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A Numerical Study on Centrifugal Pump Performance with the Influence of Non-Newtonian Fluids

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Abstract: In the present study, effects of non-Newtonian fluids on the characteristics of a centrifugal pump which was designed at 3300 rpm and 40 l/min for water were examined numerically. A numerical analysis using Computational Fluid Dynamics methodology was carried out. Water and three different non-Newtonian fluids of CMC 0.4%, CMC 0.3% and CMC 0.2% which derived from Carboxy Methyl Cellulose (CMC) solution were used in the analyses. The analyses were performed with the flow rates range of 10-80 l/min and rotor speed values of 3300 rpm and 1400 rpm. The results showed that the performance of the pump with non-Newtonian fluids was better than the water at 3300 rpm, contrary to 1400 rpm.

Keywords*:* Centrifugal Pump Performance, Closed Impeller, Non-Newtonian Fluids, CFD

Introduction

The non-Newtonian fluids are widely used in centrifugal pumps for many engineering applications especially food, medicine, production industry. Therefore, there have been several previous investigations on the centrifugal pump performance with the influence of non-Newtonian fluid such as; Zhang et al. [1] studied experimental research on the effects of non-Newtonian fluid on centrifugal blood pump performance. They found that the pump head rise with the solution was lower than that with water at the same flow rate for low rotor speeds, while it was higher for high rotor speeds, and a maximum difference of %7 was detected. Bacharoudis et al. [2] investigated centrifugal pump impeller by varying the outlet blade angle. They indicated that the rise in outlet blade angle from 20^0 to 50^0caused increment of more than 6% in the head. Shojaeefard et al. [3] studied on the effect of changing the passage width of the impeller using CFD code FLUENT. They reported that the passage width of the impeller increased from 17 to 21 mm, and the head and hydraulic efficiency rose due to the reduction of the friction losses. A numerical analysis was performed on the effects of the number of the blade on the centrifugal pumps performance at different rotational speeds by Chakraborty et al. [4], who found that pump head and efficiency increased with the rotational speed and the optimum number of the blade was 10. Yi et al. [5] carried out a numerical simulation of two-phase solid-liquid characteristics on the centrifugal pump performance. They compared the numerical result with the experimental data and reported that the influence of the solid phase characteristics was the function of flow rate. Simulations were performed in a centrifugal slurry pump for different turbulence models and operating speeds by Kumar et al. [6], and they had found a similarity between experimental and numerical results. Buratto et al. [7] studied on two open-impeller centrifugal pumps which characterized by different typology, dimension and field of application and operated with non-Newtonian pseudo-plastic fluids. The numerical results had shown that centrifugal pumps with the greater value of specific speed were much less sensitive to the fluid viscosity. An experimental and numerical analysis performed for a semi-open impeller centrifugal pump by Aldi et al. [8]. Three different non-Newtonian fluids of kaolin 30%, kaolin 35%, and kaolin 40% were used. They indicated that the experimental and numerical results were similar for water, kaolin 30%, and kaolin 40%, and the maximum difference between the experimental and numerical results was 6%. The

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effects of viscosity on the pump were investigated experimentally by Abazariyan et al. [9], who indicated that an increase in friction losses is due to increasing the viscosity.

Because the viscosity of the fluid is one of the main parameters affecting the friction losses in the flow, the pump performance characteristics also is affected by the viscosity. The effect of non-Newtonian fluids on friction loss is not exactly similar to Newtonian fluids due to the non-linear relationship between the shear stress and shear rate. Although non-Newtonian fluids are widely used in centrifugal pumps for many engineering applications, the pump manufacturers determine the centrifugal pump performance curves with water. To fill this gap, the effect of non-Newtonian fluid on the performance of a centrifugal water pump was investigated in this study. The numerical analyses were performed for water, and non-Newtonian fluids of CMC 0.2%, CMC 0.3% and CMC 0.4% with the flow rates range of 10-80 (l/min) and rotor speed values of 3300 rpm and 1400 rpm.

METHOD AND APPROACH

A closed type radial centrifugal water pump which was designed for operation with 3300 rpm and 40 l/min was used in this study. The diameter of the pump impeller was determined as 50 mm. 3-D representation of the impeller with an outlet blade angle of 19^0 and 6 blades was shown in Fig. 1.

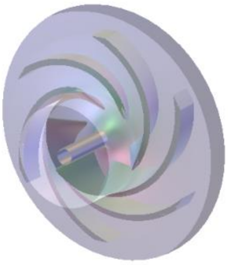


Fig. 1. 3-D visualization of the impeller

The CFD software and CFX was used to design of the pump. Turbo grid mesh which can solve complicated impeller blade problems was used in the centrifugal pump impeller. The turbo grid mesh structure of the impeller of the centrifugal pump and unstructured mesh of the volute the pump are shown in Fig. 2 (a) and (b), respectively. A fine mesh with the total number of nodes 1358265 and a total number of elements 1401968 was provided.

(a) **(b)**

Fig. 2. (a) Turbo grid structured mesh of impeller, **(b)** unstructured mesh of volute.

Several turbulence models were used by various researchers on the numerical analyses of the centrifugal pump. Kumar et al. [6] and Kaewnai et al. [10] used k-ε, k-ω and RNG k-ε turbulence model in numerical analysis, and they found that there was only 0.3% difference between turbulence models. They chose turbulence density as 1%, 5%, 10%, and the same head effect was observed in all turbulence intensities. Çellek and Engin [11] used SST and k-ε turbulence models for the investigation and optimization of centrifugal pumps by using the dynamic and broad computational fluid dynamics, and they found similar results. In this study, analyses were carried out with the k-ε turbulence model and 5% turbulence intensity.

The governing equations were the incompressible and unsteady continuity, and momentum equations can be written as follows:

$$\frac{\partial\rho}{\partial t} + \bar{\nabla}.\rho\bar{V} = 0 \qquad (1)$$

$$\rho\frac{d\bar{V}}{dt} + \bar{\nabla}P = \rho\bar{g} + \mu(\bar{\nabla}^2.\bar{V}) - 2\rho\bar{\Omega}\times\bar{V} - \rho\bar{\Omega}\times(\bar{\Omega}\times\bar{r}) \qquad (2)$$

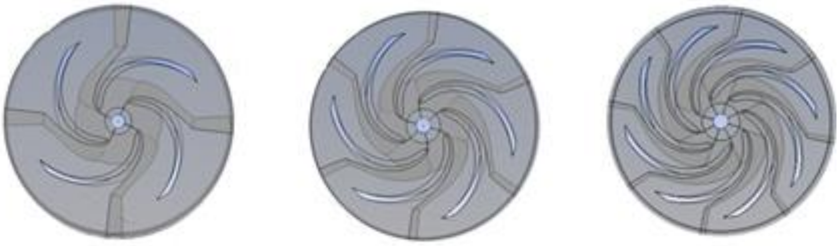
Transport equations for k and ε in the standart k- ε model are defined as:

$$\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho k u) = \nabla\left\lfloor\frac{\mu_k}{\sigma_k}\nabla_k\right\rfloor + 2\mu_k\left(\mathrm{E}_{ij}.\mathrm{E}_{ij}\right) - \rho\varepsilon \qquad (3)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla.(\rho\varepsilon u) = \nabla\left\lfloor\frac{\mu_t}{\sigma_\varepsilon}\nabla_\varepsilon\right\rfloor + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t\left(\mathrm{E}_{ij}.\mathrm{E}_{ij}\right) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (4)$$

The effective viscosity is defined as the sum of the molecular viscosity and the turbulent vortex viscosity. Where is $\mu_t = \rho C_\mu L_t\sqrt{k}$. In the turbulent vortex viscosity, C_μ is a constant, Lt is a length scale. There is a mathematical relationship which is $\varepsilon = \sqrt{k^3}/L_t$ between Lt and turbulence rate. In the transport equations for k and ε, $C_{1\varepsilon}$, C_μ, C_k, $C_{2\varepsilon}$, and σ_ε are constants. In the standard k-ε models these constants are $C_\mu = 0.09$, $C_k = 1.00$, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, and $\sigma_\varepsilon = 1.30$. E_{ij} shows the time averaging deformation rate tensor.

The numerical analyses were performed with 4 to 8 blades, as shown in Fig. 2. The outlet blade angle is 22.50, the impeller outlet diameter is 50 mm, and the centrifugal pump has blade number of 4 (a), 6 (b) and 8 (c).



(a) **(b)** **(c)**

Fig. 3. Impellers with different number of blades, **(a)** blade no:4, **(b)** blade no:6, **(c)** blade no:8

Table 1 shows the efficiency values of the numerical analysis with the different number of blades in the analysis performed with water. There was excessive loss of circulation in the number 4 blades, and the impeller losses were higher due to the excessive flow blockage and high surface friction resistance in the number 8 blades. Because the highest efficiency was found for the 6-blade impeller, the optimum number of blades was determined as 6. The analysis was performed to determine the optimum outlet blade angle of the centrifugal pump impeller at the number of blades 6. The outlet blade angle was chosen from 18^0 to 30^0, and the highest efficiency point was found as 19^0. So, the pump head was increased by about 2% by optimizing the outlet blade angle.

Table 1. Values of efficiency with the different number of the blade.

Parameters	Efficiency(%)
Blade no:4	67.2522
Blade no:5	67.8189
Blade no:6	68.7134
Blade no:7	68.3981
Blade no:8	67.7724

A rotating frame of reference approach was used in the closed type impeller of the centrifugal pump. The rotational speed of impeller was worked 1400 rpm and 3300 rpm. As the inlet boundary condition, a total pressure 1 atm and a turbulent intensity equal to

5% was imposed. The no-slip wall boundary condition was used for all the solid surfaces, and a mass flow rate condition was chosen at the outlet. k-ε turbulence model was selected, and power law was used to model the behavior of the non-Newtonian fluid.

The shear stress is defined as,

$$\tau = K\gamma^n \qquad (5)$$

The numerical analyses were performed for water and non-Newtonian fluids of CMC 0.4%, CMC 0.3% and CMC 0.2% that have similar rheological behavior with oil. The parameters K and n of the power law for CMC 0.4%, CMC 0.3%, and CMC 0.2% are given in Table 2, which were obtained a study of the flow of non-Newtonian fluids in a pipe by Pinho and Whitelaw [12].

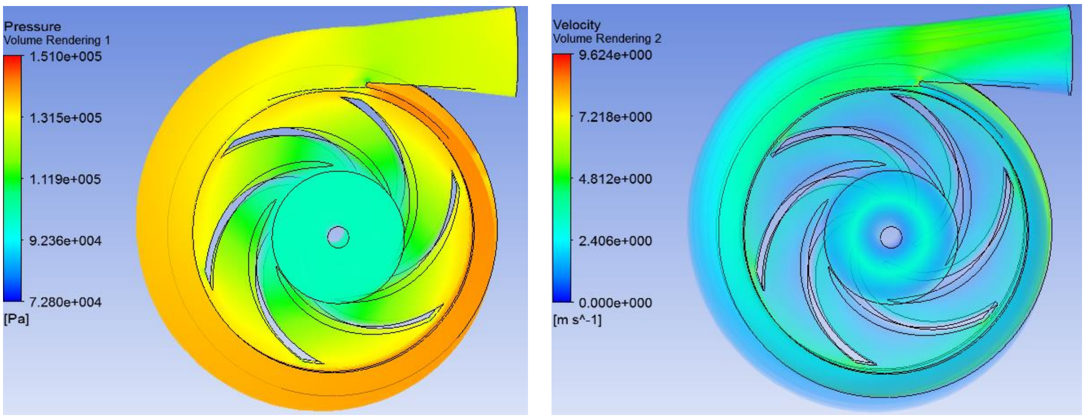
Table 2. Power law parameters *K* and *n*.

Solution	*K*(Pa.s)	*n*
CMC 0.4%	0.447	0.56
CMC 0.3%	0.184	0.64
CMC 0.2%	0.044	0.75

Results and Discussions

The centrifugal pump characteristics of non-Newtonian fluids of CMC 0.4%, CMC 0.3%, and CMC 0.2% were investigated numerically with the effects of flow rates and rotor speed, and all results were compared to those of the water values.

The pressure and velocity distributions of the pump for CMC %0.2 at Q=40 l/min are given in Fig. 4 (a) and (b), respectively. The pressure increased from leading edge to trailing edge of the impeller due to the dynamic head developed by the rotating pump impeller, while decreased towards the outlet of the volute. The highest pressure of 1.51 atm on the centrifugal pump was obtained at the outlet of the impeller. The velocity increased towards the impeller, and the highest value of the velocity of the pump impeller was 9.62 m/s.



(a) **(b)**

Fig. 4. CMC %0.2 at Q=40 l/min, **(a)** pressure distribution, **(b)** velocity distribution

The variation of the head with flow rates of all fluids at 3300 rpm were shown in Fig. 5. The head decreased with in the flow rate for all fluids. The pump head rise of the concentrations of CMC was obtained slightly higher than the value of the water. The decrement of the pump head for CMC 0.4% was more than CMC 0.3% and CMC 0.2% with rising volumetric flow rate. Head rise of centrifugal pump at Q=40 l/min for CMC 0.2% and water was 3.5377 m and 3.4701 m respectively, while the head was 3.4881 m for CMC 0.4%.

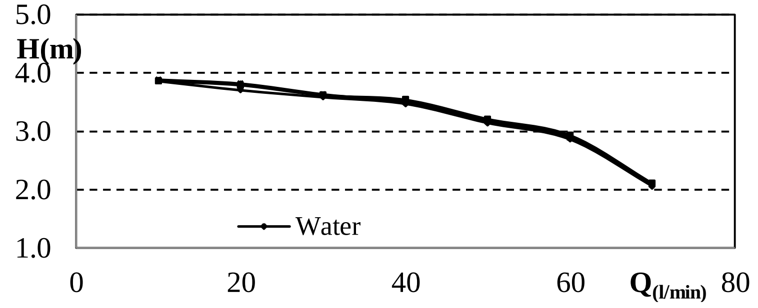


Fig. 5. The variation of the head with flow rates at 3300 rpm

The variations of the head with flow rates at 1400 rpm are also presented in Fig. 6. The pump head decreased with increase in the flow rate, similar to 3300 rpm. The highest head rise of the centrifugal pump obtained at 3300 rpm for CMC 0.2% and 1400 rpm for water. The lowest value at 1400 rpm was found for CMC 0.4%. The pump head at the flow rates of 20 l/min and rotor speed of 3300 rpm was 3.7028 m and 3.7880 m for water and CMC 0.2%, respectively. The head at 1400 rpm and 20 l/min was also found as 0.6204 m and 0.6195 m for water and CMC 0.2%, respectively.

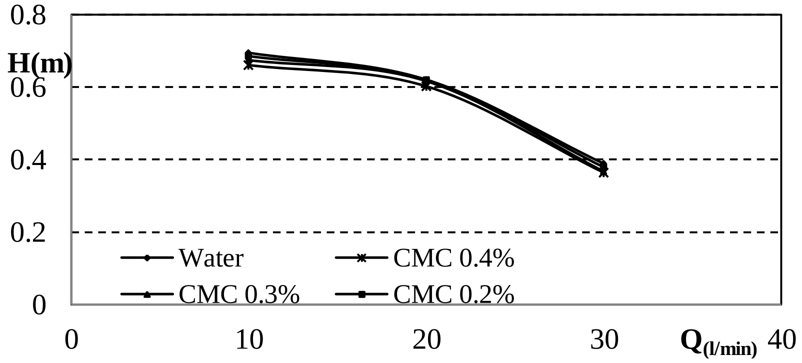


Fig. 6. The variation of the head with flow rates at 1400rpm

Fig. 7 presented the Q-η curve of fluids at 3300 rpm. The maximum efficiency of all fluids was obtained at approximately the flow rates of 40 l/min which was the BEP of the pump at 3300 rpm. The efficiency value at BEP was found 68.851% and 68.7134% for CMC 0.2% and water, respectively. The difference of about 0.2% was detected at BEP between CMC 0.2% and water, which was approximately 2% between CMC 0.4% and water.

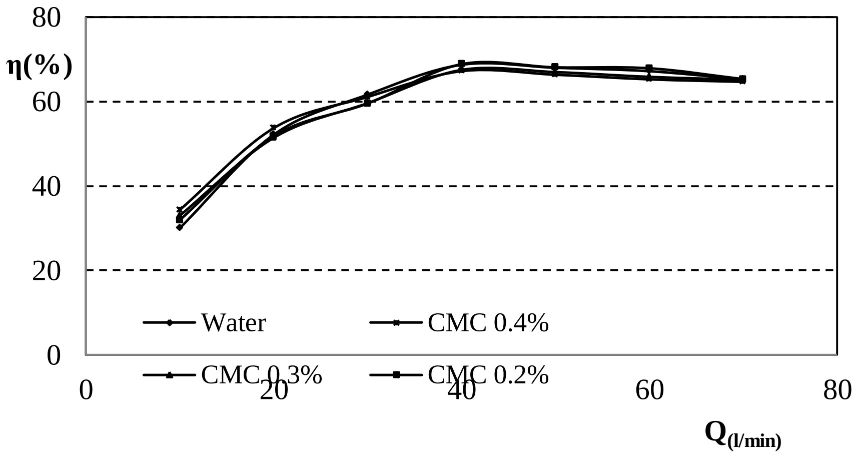


Fig. 7. The variation of efficiency with flow rate at 3300rpm

Fig. 8 showed the variation of efficiency with flow rate at 1400 rpm. The best efficiency for all fluids was obtained at approximately 20 l/min which was about 40 l/min at 3300 rpm. The efficiency values for water at 1400 rpm were higher than the values of concentrations of Carboxy Methyl Cellulose. The efficiency of CMC 0.2% for 20 l/min was obtained as 67.0506% and 51.827% at 1400 rpm and 3300 rpm respectively, while the value of water was 67.8863% and 52.1662% at 1400 rpm and 3300 rpm, respectively. The efficiency value of the CMC 0.4% was also obtained as 65.7778% and 53.7213% at 1400 rpm and 3300 rpm, respectively.

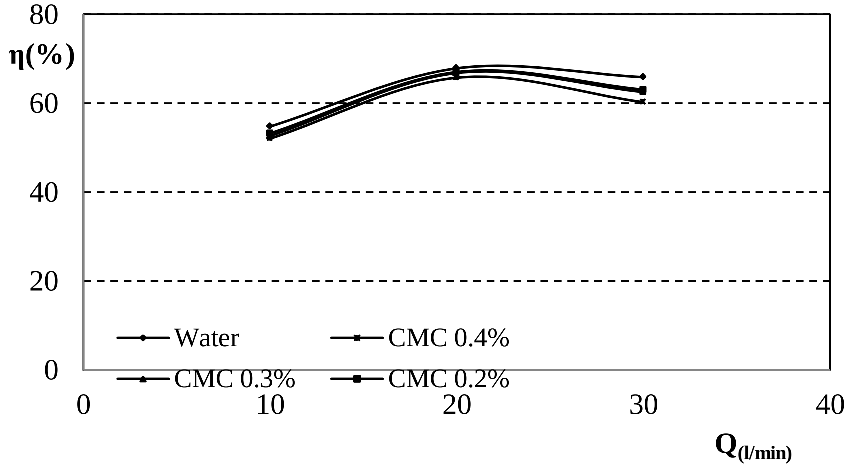
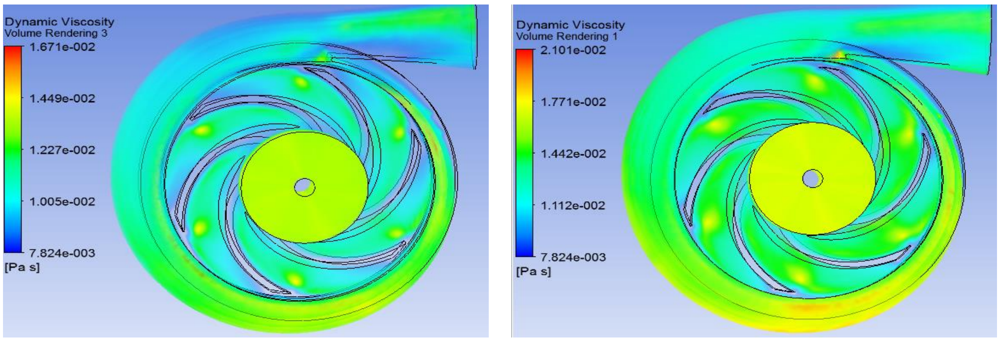


Fig. 8. The variation of efficiency with flow rate at 1400 rpm.

The viscosity values of the CMC %0.2 at best efficiency point for 3300 rpm and 1400 rpm are presented in Fig. 9 (a) and (b), respectively. The viscosity values of the near the trailing edge of the blades were higher than the values of near to the leading edge for both the rotor speeds. In addition, viscosity increased towards the outlet of the volute and reached the highest value in the area of the volute tongue. The values of the average and highest viscosity at 1400 rpm were higher than the values at 3300 rpm.



(a) **(b)**

Fig. 9. Viscosity values of CMC %0.2 in centrifugal pump volume, **(a)** 3300 rpm and 40 l/min, **(b)** 1400 rpm and 20 l/min.

Conclusions

In this study, a numerical analysis was performed on the performance characteristics of the centrifugal pump with the flow rates range of 10-80 l/min, rotor speed values of 3300 rpm and 1400 rpm, and the fluids of the water, CMC 0.4%, CMC 0.3%, and CMC 0.2%. The head and efficiency of the centrifugal pump with water increased with blade number and outlet blade angle optimization. The BEP was obtained at the flow rates of approximately 40 l/min and 20 l/min at 3300 rpm and 1400 rpm for all fluids, respectively. The head rise of the pump with solutions of Carboxy Methyl Cellulose was found slightly lower than the water at 1400 rpm, the contrast to the values at 3300 rpm at the same flow rate and high rotor speed. The best value of the performance characteristics of the centrifugal pump was obtained for CMC 0.2% at design parameters.

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Nomenclature

g	Gravitational acceleration [m/s^2]
H	Head [m]
k	Turbulence kinetic energy [m^2/s^2]
K	Viscosity consistency [Pa.s]
n	Power law index [-]
P	Pressure [N/m^2]
Q	Volumetric flow rate [l/min]
r	Radius from reference point [m]
$\vec{V}$	Velocity vector [m/s]

Greek symbols

$\dot{\gamma}$	Shear rate [s^{-1}]
$\vec{\nabla}$	Operator = $i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}$
ε	Turbulence dissipation rate [m^2/s^3]
η	Efficiency [%]
μ	Viscosity [kg/m.s]
ρ	Density [kg/m^3]
σ	Prandtl number
Ω	Angular velocity [rad/s]

Subscripts

t	Turbulence

Abbreviations

BEP	Best Efficiency Point