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다단원심펌프 작동유체 온도에 따른 펌프 수력성능 및 흡입성능의 열역학적 특성

쉬레스트 우즈왈* · 김대훈** · 최영도***†

Thermodynamic Characteristics of the Hydraulic and Suction Performances by the Working Fluid Temperature of Multistage Centrifugal Pump

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Key Words : Multistage centrifugal pump(다단원심펌프), Performance(성능), Working fluid temperature(작동유체 온도), Viscosity(점성)

ABSTRACT

High pumping performance is essential for the boiler in industrial processes and thermal power plants. The multistage centrifugal pump is one of the options for the boiler feed pump because it can deliver a wide range of head and flow rates. The boiler feed pump operates at a wide range of temperatures, and the working fluid properties are sensitive to the temperature. The change in the thermodynamic properties of the working fluid (viscosity, density, and thermal conductivity) will affect the head and efficiency of the multistage centrifugal pump. Besides the hydraulic performance of multistage centrifugal pumps, the thermodynamic properties of the working fluid will adversely affect the structural stability of the pump. It is necessary to understand the influence of working fluid thermodynamic properties on the performance of a multistage centrifugal pump to design and operate the pump appropriately.

1. Introduction

The thermal power plant generates electricity by converting thermal energy into mechanical and electrical energy. The process involves the hot water circulation from the feedwater tank to produce steam, which drives the gas turbine to generate electricity. The circulation of the water or other fluids is required to maintain a consistent temperature and avoid failure. The multistage centrifugal pump is one of the options for the circulating pump in the thermal power plant because it can handle very high pressure and maintain a constant flow rate. The multistage centrifugal pump consists of two or more centrifugal pump impellers in a series of connections. The diffusers and the return vanes are connected with the impellers to direct the flow from one stage to another. The fluid enters the first impeller under pressure in the suction line and drains at elevated pressure. After leaving the first impeller, the fluids enter the second impeller and increase the pressure. Finally, the multistage centrifugal pump increases the discharge pressure enormously. Multistage centrifugal pumps play a crucial role in the operation of thermal plants

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effectively and cost-effectively generate electricity.

The centrifugal pump operates at a higher temperature for unique purposes such as boiler feed pump(1) and organic Rankine cycle(2). When a centrifugal pump operates at a higher temperature, necessary precautions should be taken(3). Hydraulic instability exists in the boiler feed pump, which decreases its performance of boiler feed pump(4). The thermodynamic properties of the water are dependent on water temperature. Saloum and Maksimov investigated the effect of water temperature on the performance of a water heat pump(5). The centrifugal pump can handle a wide range of viscosities(6). Ippen experimented on the centrifugal pump to understand the effect of viscosity on the pump head and power(7). The temperature rising in the centrifugal pump influences the hydraulic loss in the pumping system(8). Li et al. used oil with various kinematic viscosities to evaluate the centrifugal pump performance(9). Shojaeefard et al. investigated the role of water and oil viscosities in the centrifugal pump performance(10). In part load conditions, the effect of viscosity on a single-stage centrifugal pump is smaller than in the best efficiency point (*BEP*) and the full load conditions(11). When the pump operates at a higher water temperature, it induces stress and high vibration and leads to the failure of the whole system(12). Furukawa et al. found that the peak pressure fluctuation amplitude occurs at blade passing frequency(13). The return vane influenced the internal flow field of the multistage centrifugal pump. Huang et al. showed that reverse flows exist at the outlet of the impeller, which induces asymmetrical and unstable flow(14). Experiments by Kawashima et al.(15) showed that the diffuser vane influenced the performance and flow field of the impeller. The pump cavitation is highly dependent on the water temperature. Rundev et al. established the correlation between the vapor-liquid ratio and water temperature on a centrifugal pump(16). Kim and Song studied the effect of water temperature on the critical cavitation number(17). Dular and Coutier-Delgosha showed the temperature variation in the latent heat exchanges during the vaporization and condensation(18). With the increase in the water temperature and flow rate, the cavitation process speeds up and widens the downstream diffusion(19).

Fig. 1 shows the variation of the centrifugal pump performance with a change in the fluid viscosity. The centrifugal pump performance is directly dependent on the fluid viscosity. However, limited study results are available for multistage centrifugal pump performance with high water temperature.

Fig. 2 shows the variation of water viscosity and density according to the temperature. Fig. 3 shows that the centrifugal pump efficiency is increased with the rise in water temperature. Fig. 4 shows that the centrifugal pump head decreases with the rise in water temperature, and head drop will decrease the pump efficiency. There is no proper study about the effect of water temperature in the multistage centrifugal centrifugal pump. In this study, numerical analysis was conducted with a change in water temperature to understand water temperature's effect on the hydraulic and suction performance of the multistage centrifugal pump.

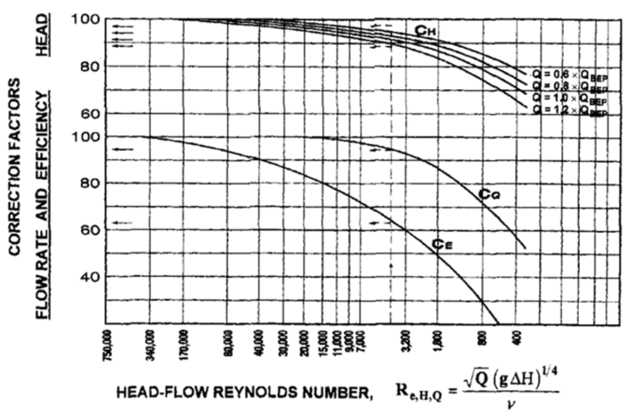

Fig. 1 Viscous fluid effects on centrifugal pumps (20)

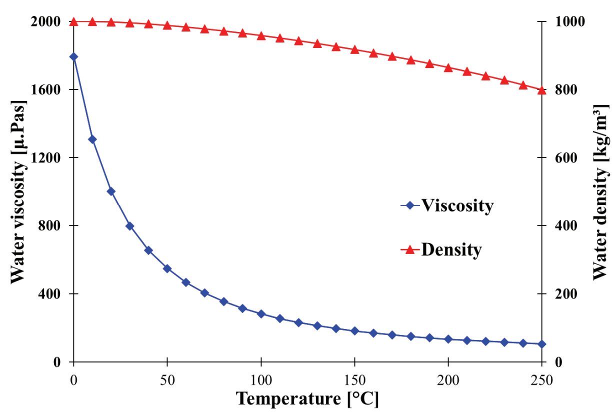

Fig. 2 Variation of water density and viscosity according to the temperature change (21)

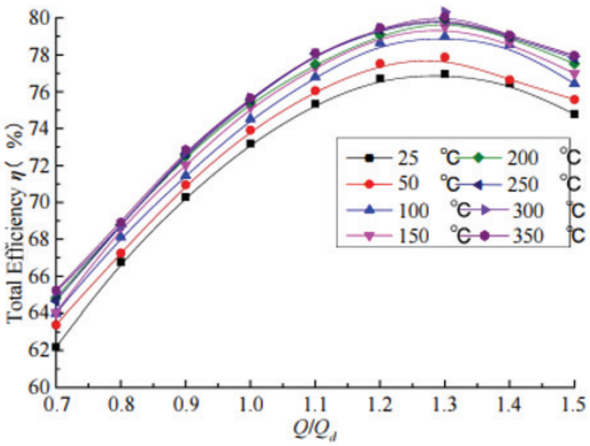

Fig. 3 Performance curves of centrifugal pump with various water temperatures (22)

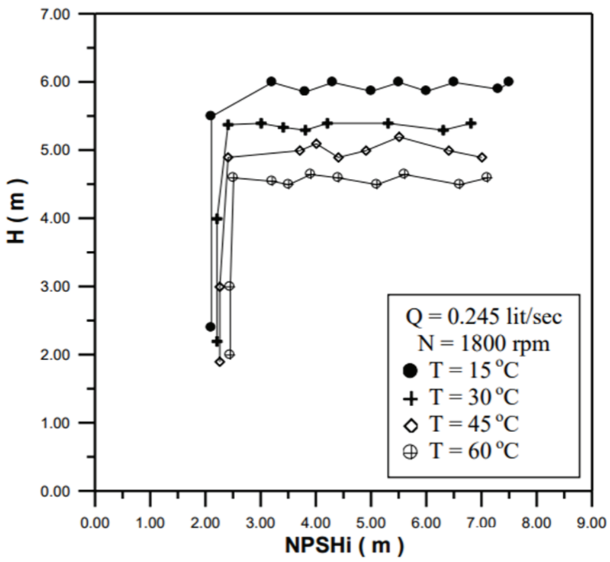

Fig. 4 Variation of pump head with NPSH at various water temperatures (23)

2. Modeling and Methodology

2.1 Pump modeling

The multistage centrifugal pump comprised a suction volute, impeller, return vane, diffuser, and discharge volute. Fig. 5 shows the 3D modeling of the multistage centrifugal pump. The multistage centrifugal pump was designed considering the requirement of a specific speed of the centrifugal pump. The diffuser and return vanes are designed according to the outlet flow angle of the impeller[24]. The specific speed N_s, which is defined as shown in Eq. (1), of the single-stage centrifugal pump is 107 [min^{-1}, m^3/min, m].

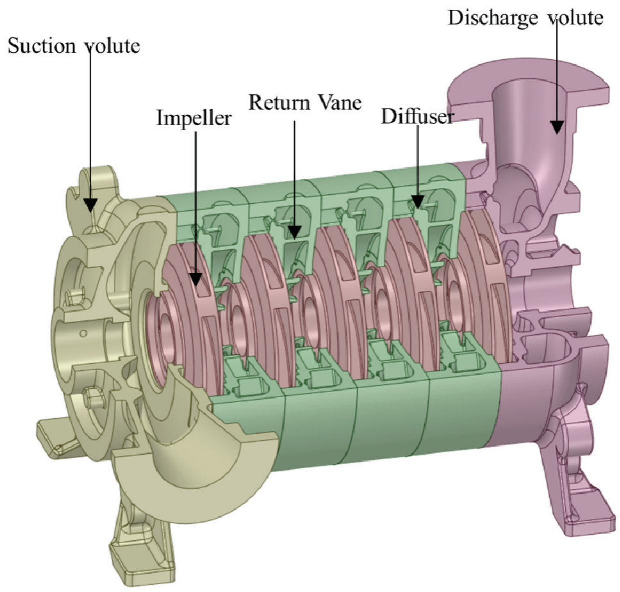

Fig. 5 3D Modeling of the multistage centrifugal pump

$$N_s = \frac{n\sqrt{Q}}{H^{0.75}} \tag{1}$$

where n is rotational speed (min^{-1}), H is effective head (m), Q is flow rate (m^3/s).

2.2 Numerical methodology

The numerical grids for the impeller and return vane are shown in Fig. 6. ANSYS CFX[25] and Fluent[25] were used for CFD analysis and comparing the CFD analysis results. ANSYS CFX[25] is suitable for rotating machinery, and ANSYS Fluent[25] is preferable for thermal analysis. ANSYS ICEM 19.2[25] was used to generate hexahedral grids for a multistage centrifugal pump. Fig. 7 shows the mesh dependency test for the multistage centrifugal pump CFD analysis. 13.4 million mesh nodes were used for CFD analysis with a $y+$ value less than 30 for the impeller, return vane, and diffuser vane.

The inlet and outlet boundary conditions for the multistage centrifugal pump were static pressure and mass flow rate. The frozen rotor interface model was used. The detailed boundary conditions are shown in Table 1. The cavitation analysis is conducted using a mixture of water and water vapor. The Rayleigh-Plesset equation was used to evaluate the cavitation in the multistage centrifugal pump.

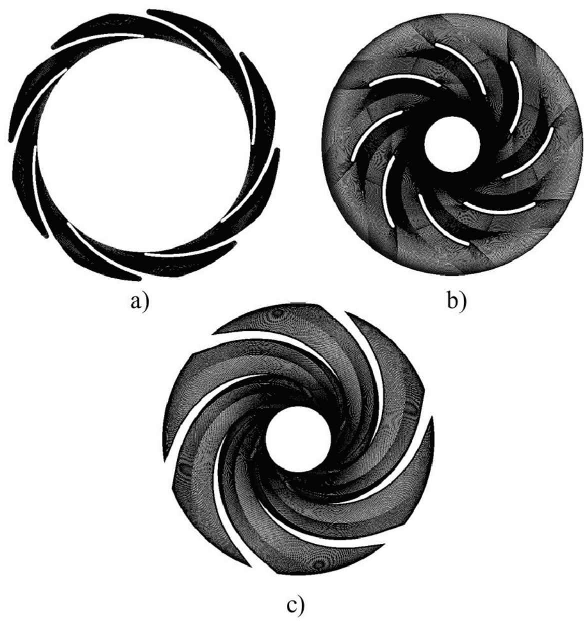

Fig. 6 Numerical grids of multistage centrifugal pump a) diffuser vane b) return vane and c) impeller

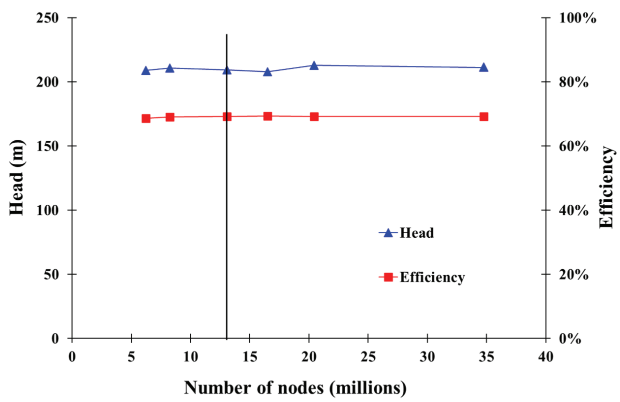

Fig. 7 Mesh dependency test for CFD analysis at Q/Q_{BEP}=1.0

Table 1 Boundary conditions for multistage centrifugal pump CFD analysis

Parameter/Boundary	Conditions / Value	
Analysis type	Steady	Unsteady
Inlet	Static pressure	Static pressure
Outlet	Mass flow rate	Mass flow rate
Rotational speed	1750 min^{-1}	1750 min^{-1}
Turbulence model	SST	SAS-SST
Time step		0.00038 sec
Interface model	Frozen rotor	Transient rotor stator
Working fluid	Fresh water	

The following performance measures are used to evaluate the performance of the multistage centrifugal pump.

$$H = \frac{p_{out} - p_{in}}{\rho g} \tag{2}$$

$$P = \sum_{i=1}^{5} T_i \omega \tag{3}$$

$$\eta = \frac{\rho g Q H}{P} \tag{4}$$

where P is input power (W), T_i is torque input in i^{th} impeller (Nm), g is acceleration due to gravity (m/s^2), p_{in} and p_{out} are inlet and outlet total pressure, respectively. ρ is density of water (kg/m^3), ω is rotational speed (rad/s), η is pump efficiency.

3. Results and Discussion

3.1 Performance curves of multistage centrifugal pump at the working fluid temperature of 25 °C

The performance curves of a multistage centrifugal pump are prepared by changing the flow rate at the working fluid temperature of 25°C. Fig. 8 shows the performance curves of the multistage centrifugal pump. Fig. 8 shows the comparison between CFX and Fluent CFD analysis results. CFD analysis showed a good correlation between CFX and Fluent. The design point and the best efficiency point (*BEP*) match well with both CFX and Fluent. It implies that CFD analysis is acceptable. The design and best efficiency points of the multistage centrifugal pump match well with each

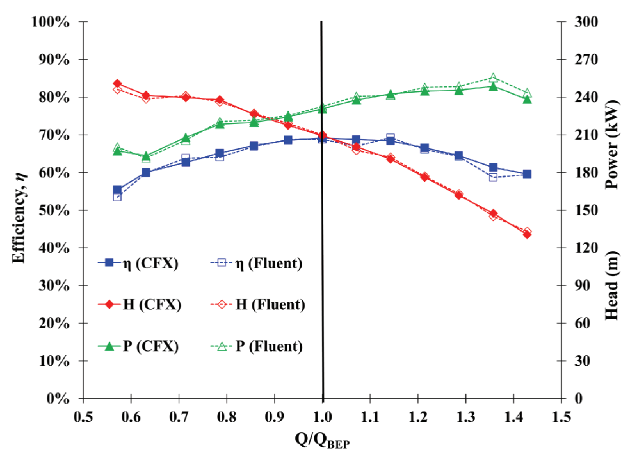

Fig. 8 Performance curves of multistage centrifugal pump at water temperature 25°C

other. It infers that the design of the multistage centrifugal pump is satisfactory. The pump achieved 70% efficiency with a net head of 210 m.

3.2 Internal flow in multistage centrifugal pump at the working fluid temperature of 25°C

The multistage centrifugal pumps are used to increase the discharge pressure significantly. Fig. 9 shows the velocity streamlines at the 4th stage of the multistage centrifugal pump with various flow conditions. The circulation flow in the impeller is visible at Q/Q_{BEP}=0.65. The circulation flow is predominantly at the impeller outlet. At Q/Q_{BEP}=1.00, the velocity streamlines are smooth without recirculation flow. At Q/Q_{BEP}=1.35, the velocity magnitude is above 25 m/s at the impeller passage. The velocity streamlines suggested that Q/Q_{BEP}=1.00 has a low recirculation flow and pressure loss.

3.3 Performance curves of multistage centrifugal pump at various water temperatures

From Eq. (4), it can be seen that efficiency is closely related to the density of the working fluid, and the pump efficiency changes proportionally as the density changes. The density of the working fluid water of the pump changes according to temperature, and as shown in Fig. 7, the viscosity and the density of the water change according to the temperature change.

Fig. 10 shows the performance curves of a multistage centrifugal pump at various temperatures. The maximum efficiency of the multistage centrifugal pump is observed at 25°C. The pump efficiency is decreased from 70% to 55% when the water temperature rises from 25°C to 250°C at the BEP. At Q/Q_{BEP}=0.65, the efficiency drops from 60% to 53% when the water temperature increases from 25°C to 250°C. When the temperature increases from 25°C to 250°C, the pump efficiency drops from 61% to 31% at Q/Q_{BEP}=1.35. It implies that temperature rise has a significant impact on the pump performance.

Fig. 11 indicates the effect of water temperature on the pump performance. When temperature increases from 25°C to 100°C, the efficiency and head drops are 3.9% and 5.7%, respectively, at Q/Q_{BEP}=1.00. The pump performance is stable from 25°C to 100°C water temperature. When the temperature is more than 150°C, the pump performance decreases drastically. When the temperature rises from 25°C to 250°C, efficiency and head decreased by 20.5% and 28.6%, respectively, at Q/Q_{BEP}=1.00.

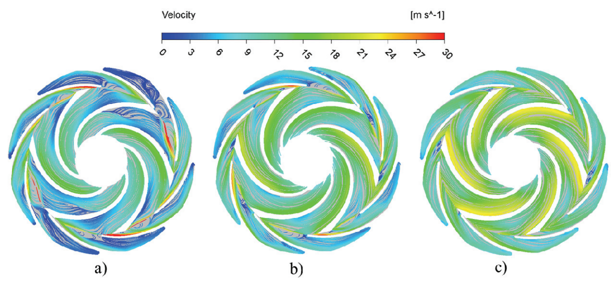

Fig. 9 Velocity streamlines in the multistage centrifugal impeller at 4th stage (25°C) : a) Q/Q_{BEP}=0.65 b) Q/Q_{BEP}=1.00 and c) Q/Q_{BEP}=1.35

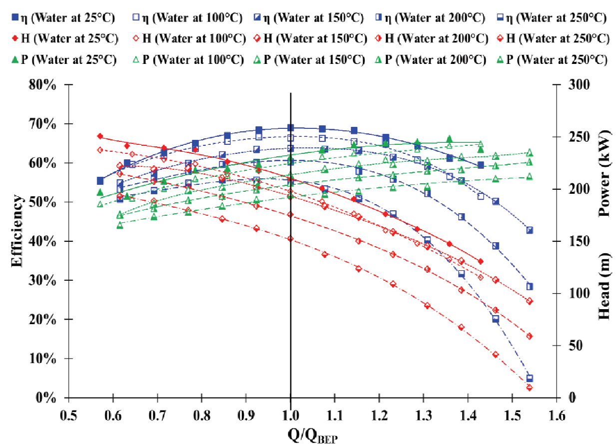

Fig. 10 Performance curves of multistage centrifugal pump according to various water temperatures by ANSYS CFX

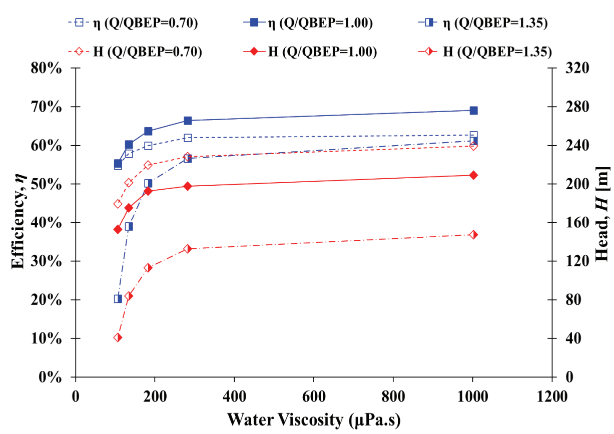

Fig. 11 Variation of multistage centrifugal pump efficiency and head with water viscosity

3.4 Pressure distribution in multistage centrifugal pump at various water temperatures

Fig. 12 shows the pressure distribution in the multistage centrifugal pump at various flow rates and water temperatures. The increase in static pressure is dependent on the flow rate. At Q/Q_{BEP}=0.65 and 25°C, the discharge pressure reaches 2500 kPa, but at Q/Q_{BEP} and 25°C=1.35, the discharge pressure drop to 1500 kPa. At Q/Q_{BEP}=1.00, the pressure increases gradually at the interface between stages. At Q/Q_{BEP}=0.65, the discharge pressure is decreased by 22% when the water temperature rises from 25°C to 250°C. The linear pressure distribution pattern is similar from the 1st to 5th stages of the multistage centrifugal pump except for the diffuser and return vane regions at Q/Q_{BEP}=0.65. At Q/Q_{BEP}=1.00 and when the temperature rises from 25°C to 250°C, the discharge pressure is reduced by 32.5%. The pressure distribution in the multistage centrifugal pump changes drastically, and the discharge pressure drops by 65% when the temperature rises from 25°C to 250°C at the high flow rate of Q/Q_{BEP}=1.35. The pressure drop at the impeller inlet and outlet causes a significant efficiency drop in the multistage centrifugal pump at Q/Q_{BEP}=1.35. Fig. 13 shows pressure contours at Q/Q_{BEP}= 1.35 and 250°C. The sudden drop of pressure is observed at the outlet of the return vane in Fig. 13. It implies that recirculation flow and vortex formation at the impeller inlet causes a pressure drop.

Fig. 14 shows the blade loading in the 5th stage impeller at Q/Q_{BEP}=1.00 with various water temperatures. The blade loading showed that the pressure decreases drastically in the impeller flow passage with temperature rise. At the leading edge (LE), the crossover between the blade pressure and suction sides is visible when the pump operates at a high temperature. The crossover between the blade pressure and suction sides indicates the negative work done in the centrifugal pump and increases the input power. The rise in water temperature decreases water density and viscosity, which shows a drastic pressure drop. At 25°C and Q/Q_{BEP}=1.35, the outlet pressure at the 5th stage impeller is 1500 kPa 3 times higher than the outlet pressure at 250°C and Q/Q_{BEP}=1.35.

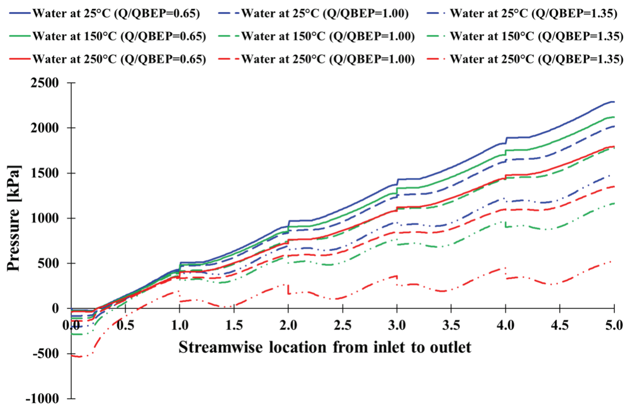

Fig. 12 Pressure distribution from inlet to outlet of multistage centrifugal pump at various water temperatures and flow rates

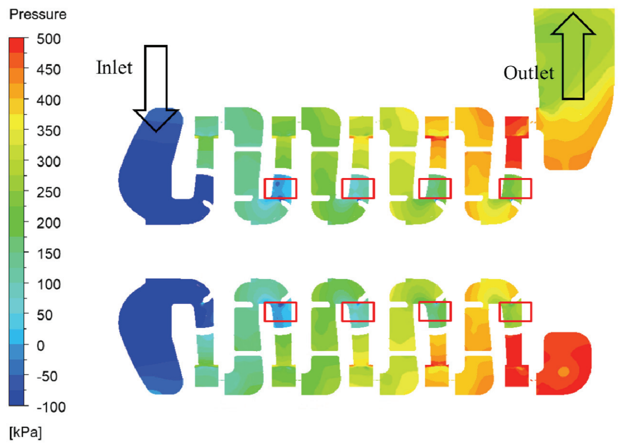

Fig. 13 Pressure contours in the multistage pump at Q/Q_{BEP}=1.35 and water temperature 250°C

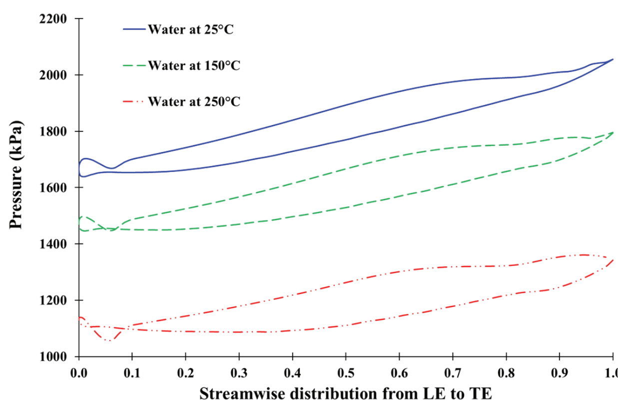

Fig. 14 Pressure distribution from LE to TE at 5th stage impeller and Q/Q_{BEP}=1.00 a) 25°C b) 150°C c) 250°C

3.5 Volumetric efficiency in multistage centrifugal pump at various water temperatures

The leakage flow and volumetric efficiency are shown in Fig. 15 and Fig. 16, respectively. The volumetric efficiency is calculated using Eq. (5)[26].

$$\eta_v = \frac{Q}{Q + \Delta q} \tag{5}$$

where η_v is volumetric efficiency, Q is design flow rate (m^3/s) and Δq is leakage flow from the clearance gap.

Fig. 15 shows performance curves comparison between without and with leakage gap in a multistage centrifugal pump. The leakage flow rate increases with an increase in flow rate. Fig. 16 shows that the leakage flow rate increases with an increase in the water temperature and a decrease in flow rate. Fig. 17 shows a drop in volumetric efficiency with a rise in water temperature. The volumetric efficiency decreases with an increase in water temperature. It implies that the performance of a multistage centrifugal pump decreases with an increase in water temperature.

3.6 Suction performance of multistage centrifugal pump at various water temperature

The cavitation number is used to calculate the suction performance. The cavitation number is calculated by using Eq. (6).

$$\sigma = \frac{p_{in_{static}} - p_{vap}}{\rho g H} \tag{6}$$

where $p_{in_{static}}$ and p_{vap} are inlet static and saturated vapor pressures, respectively.

Fig. 18 shows the suction performance of the multistage centrifugal pump at the working fluid temperature of 25°C. The critical cavitation number (σ) is the point in the suction performance when efficiency is dropped by 3%. At Q/Q_{BEP}=0.65 and 1.35, the critical cavitation numbers are 0.04 and 1.32, respectively. The critical cavitation number increased drastically with the increase in flow rate, which implies that the multistage centrifugal pump is highly susceptible to

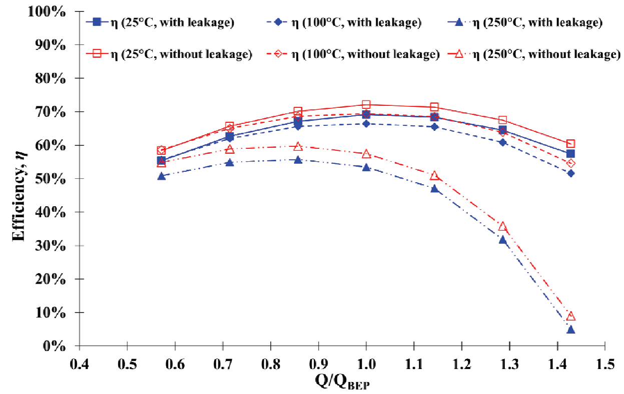

Fig. 15 Performance curves comparison without and with leakage in multistage centrifugal pump at various water temperatures

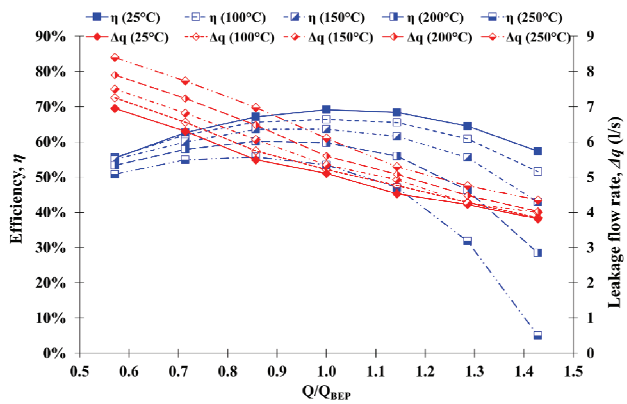

Fig. 16 Leakage flow rate in the multistage centrifugal pump at various water temperatures

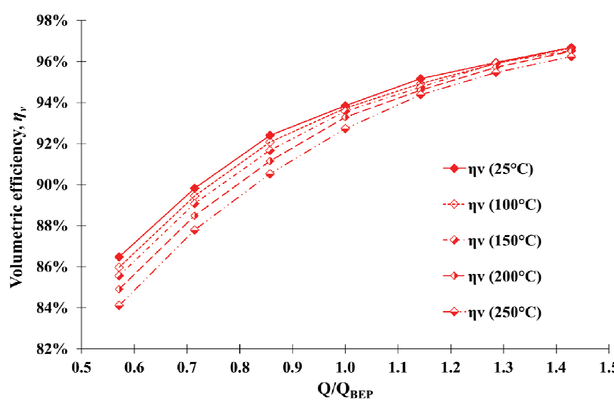

Fig. 17 Volumetric efficiency in the multistage centrifugal pump at various water temperatures

cavitation at a higher flow rate.

Fig. 19 indicates the suction performance with variation in water temperature at Q/Q_{BEP}=0.65. When the water temperature rises from 25°C to 250°C, the critical cavitation number increases from 0.04 to 0.08.

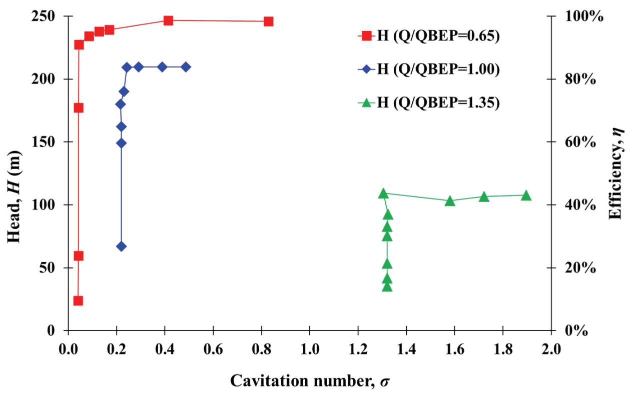

Fig. 18 Suction performance of multistage pump at 25°C with various flow rates

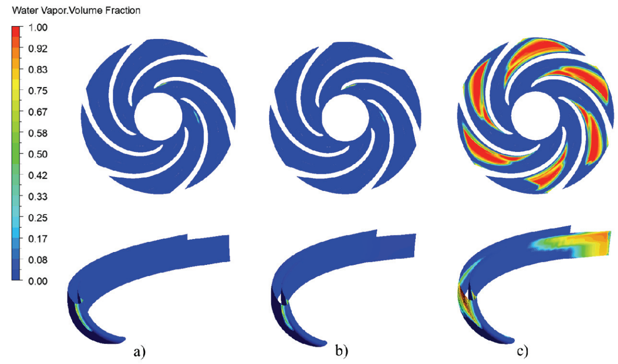

Fig. 20 Vapor volume fraction distribution in 1st stage impeller flow passage at σ =0.22 and Q/Q_{BEP}=1.00 a) 25°C b) 150°C c) 250°C

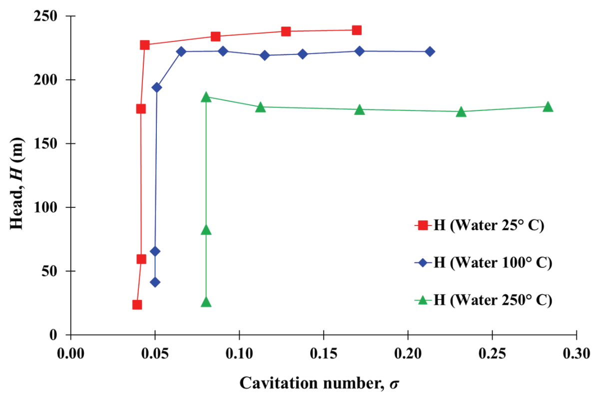

Fig. 19 Suction performance of multistage pump at Q/Q_{BEP}=0.65 with various water temperatures

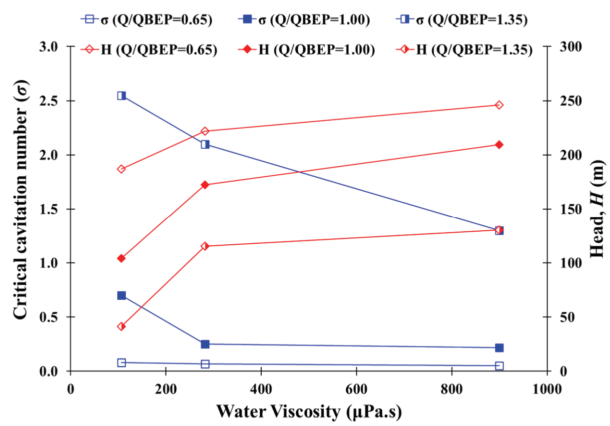

Fig. 21 Critical cavitation number and head of multistage centrifugal pump at various water viscosities by temperature change

It implies that the possibility of cavitation is increased drastically with rises in water temperature. Besides an increase in cavitation possibility, the performance of the multistage centrifugal pump is dropped by reducing the head with an increase in water temperature. The head decreased from 240m to 180m with an increase in water temperature from 25°C to 250°C in a multistage centrifugal pump.

Fig. 20 shows the vapor volume fraction distribution in the 1st stage impeller of a multistage centrifugal pump. At Q/Q_{BEP}=1.00 and σ=0.22, the vapor volume fraction distribution is compared in 1st stage of a multistage centrifugal pump with various water temperatures. The vapor volume fraction is visible in the impeller flow passage at 250°C water rather than 25°C water. It clarifies that the cavitation possibility increases with the rise in water temperature.

Fig. 21 shows the correlation between the critical cavitation number and the head of the multistage centrifugal pump. The critical cavitation value increases and the head decreases gradually with a decrease in water viscosity. The high critical cavitation number means the possibility of cavitation increases in a multistage centrifugal pump. At full load conditions, the critical cavitation number increases, and the head reduces rapidly with decreases in water viscosity. Hence, the drop in water viscosity reduces the head and increases the cavitation possibility in a multistage centrifugal pump.

4. Conclusion

The numerical analysis was conducted for the multistage centrifugal pump with various water temperatures. The hydraulic and suction performance of the multistage centrifugal pump is highly dependent on the water temperature. When the water temperature increases, the thermodynamic properties of water, such as water viscosity and density, change and directly influence the performance of the multistage centrifugal pump. The hydraulic performance of a multistage centrifugal pump decreases gradually with an increase in water temperature. The discharge pressure in the multistage centrifugal pump decreases gradually with a drop in water viscosity. The discharge pressure decreases when the water viscosity decreases.

The suction performance decreases with a drop in water viscosity by the temperature increase. Therefore, the rise in water temperature affects a multistage centrifugal pump's hydraulic and suction performance.

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