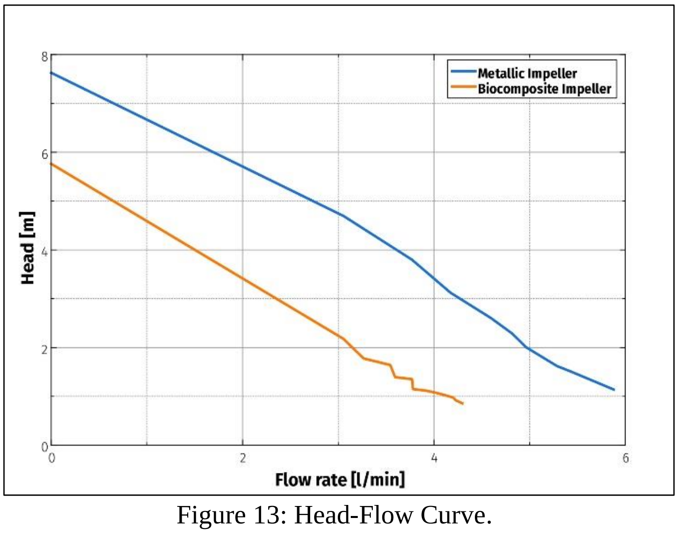

Figure 13: Head-Flow Curve.
Source: Authors, (2024).

However, at the same flow rate, the impeller made of pineapple fiber biocomposite was found to have 40% to 50% lower head. This discrepancy is attributed to their lower stiffness, which allows them to deform more easily under load. This results in additional energy losses due to friction and turbulence in the fluid flow. In addition, their tendency to resonate contributes to less stable operation. Figure 14 compares the hydraulic power of the pump with the two impellers as a function of flow rate.

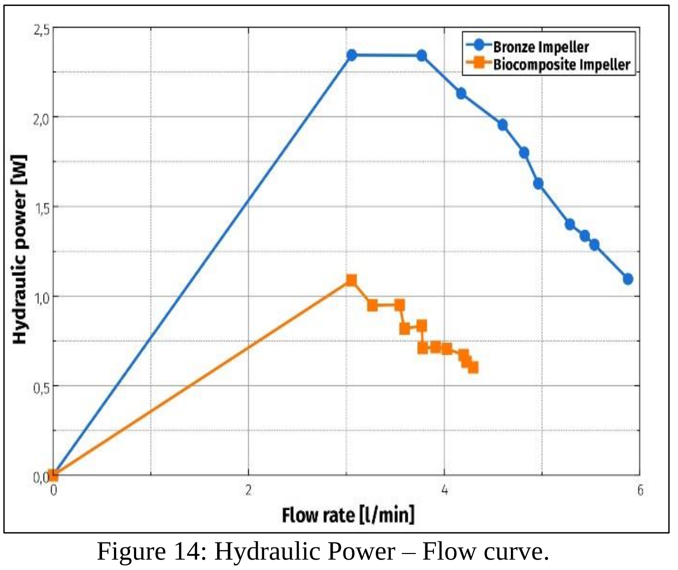

Figure 14: Hydraulic Power – Flow curve.
Source: Authors, (2024).

The metal impeller pump produced more power than the biocomposite impeller pump. This power advantage is clearly due to the ability of the metallic material to generate a higher head at the same flow rate. The maximum power output of the metallic impeller was 2.35W compared to 1.088W for the biocomposite.

The efficiency comparison of the two impellers is shown in Figure 15 and it is observed that the biocomposite impeller was less efficient than the conventional metallic impeller.

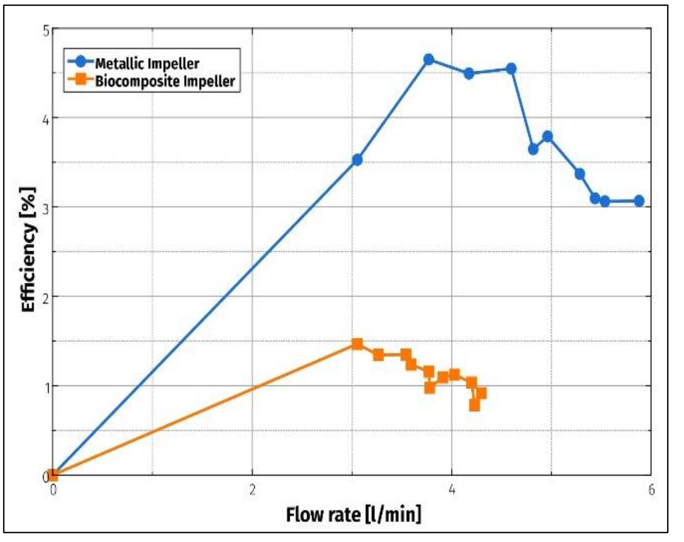

Figure 15: Efficiency - flow curve.
Source: Authors, (2024).

The metal impeller reached its maximum efficiency at a flow rate of approximately 3.77 l/min, with an efficiency value of 4.65%, while the biocomposite impeller reached it at 3.05 l/min, with a maximum efficiency value of 1.47%. This difference is attributed to a lower hydraulic head of the biocomposite impeller. In addition, as noted by Cao et al. [2], impeller manufacturing and installation tolerances can also have a significant impact on this parameter.

IV. CONCLUSIONS

The fabrication of a peripheral pump impeller using pineapple fiber reinforced biocomposite material was carried out, highlighting the potential and feasibility of exploring sustainable alternatives in engineering and industrial applications. Mechanical characterization of the biocomposite material revealed a tensile stress of 254 MPa and a modulus of 5.04 GPa. Scanning electron microscopy (SEM) revealed limited adhesion between matrix and fibers in the pineapple biocomposite material. This phenomenon is attributed to the hydrophobic nature of the matrix and the hydrophilic properties of the fibers, resulting in a decrease in load transfer from the resin to the fibers, which directly affects the stiffness of the material. When comparing the dynamic properties, especially the natural frequencies, of the pineapple biocomposite impeller and the metallic impeller, a decrease in the natural frequencies of the biocomposite material was observed. In addition, the natural frequencies of the blades in the biocomposite material are close to the operating frequency of the pump, raising the possibility of the resonance phenomenon. The impeller made of biocomposite material reinforced with pineapple fibers showed a lower hydraulic response compared to the impeller made of conventional material, mainly due to lower stiffness. This reduction in stiffness results in a loss of efficiency in the transfer of energy from the motor to the pumped fluid. In addition, the impeller resonates with the operating frequencies of the pump, resulting in excessive vibration.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Sergio Andrés Gómez.
Methodology: Sergio Andrés Gómez.
Investigation: Sergio Andrés Gómez, Alfonso Santos Jaimes and Edwin Cordoba Tuta
Discussion of results: Sergio Andrés Gómez, Alfonso Santos Jaimes and Edwin Cordoba Tuta
Writing – Original Draft: Sergio Andrés Gómez, Alfonso Santos Jaimes and Edwin Cordoba Tuta
Writing – Review and Editing: Sergio Andrés Gómez, Alfonso Santos Jaimes and Edwin Cordoba Tuta
Supervision: Sergio Andrés Gómez, Alfonso Santos Jaimes and Edwin Cordoba Tuta
Approval of the final text: Sergio Andrés Gómez, Alfonso Santos Jaimes and Edwin Cordoba Tuta

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