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Experimental and FEM Vibration Analysis of Impellers used for Water Pump

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ABSTRACT

The impeller is an essential component of the water pump. Vibrations of the impeller have a significant effect on the pump's performance, as well as posing some damaging effects. In this study, the vibration of three different types of impellers for water pumps (brass, bronze, and plastic) was evaluated experimentally and compared with computational finite element method (FEM). A number of variables includes temperature, flow rate, impeller material composition, and the chemical composition of water been studied. The findings indicated that vibration issues increased as flow rate increased. The plastic impeller has the highest vibration rate compared to brass and bronze impellers under the identical testing conditions. The vibration rate of impellers tested in seawater is higher than that them tested in tap water. Increasing the temperature of the water accelerates the vibration process. Cavitation occurs in seawater at a lesser Net Positive Suction Head (NPSH) than in tap water.

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1. INTRODUCTION

Pumps are devices that move fluids mechanically usually by converting electrical energy into hydraulic energy [1]. An impeller is a component of a pump that rotates at high speeds and act as propellers to raise the pressure and flow of fluids [2]. Impellers are made of various types of materials, the most popular of which are brass, bronze and plastic. Brass is a metal alloy consisting primarily of copper and zinc, while bronze is a metal alloy composed primarily of copper with tin as the main additive, but also containing manganese, arsenic, iron, and silicon [3]. Plastic impellers are less costly, offer a wide range of chemical resistance and lighter in comparison to metal impeller types.

There is a widespread use of pumps in Iraqi cities for lifting water from reservoirs to storage tanks. Among the most serious problems associated with water pumps is impeller vibration which reduces pump life, pumping power, and affecting the pump's stability [4]. A variety of factors affect impeller vibration, including bent shaft, unbalance, reaction force, cavitation, flow rate, pressure, temperature, liquid properties, and the type of materials used in impeller manufacturing. The most common problem affecting impeller pumps vibration is the cavitation phenomenon. The use of net positive section head (NPSH) is one way to detect water pump cavitation. The NPSH is a measure of the pressure experienced by water on the suction side of a water pump. It is used to avoid running a pump under certain conditions that could cause cavitation formation [5].

There have been several studies and publications relating to vibration problems or the performance of impeller materials used in water pumps. Birajdar et al. [6] outlined several general causes and sources of centrifugal pump vibrations. An explanation is given of how vibration in centrifugal pumps can be diagnosed and how its remedies can be determined. Tang et al. [7] used a three dimensional finite element method to analyze the large plastic impeller. As well as given working conditions and structure parameters of plastic impellers, they discovered the major causes of broken plastic impellers in water pumps. Albraik et al. [8] demonstrated that the root of vibration in the pump could be caused by hydrodynamic motion, i.e., fluid flow disruption is a typical cause of hydrodynamic vibration. Muhammad et al. [9] studied centrifugal pump impeller vibration, natural frequency, and mode shapes using the finite element method. Researchers discovered that changing the number of impeller blades had a slight effect on natural frequencies, while changing the thickness of the impeller had a significant effect. Rakibuzzaman et al. [10] applied computational fluid dynamics to study cavitation in centrifugal pumps. At different flow operating conditions, they plot NPSH characteristic curves and a relationship has been found between cavitation incipient and NPSH curve. Wei et al. [11] studied the vibration issues of the pump impeller under mixed-flow fluid contact using experimental and the finite element technique. They demonstrated that the impeller's deformation and the blade's stress distributions had a significant impact on the impeller blade's typical vibration level. Jiaxing et al. [12] Utilizing both a computational model and an experimental technique examined the vibration characteristics and instabilities brought on by the emergence of cavitation in a centrifugal pump. Their findings showed that the abrupt rise in vibration intensity at the testing spots might be used to detect the onset and progression of cavitation. Baoling et al. [13] used computational and experimental methods to examine the centrifugal pump's impeller vibration. They demonstrated how impeller vibration is one of the key issues that must be taken into account throughout the design and production of the pump.

In this paper, vibration analysis was performed using FEM and experimentation on three different types of materials used in impellers for water pumps in order to reduce vibrations, improve pump performance and determine what type of impeller materials is suitable for both tap and Arab Gulf seawater. A cavitation rig test is collected in the laboratory and performed to evaluate all factors affecting cavitation within a test tap and Arab Gulf seawater, and this permits to determine how various operating conditions impact impeller vibration.

2. RESEARCH METHOD

2.1 MATERIALS AND SPECIMEN FOR TESTING

Figure 1 a, b and c show the brass, bronze and plastic impeller specimens have double section. Brass impeller is 60 mm in diameter, 36 blades, 8 mm thick, and weighs 100 gm. This type of impeller is manufactured by Shubham Industries, Gujarat, India. The bronze impeller have a diameter 60 mm, 5 blade, a thickness of 12 mm and weight 200 gm is manufactured by India button factory, Gujarat, India. The plastic impeller of closed form has 61 mm outside diameter, 10 mm thickness, and 40 gm weight. The main constituents of the brass and bronze impeller are analyzed in a laboratory using a 210/211VGP atomic absorption spectrophotometer and the results are illustrated in Table 1 and Table 2 respectively. The plastic impeller was made from polypropylene manufactured by Hebei Jiangzhi Machinery Equipment Co., Ltd., India.


a) Brass impeller specimen


b) Bronze impeller specimen


c) Plastic impeller specimen

Figure 1. Impeller specimens

Table 1. The material constituents of impeller brass specimen

Elements	Cu	Al	Fe	Pb	Ni	Mn	Si	Zn
wt. %	balance	0.8	0.7	0.9	1	0.2	0.05	15

Table 2. The material constituents of impeller Bronze specimen

Elements	Cu	Pb	Fe	P	Mn	Sn	Zn
wt. %	balance	0.05	0.1	0.2	0.3	12	0.3

2.2 APPARATUS AND VIBRATION MEASUREMENT

Vibration is the periodic or cyclic movement over time of an object around a center static position. Measurements of vibration in the apparatus can be made in terms of displacement, velocity, acceleration, and frequency. Additionally, each of these parameters may be quantified in the time domain in a variety of ways, including peak to peak, peak, average ratio, and RMS level [14]. The digital vibration meter (vibrometer) model Graigar AV-160B digital portable vibration was used as shown in Figure 3. Three vibration parameters may be measured by this type of vibrometer: displacement, velocity, and acceleration. Because it can sustain operation temperatures of up to 50oC, this kind is employed. By placing vibration sensors on the surface of the volute along the radial route of the impellers, the vibration parameters of the impellers undergoing testing may be determined. Tests were conducted using the home electric water pump model TM 40, which is depicted in Figure 4 and has the characteristics listed in Table 3. This kind of water pumps is commonly and widely used in Iraq.

Figure 3. AV-160B digital portable vibration

Figure 4. Electric water pump model TM 40

Table 3. Electric water pump model TM 40 properties

Power	0.5 HP (370 W)
Voltage	220-240 V
Speed	2850 RPM
Head	35 m
Flow	35 l/min max
Input and output pipe diameter	0.75 inch (1.9 cm)

A method to regulate the flow rate to a pump is throttling the water intake by opening and closing a valve at the pump’s inlet pipe. A flow rate gauge is installed at the pipe that leads to the pump, and a second one is installed at the discharge pipe to measure the amount of flow rate entering and exiting the pump. For conducting a test to measure amplitudes, acceleration and velocity of vibration of impellers, the pump drawing water from the lower main tank and pumping it through the delivery pipeline to a tank located at an altitude of 30 m.

The seawater used in test is gained from Arabian Gulf southern Iraq. Using a pH-meter, the seawater's pH was measured, and the average reading was 8.1, while the value of the total dissolved solids, i.e., TDS was determine experimentally and has a value of 42.5 g/l. The utilized tap water has a pH of 7.3 and a TDS of 590 mg/l.

2.3 CAVITATION TEST RIG

To avoid cavitation in centrifugal pumps, the pressure of the fluid at all points within the pump must remain above saturation pressure. The quantity used to determine if the pressure of the liquid being pumped is adequate to avoid cavitation is the net positive suction head (NPSH). The net positive suction head is the difference between the pressure at the suction of the pump and the saturation pressure for the liquid being pumped. Cavitation test rigs can be designed in a variety of ways. Introducing cavitation into a pump system is one of the most important features of any test rig [15]. According to a schematic diagram shown in Figure 5, a closed loop configuration was selected for this research. It consists of a centrifugal pump driven by a DC current motor, pressure measuring devices, a flow orifice meter, a speed control unit, suction and delivery pipelines, and valves. Control valves and connecting pipes are connected with plastic connections with a diameter of 1 in. Suction lines are composed of tubes connected to valves that control flow rates and pressure gauges. A nozzle valve is located at the end. In the discharge line, there is a valve that controls the flow rate, as well as a connection pressure gauge and an orifice meter that measure it.

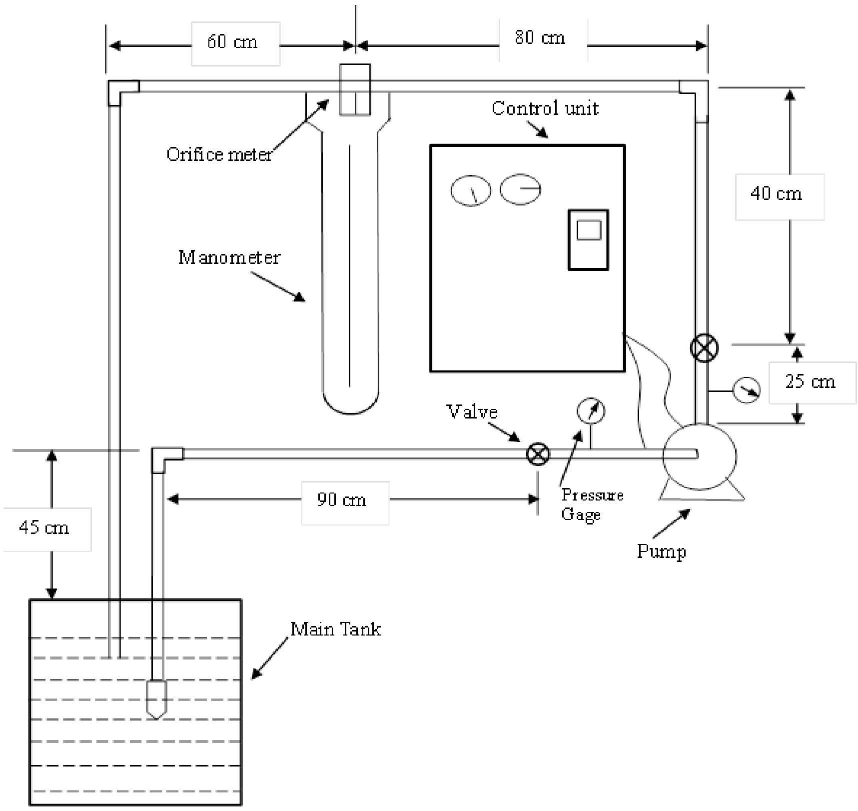


Figure 5. A schematic diagram of cavitation test rig

The net positive suction head (NPSH) can be defined as:

$$NPSH = \frac{p_s}{\gamma_s} + \frac{v_s^2}{2g} - \frac{p_v}{\gamma_v} \quad (1)$$

Where,
p_v = vapor pressure (m, in).
γ_v = specific weight of the vapor.
p_s = static pressure in the fluid close to the impeller Pa (N/m^2).
γ_s = specific weight of the liquid.
v_s = velocity of fluid (m/s)
g = acceleration of gravity (9.81 m/s^2)

We conducted the cavitation test on the pump by running it at the required speed and flow rate ratio, then reducing the inlet pressure step by step until we reached the inception condition. The delivery valve was used to regulate the flow rate at each step, and the inlet pressure was then further decreased until developed cavitation and fall off in the head were apparent. Orifice meter was utilized for measuring the flow rate.

2.4 FINITE ELEMENT ANALYSIS (FEM)

For the purpose of identifying displacements, vibration velocity, and acceleration, a FEA modal analysis of the impeller pump was performed. The analysis was performed to determine the high amplitude (displacement) by the FEM model. The pipe connections, casing, bearing, and motor coupling were not taken into account while analyzing the impeller pump since their effect on the analysis was minimal. Table 4 lists the impeller materials that were employed for the analyses and are regarded as isotropic materials.

The finite element method for three dimensional (3D) of impeller analysis is used to solve the following differential equation [19, 20]:

$$M\,\ddot{u}(t) + C\,\dot{u}(t) + K\,u(t) = F(t) \quad (2)$$

And,

$$F(t) = F_i(t) + F_s(t) \quad (3)$$

Where,
M: a system of n * n order mass matrix.
C: a system of n * n order damping matrix.
K: is n * n order stiffness matrix for the system.
$\ddot{u}(t)$, $\dot{u}(t)$ and u(t): the acceleration, velocity and displacement response of the system order n column respectively.
F(t): a column vector of n order load.
F_i (t): inertia force vector quantity.
F_s (t): elastic force vector quantity.

A damping matrix is proportional to system's mass and stiffness matrices and given as:

$$C = \alpha \bar{M} + \beta \bar{K} \quad (4)$$

Where,
α and β are damping coefficient.

Table 4. Brass, bronze and plastic impeller properties [16, 17, 18]

Materials	Properties					
	Density (Kg/m^3)	Young modulus (Gpa)	Poisons ratio	Yield stress (Mpa)	Tensile stress (Mpa)	Porosity %
Brass	8.53	102	0.35	310	450	30
Bronze	8.7	96	0.34	125	240	36
Plastic	1.20	2.2	0.38	31	45	40

Figure 6 a and b depicts the impeller pump's meshing mode for the brass, bronze, and plastic types. ANSYS R15.0 FEA software is used to create the impeller specimen's three-dimensional finite element mesh. Six nodes uniform triangular element (prism) were employed for FEM analysis as shown in Figure 6 c. These sorts of elements are employed because impellers are thick structures and have a constant thickness [21]. Each element has 3 degree of freedom (dof) at each node. Primary employed 1500 solid element for analysis, and then the finite element mesh is increased to a total of 2000 elements for a results convergence.

Boundary conditions are applied to the impellers after effective meshing achieved. In computational finite element analysis, the following boundary conditions are applied:

- Rotational velocity:

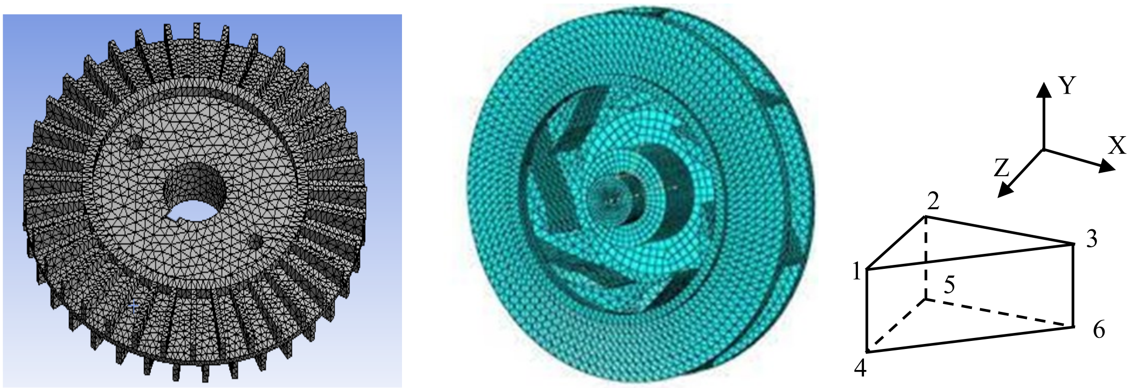
1. Rotational Velocity is given in direction of Z axis,
2. Rotational velocity of 150 rad/s (1500 rpm).

- Displacement:

1. X -Y component - free
2. By putting a cylindrical support in the impeller center, it was constrained, Z component 0 mm.

- Temperature, pressure and flow rate

1. Temperature of 25°C.
2. The pressure of 2 bars was applied to the impeller's surface and blades on both sides.
3. Flow rate of 35 l/min.



a) Brass impeller b) Plastic and bronze impellers c) 6- nodes tranguler elenents

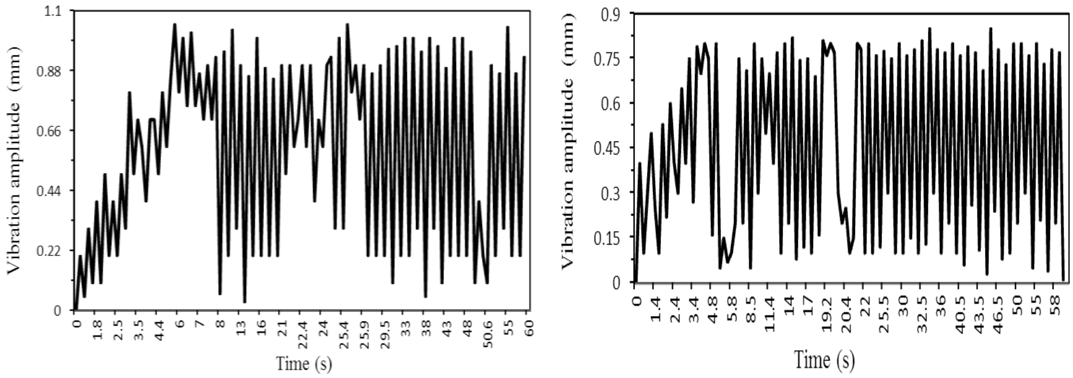
Figure 6. FEA meshes of water pump impellers and triangular element shape

3. RESULTS AND DISCUSSIONS

Based on experiments and finite element simulations, Figures. 7, 8, 9, 10, 11 and 12 illustrate the distribution of vibration amplitude in (mm) vs. time (s) for brass, bronze and plastic impellers in sea and tap water at flow rate 35 l/min and temperature 25ºC. As you can see from Figures 7-12, the values of maximum vibration amplitude of plastic impeller obtained from experimental method tested in sea and tap water are 1.48 and 1.34 mm respectively, while the values obtained from FEM are 1.43 and 1.25 mm respectively. The values of maximum vibration amplitude of brass impeller obtained from experimental method tested in sea and tap water are 1.05 and 0.81 mm respectively, while the values obtained from FEM are 0.93 and 0.77 mm respectively. The values of maximum vibration amplitude of bronze impeller obtained from experimental method tested in sea and tap water are 0.49 and 0.44 mm respectively, while the values obtained from FEM are 0.45 and 0.41 mm respectively.

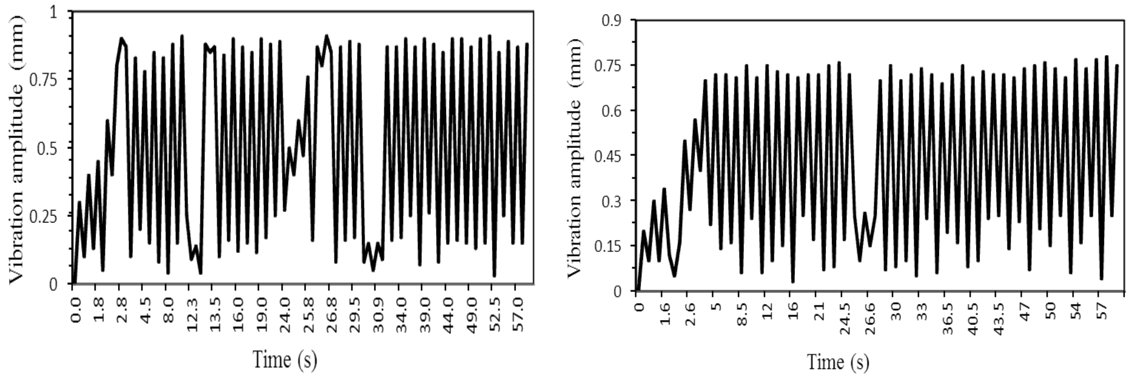
Tthe amplitudes of vibration obtained by the experimental method are larger than those obtained by the FEM. This attributed to various factors, some of them related to difficulties in measurement of vibration amplitudes during test, and others to the instrumental and random errors. Also, the FEM is an approximation method and calculation results are based on idealized state and depend on boundary conditions applied.

According to the results of tests conducted in sea and tap water, plastic impellers exhibit greater vibration amplitudes than brass and bronze impellers. The reason for this can be attributed to a variety of factors related to material properties, especially porosity and density. In Table 4, it can be seen that the density of the plastic impeller is much lower than the density of brass and bronze, i.e. the density is 1.2, 8.53, 8.7 g/cm3 respectively, while the porosity is greater, i.e., 40%, 30% and 36% respectively. The density of bronze impeller material is higher than that of brass impeller. Frequency displacement values are inversely proportional to mass density [22, 23, 24]. It was important to note that the frequencies displacements were highly sensitive for small values of mass density. A bronze is more brittle material in comparison to brass and plastic materials and it has a lower modulus of elasticity as given in Table 4. The elastic modulus and damping capacity (the ability to absorb vibration) have an inverse relationship, i.e. decreasing elastic modulus results in greater damping capacity [25]. It appears that the impeller material composition and properties impact damping capacity, and bronze impellers are less likely to be affected by vibration compared with brass and plastic impellers. On the other hand, porosity directly proportional with vibration process, i.e. increasing porosity of impeller material leads to increase the vibration amplitude [26].



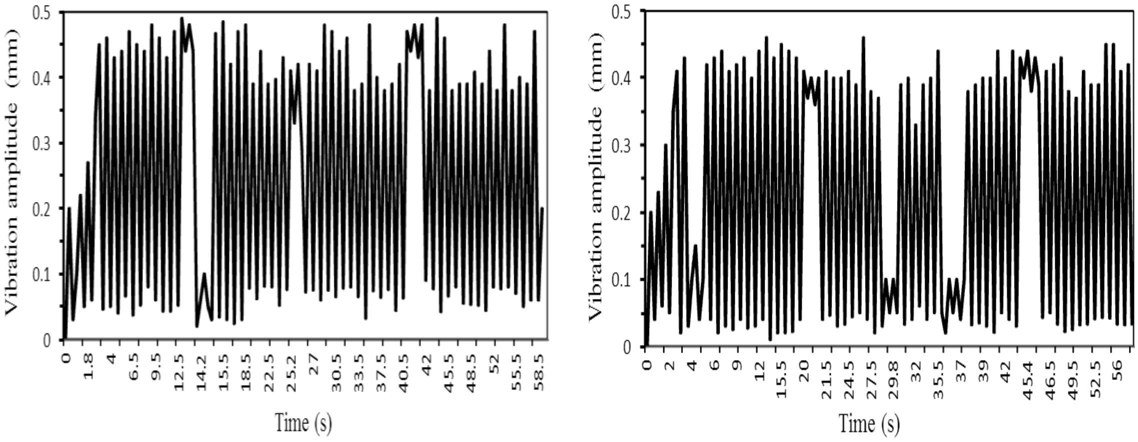
a) Brass impeller tested in seawater b) Brass impeller tested in tap water

Figure 7. Vibration amplitude (mm) vs. time (s) at 35 l/min and 25ºC obtained from experimental work.



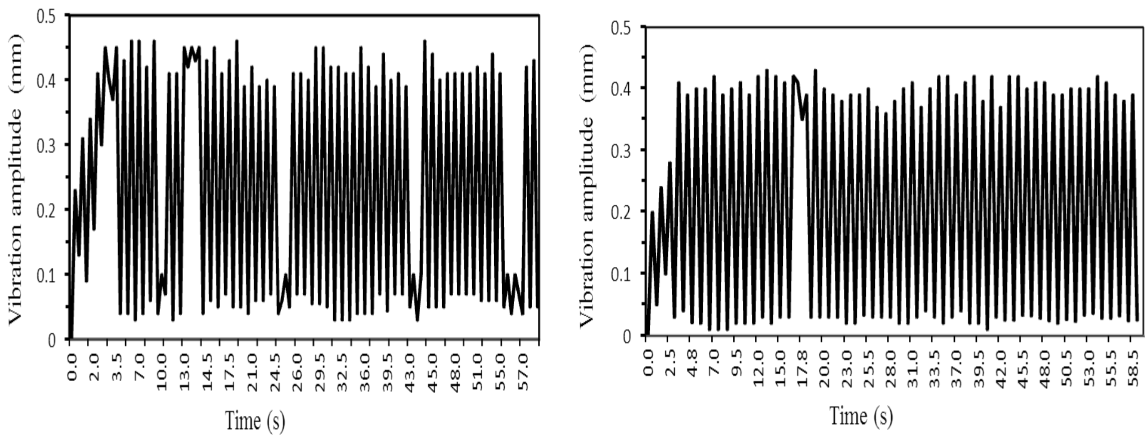
a) Brass impeller tested in seawater b) Brass impeller tested in tap water

Figure 8. Vibration amplitude (mm) vs. time (s) at flow rate 35 l/min and 25°C obtained from FEM.



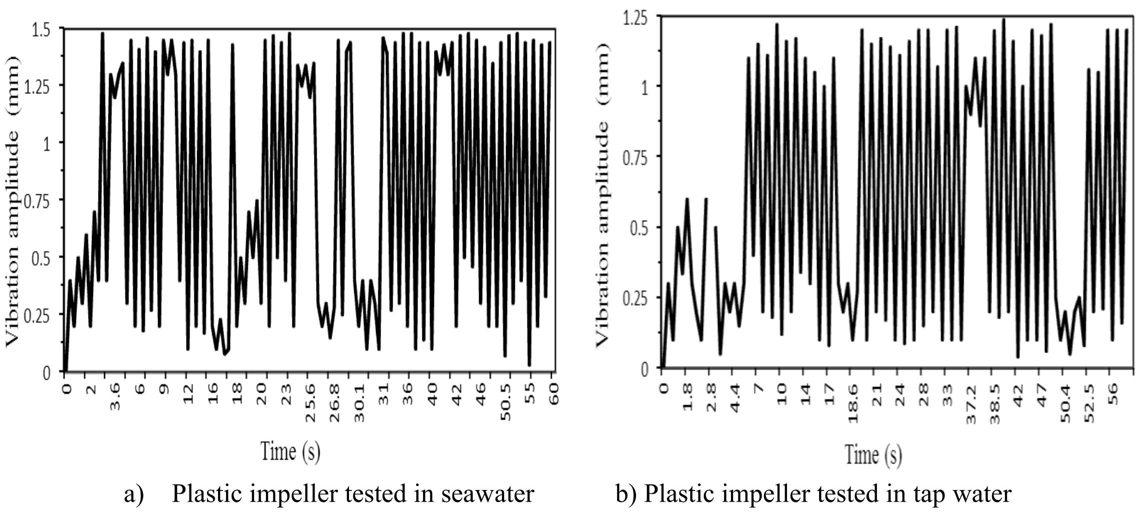
a) Bronze impeller tested in seawater b) Bronze impeller tested in tap water

Figure 9. Vibration amplitude (mm) vs. time (s) at flow rate 35 l/min and 25°C obtained from experimental measurement



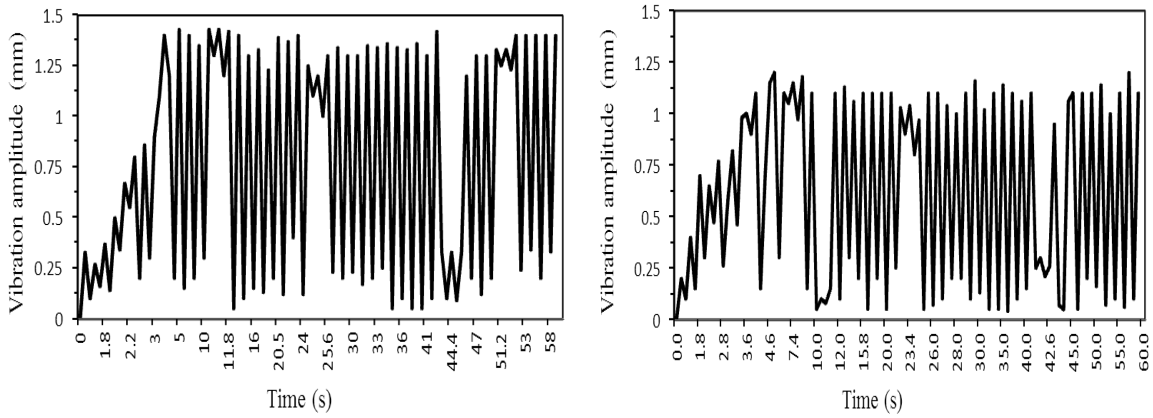
a) Bronze impeller tested in seawater b) Bronze impeller tested in tap water

Figure 10. Vibration amplitude (mm) vs. time (s) at flow rate 35 l/min and 25°C obtained from FEM.



a) Plastic impeller tested in seawater b) Plastic impeller tested in tap water

Figure 11. Vibration amplitude (mm) vs. time (s) at flow rate 35 l/min and 25°C obtained from experimental measurement

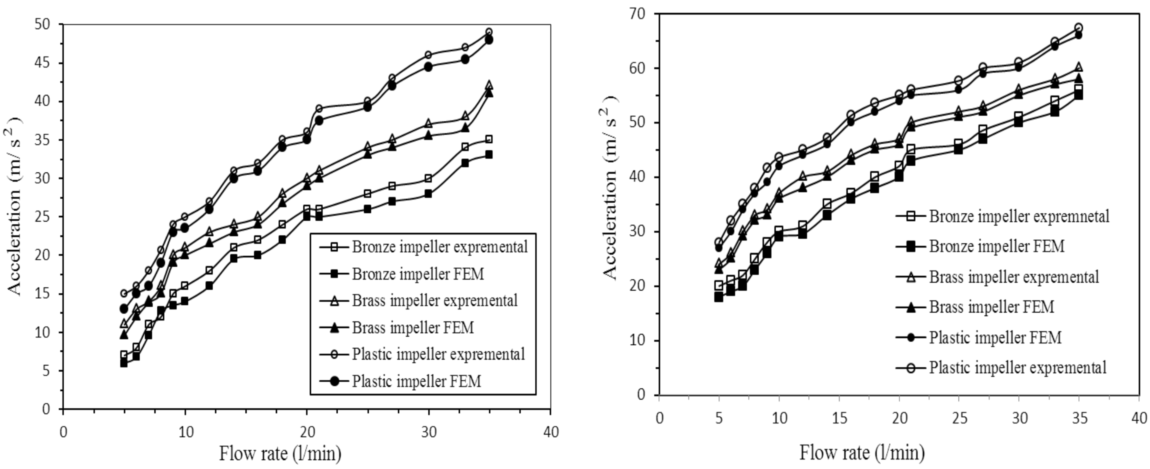


a) Plastic impeller tested in seawater b) Plastic impeller tested in tap water

Figure 12. Vibration amplitude vs. time (s) at flow rate 35 l/min and 25^{o}C obtained from FEM.

Figure 13 shows vibration acceleration (m/s^2) at various flow rates in range from 5 to 35 l/min obtained from FEM and expremental measurment. Experimental findings showed that vibration acceleration increases when flow rate increases for all types of impellers tested. Increasing the flow rate through a test l increases the level of noise and vibration amplitude due to the unstable flow which in turn, causes an increase in the pressure swings inside the pump. As the flow rate is increased from the lower value to the higher value the degree of initiation of cavitation developed, and as a result, the cavitation effects contributed significantly to an increase the overall vibration.

Moreover there is a large difference in vibration acceleration values when compared the fluid uses for testing (tap and seawater). Both density and the chemical composition of the seawater have a considerable effect on the impeller pump vibration process. Seawater is composed of a mixture of water molecules H_2O, salts, dissolved gases, organic materials, and un-dissolved particles. These materials in seawater precipitate on the impeller, inlets and outlets of pipelines of the pump and cause blockage in pumps which generate vibrations. The concentration of these elements in seawater is larger than tap water which makes the vibration of impellers is large then compared to tap water. The density of seawater ranges from 1020 kg/m^3 to 1035 kg/m^3, which is larger than tap water (1000 kg/m^3) [27]. A high density of seawater has a significant effect on the altitude to which the water can lift and then in vibration, because increasing the density of water increases the weight of the water pumping. Whenever salts, undissolved particles, and other organic compounds from seawater collide with impeller surfaces, this increases damage and influences the vibration process.

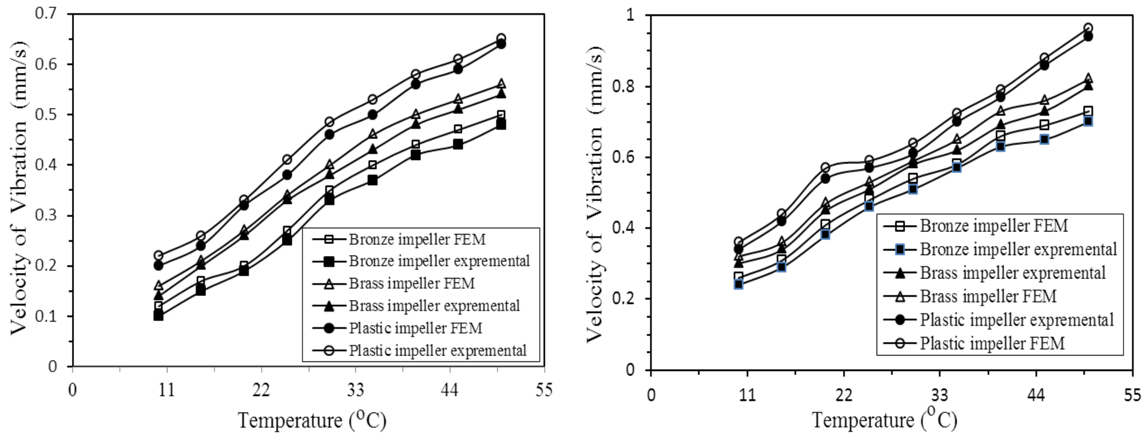


a) Impellers tested intap water b) Impellers tested in seawater

Figure 13. Values of vibration acceleration at various flow rates at 25^{o}C.

Figure 14 a and b illustrated the effect of temperature variation in the vibration phenomenon at constant speed of rotation and flow rates obtained from experimental and FEM. It can be seen from Figure 14 that a temperature variation have significant effects and when temperature rises from 5°C to 50°C, the vibration velocity of all types of impeller tested will be increased. Water properties and material properties of impellers are affected by temperature, which has a negative impact on vibration processes. One of the important properties of water that depend in temperature is the viscosity. The viscosity of seawater is higher than that of tap water because of its higher salinity. High water viscosity clearly results in degradation in pump performance, increasing pressure loss decreases flow rate and also wears damage, which could lead to vibration and even the pump failure.

Coefficient of thermal expansion is one of the most important properties that influence vibration amplitude and is affected by temperature. The thermal expansion coefficients for impellers made of bronze, brass, and plastic are18 $*10^{-6}$ /ºC, 19 $*10^{-6}$ /ºC and $75*10^{-6}$ /ºC respectively [28, 29]. The stability of the impeller during operation is significantly influenced by the thermal expansion coefficient and a large thermal expansion coefficient will lead to a large position shift of impellers. Additionally a large thermal expansion coefficient will generate a large thermal stress and as a result will generate a large instability in impellers during operation, this leads to increases vibration rate amplitude [30, 31]. Furthermore, thermal gradient can affect impeller size, which directly impacts the vibration process, especially for plastic impellers [32]. In comparison to metal impellers, plastic impellers are more affected by temperature and become soft. This causes the vibration amplitude to be larger.



a) Impellers tested in tap water b) Impellers tested in seawater

Figure 14. The effect of temperature on the values of vibration at flow rate 35 l/min

In both Tables 1 and 2, various elements are added to brass and bronze impellers. In vibration processes, these elements have different effects. In all phases, lead remains insoluble, and it is dispersed along grain boundaries in the present state. Since lead has a high damping capacity, it is also added as a material to control sound and mechanical vibrations [33]. The addition of iron to brass or bronze impeller materials improves their vibration and wear resistance. The other materials that are added to impellers have different effects, but they are mostly used to improve corrosion resistance and mechanical properties [34].

Figures 15 and 16 shows the curves of Head (m) vs. NPSH (m) at 35l/min flow rates obtained from cavitation test and theoretical calculation. It can be noted that NPSH reach the collapse state, the point at which the lifting mark drops suddenly. It can be seen that for plastic impeller, the collapse occurs at the point of the suction gradient when the NPSH values are 1.52 m and 1.06 m for sea and tap water respectively. In the case of brass impeller, the collapse occurs at the point of the gradient when the the NPSH values is 2.14 m, and 1.94 m for sea and tap water respectively. In the case of bronze impeller the collapse occurs at the point of the gradient when the NPSH values are 3.26 m, and 2.6 m for sea and tap water respectively. These means the drops of the cavitation may occurs at different points for different impeller materials. It can be seen from the Figures 15 and 16 that the NPSH for the impeller pump in the case of test in seawater is lower than in the case of test in tap water.

Both pure water and seawater have dissolved gasses in water, but these gases are less soluble at lower temperature. When temperature raising, these gases becomes too soluble and form some bubbles in the water [35]. Sometimes the formation of bubbles refers as cavitation in water pump. These bubbles can collapse and cause a shock wave that causing significant damage to the impeller, and mostly causes vibration. These bubbles increase with increase water temperature and contact these bubbles with impeller inducing the flow instabilities and increase vibration process.

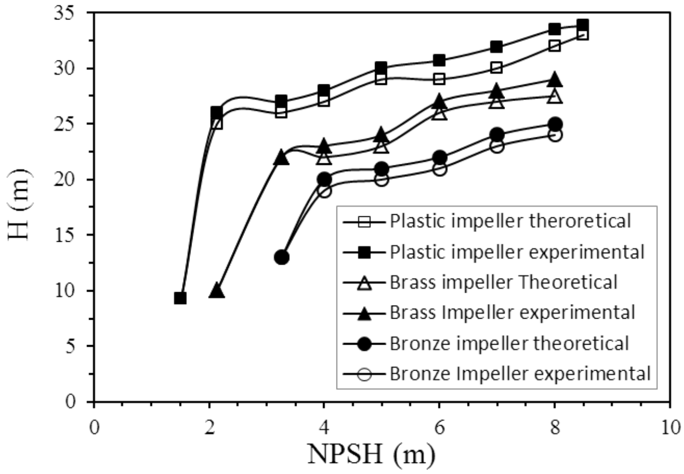


Figure 15. The Head (m) vs. NPSH (m) at 35l/min flow rate in tap water

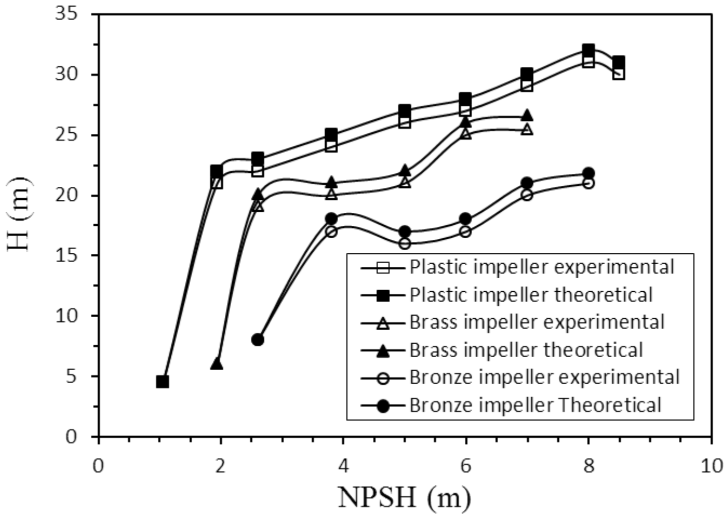


Figure 16. The Head (m) vs. NPSH (m) at 35l/min flow rate in seawater

4. CONCLUSION

An analysis of three types of impellers, brass, bronze, and plastic was conducted using experimental vibration measurements, FEM, and NPSH predictions. The results indicated that there is greater vibration amplitude for plastic impeller, smaller vibration amplitude for bronze impellers, and moderate vibration amplitude for brass impeller. The experimental results show that the vibration acceleration of all types of impeller tested is increased as flow rate is increased. The temperature has more influences on the vibration problems of three types of impellers tested and the increased of temperature leads to increase cavitation and enhance the vibration effects. The seawater has more influence in the vibration problems compared to the tap water. Cavitation occurs in seawater at a lesser Net Positive Suction Head (NPSH) than in tap water. Additionally, the high salt content in saltwater hastens the beginning of cavitation and also the incidence of breakdown cavitation.

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