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The Characteristics of a Pump at Nearly Saturated State

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Abstract

A set of experiments using a 1/10 scale model pump which was manufactured to simulate performance of reactor coolant pump(RCP) of Y.G.N # 3 and 4, was executed in single phase(at atmospheric pressure and room temperature) and near-saturation(300~600kPa). The pump characteristics in single phase flow was similar to the characteristics of the RCP. The pump characteristic curves at nearly saturated state were correlated in terms of flow coefficient and head coefficient for subcooled temperature using the cavitation number defined as $C_a = \frac{v_l h_{fg} \Delta T_{sub}}{v_g (\pi N D)^2 T}$, which can be predicted the cavitation possibility.

The pump behavior around the saturated temperature almost consists with single phase behavior until the cavitation occurs. When cavitation occurs(when the flow coefficient is about 0.12), the pump head rapidly degrades. In this situation, subcooled temperature is about 1.8~8℃ and cavitation number of model pump is 1.0~1.7.

1. Introduction

Usually a Pressurized Water Reactor (PWR) works at very high pressure(~15MPa) and temperature(~350℃) with no phase change of the cooling fluid in the circuit. The cooling fluid is circulated through the system by the Reactor Coolant Pump(RCP) which is designed to operate in a single phase condition(liquid). For this reason, only its single phase characteristics are known. However, through the lifetime of the PWR, there will be abnormal situations like Small Break LOCA(SBLOCA), in which the system condition is near saturation or two phase. Even in these abnormal situations, sometimes it is inevitable to operate the RCP at nearly saturated or two phase flow conditions for the removal of the decay heat of the core.

The operation of the pump in these conditions necessitates the characteristic informations of the pump in these situations. Through the various experimental works, it is also well-known that pump characteristics in near-saturation or two-phase condition are quite different from those of single phase condition.

The pump characteristics of the single phase can be obtained analytically or experimentally. However, the two-phase pump characteristics can be obtained experimentally only.

2. Theory

2.1. Theoretical Equation

2.1.1. Single-Phase Flow

Using the pump geometry, the velocity diagram at the impeller-blade tips was constructed(Fig. 1). Euler's general equation for turbomachinery was used to express the work done on the unit fluid mass flowing through the pump in terms of the moment of momentum of the flow[1],[2],[3],[4].

$$\frac{\dot{W}}{\dot{m}} = g_c(h_{02} - h_{01}) = U_2 c_{\theta 2} - U_1 c_{\theta 1} \quad (1)$$

It was assumed that there was no inlet swirl to the pump in the absence of preswirl-guide vanes. This implies $c_{\theta 1}=0$, then equation (1) can be simplified to;

$$g_c \Delta h_0 = U_2 c_{\theta 2}$$

From velocity triangle, we have

$$c_{\theta 2} = U_2 - c_{m2} \tan\beta_2 \quad (2)$$

where the angle β_2 is the relative flow angle at the impeller blade tips, which differs from the exit vane angle β_2' by the deviation δ. This deviation angle is affected by real fluid-flow phenomena(e.g friction, turbulence, boundary-layer separation, etc.). The slip factor used to estimate the deviation angle in centrifugal pump is defined as

$$\mu \equiv \frac{c_{\theta 2}}{c_{\theta 2}'} = \frac{U_2 - c_{m2}\tan\beta_2}{U_2 - c_{m2}\tan\beta_2'} \quad (3)$$

This study quotes the Busemann's correlation and gives

$$\mu = \frac{A - B\phi_2 \tan\beta_2'}{1 - \phi_2 \tan\beta_2'} \quad (4)$$

For the model pump, A = 0.77 and B = 1.0 were used [1].

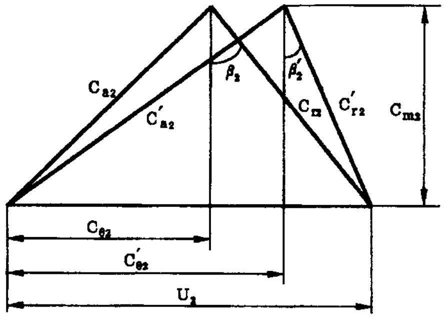

Fig. 1. Velocity Diagram for Rotor Outlet

$$\Psi = 1 - \phi_2 \tan\beta_2 \quad (5)$$

Combining equation (3), (4) and (5), we have $\Psi_{spth} = 0.77 - \phi_2 \tan\beta_2'$.

For the model pump, $\beta_2' = 62°$.

Then

$$\Psi_{spth} = 0.77 - 1.8807\phi_2 \quad (6)$$

In this study, this equation is theoretical basic equation which is related with the theoretical head coefficient and flow coefficient for single-phase flow.

2.1.2. Two-Phase Flow

Two-phase flow is treated as two separated mass flows, liquid and vapor, which are assumed to leave the impeller at the same relative angle, but at different velocities. Theoretical head coefficient for single phase flow assumed that fluid properties do not vary across the pump. Theoretical equation, which is related with the theoretical head coefficient and flow coefficient for two-phase flow is defined as following[4],[5],[6] :

$$\Psi_{tpth} = 0.77 - R\left[(1-x)\frac{(1-\beta)}{(1-\alpha)}\phi_{tp} + \frac{\beta}{\alpha}x\right]\phi_{tp} \quad (7)$$

where R is 1.8807, x is mass quality, α is void

Table 1. Cavitation Number of Prototype and Model Pump

Items \ Pumps	Prototype Pump	Model Pump	
Pump Speed (rpm)	1190	1750	
Diameter (m)	0.94	0.094	
h_{fg} (kJ/Kg)	965.7 (P=15.5MPa, T=344.9℃)	100kPa, T=99.63℃ 300kPa, T=133.55℃ 600kPa, T=158.85℃	2258.0 2163.8 2086.3
υ_g (m^3/kg)	9.807×10^{-3}	100kPa 300kPa 600kPa	1.694 0.606 0.316
υ_l (m^3/kg)	9.807×10^{-3}	100kPa 300kPa 600kPa	1.043×10^{-3} 1.074×10^{-3} 1.1×10^{-3}
Cavitation Number $\frac{\upsilon_l h_{fg}\Delta T_{sub}}{\upsilon_g U^2 T}=\frac{\upsilon_l h_{fg}\Delta T_{sub}}{\upsilon_g (\pi ND)^2 T}$	$0.140\Delta T_{sub}$	100kPa 300kPa 600kPa	$0.188\Delta T_{sub}$ $0.387\Delta T_{sub}$ $0.616\Delta T_{sub}$

fraction theoretically calculated by drift flux model and β is volumetric quality calculated from flow rates of liquid and vapor measured in experiment.

The head loss ratio, H^* is defined as an efficiency parameter which compares the losses in the pump in two-phase flow to the losses in single-phase flow at the same flow coefficient. Therefore, the head loss ratio is equal to

$$H^* = \frac{\Psi_{tpth} - \Psi_{tp}}{\Psi_{spth} - \Psi_{sp}} \tag{8}$$

When the relation of the characteristics of a pump in single-phase and two-phase flow are known, it is possible to predict two-phase flow parameters(head and flow rate) of the pump in accidents or transients from the given single phase characteristics of the RCP. Also, when the system conditions are abnormal, the conditions can be determined from the operating parameters of the pump(such as void fraction from the head loss coefficient).

2.1.3. Cavitation

Taking into account the possibility of cavitation, cavitation number is defined as $C_a = \frac{P-P_v}{\rho U^2}$ where P is system pressure, P_v is the vapor pressure of fluid, ρ is the density of fluid, U(=πND) is the speed of fluid in pump, N is pump speed and D is impeller diameter.

The relation of saturation temperature and pressure can be shown by using the Clapeyron-Clausius relation for near saturation.

$$\frac{dP}{dT} \doteqdot \frac{P}{RT^2} h_{fg} \tag{9}$$

This can be approximated as follow by assuming that

$$P \simeq P_v,\ T \simeq T_v$$

$$P - P_v = \Delta P,\ T - T_v = \Delta T_{sub}$$

then,

$$\Delta P = P \cdot \frac{h_{fg}\Delta T_{sub}}{RT^2} = \frac{\rho_g h_{fg}\Delta T_{sub}}{T} \tag{10}$$

Table 2. Specification of Y.G.N #3 & 4 RCP and Model Pump

Pumps / Items	RCP(Y.G.N # 3 & 4)	Model Pump
Type	Vertical, Single stage	Vertical, Single stage
Design head (m)	105.156	2.27
Design speed (rpm)	1190	1750
Design flow (m^3/s)	5.3879	0.0079
Outdiameter of impeller (cm)	93.98	9.4
Diameter of pump inlet & outlet (cm)	76.2	7.62
Power(kW)	6330.5	0.75
Operating temperature (℃)	296.1	158.85
Operating pressure (MPa)	15.6	0.6
Manufacture	KSB(Germany)	Handol(Korea)

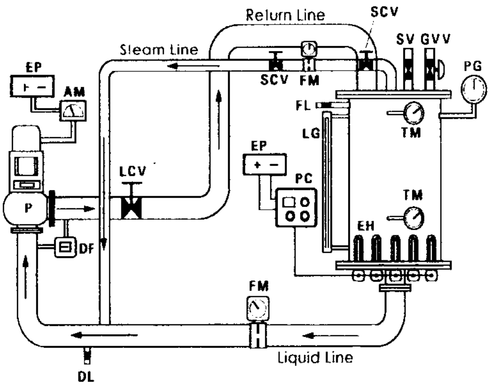

Fig. 2. Schematic Diagram of the Test Loop

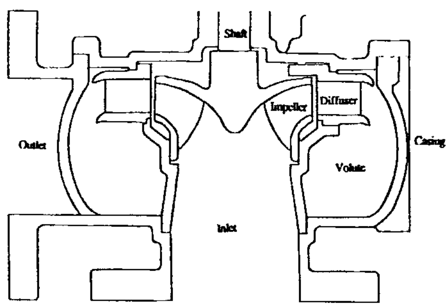

Fig. 3. Schematic Diagram of the Model Pump

where, P_v is system pressure, T is saturation temperature at P, T_v is temperature of fluid and P_v is saturation pressure at T_v. h_{fg} is constant since ΔT defined as $T - T_v$ is not large.

Therefore, cavitation number is defined as follows (see Table 1).

$$C_a = \frac{\Delta P}{\rho U^2} = \frac{\rho_g h_{fg} \Delta T_{sub}}{\rho_l U^2 T} = \frac{v_l h_{fg} \Delta T_{sub}}{v_g U^2 T} \quad (11)$$

3. Experiments

In abnormal conditions, most of the PWR system get to the near-saturation condition, and some parts of system may be in two-phase flow condition. If the situations are more deteriorated, the flow may be in two-phase at inlet of RCP. However, most of transients were near saturation conditions. Therefore, when RCP is operated in abnormal situations, we are to determine the operating temperature range and obtain the pump head in this study.

Dimensionless numbers(flow coefficient, head coefficient and specific speed) that govern the geometry and performance of a pump were decided to use the similitude. A 1/10 scale RCP model pump of Y.G.N #3 & 4 was designed and manufactured. An experiment facility which consists of this model pump is set. The experiments of single-phase and near saturation were performed at its experimental conditions (100~600kPa, saturation temperature). The single-phase experiment was to find out the RCP characteristics in single phase, and near saturation experiment was to determine the operating range of the pump in near saturation.

3.1. Experimental Facilities

The system was consisted of a closed loop through which water was circulated under the experiment conditions. It had cylindrical pressure vessel, charge and discharge line, model pump and measurement systems as shown in Fig. 2.

Using the dimensionless numbers and similitude principle, a 1/10 scale RCP model pump of Y.G.N #3 & 4 was designed and manufactured(see Table 2 and Fig.3). It had impeller with 6 blades and diffuser with 10 blades, and was designed to be operated at 700kPa. Impeller and diffuser was made of SSC13 to protect the corrosion and erosion by water. The pump had a water jacket to prohibit over-heating in pump seal section because it was operating under high temperature, high pressure. Inlet and outlet were 3 inches, and they were each connected with the same size piping(see Fig.3).

A cylindrical tank(pressure vessel), which had 50cm inside diameter and 100cm in height, was used as a heating tank and saturated water supply tank.

The power of electric heaters in pressure vessel was controlled to keep the system pressure around 100~600kPa.

Saturated water was introduced from the bottom of the pressure vessel and this water mass flow rates was measured with orifice plate manufactured in RCM. This orifice plate was previously calibrated, and water flows were accurate to ±3%.

The water went to the model pump and returned to the pressure vessel.

Inlet and outlet pressure difference across the pump was measured with pressure transducer manufactured in OMEGA(model PX273-200DI). The accuracy of the transducer was ± 0.75%(0.1psi).

The measurement systems were set to measure the pressure in tank and the temperature of liquid. The pressure gauge has the range from 0 to 200 psi and the thermocouple has from 0 to 300℃. They were precalibrated with zero adjusting settings in OMEGA Co..

4. Results

4.1. Single-Phase Flow Test Results

The experiments were executed to find out the single-phase characteristic of the pump. It was performed at the atmospheric pressure, room

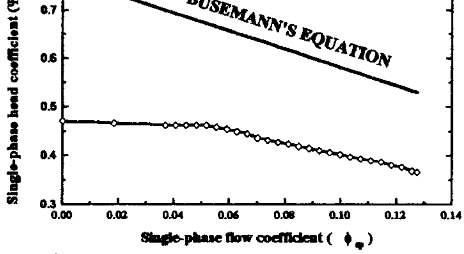

Fig. 4. Single Phase Pump Performance : Theoretical(Busemann's Equation) and Experimental Performance

temperature.

The main parameters, inlet and outlet pressure difference across the pump and flow rate at the inlet of the pump, were measured by controlling the flow control valve.

The data were correlated in terms of flow coefficient and head coefficient(see Fig.4). Flow coefficient represents the ratio between a characteristic fluid velocity and the local rotor velocity, and it was defined as following

$$\phi=\frac{c_m}{U}=\frac{Q}{AU} \tag{12}$$

where A is flow area at the impeller tip. Head coefficient represents the ratio between the energy given to the mixture and kinetic energy. The mixture would be at a velocity equal to the local impeller tip speed. Head coefficient was defined as

$$\Psi=\frac{g\Delta H}{U^2} \tag{13}$$

At the Fig.4, in Busemann's equation which is theoretical characteristic equation of the pump, the head coefficient monotonically decreases as the flow coefficient increases. However, in this experiment, it was observed that Ψ was almost constant(about 0.46) when ϕ was below 0.052, then it slowly decreases as the flow coefficient increases further. The head coefficient was about 0.366 when flow coefficient was about 0.127 (i.e., at the maximum flow rate(about 0.0057 m^3/s)), and it was about 0.47 when the flow coefficient was zero.

4.2. Near-Saturation Test Results

The experiments were performed to observe the behavior of the reactor coolant pump near saturation. Tests were executed by measuring flow rate and head with subcooled temperature (cavitation occurring temperature) and the fixed system pressure, 100, 300, 600kPa. The subcooled temperature(ΔT_{sub}) was defined as the difference between saturation temperature and fluid temperature in given system pressure.

According to the fluid temperature approaching at the saturation temperature of the system, the cavitation was occurred and the head was sharply dropped.

The data was correlated in terms of flow coefficient and head coefficient for system pressure, 100, 300, 600kPa(see Fig.5). Throughout the experiments, subcooled temperature was 8, 4.5, 1.8℃ comparable to

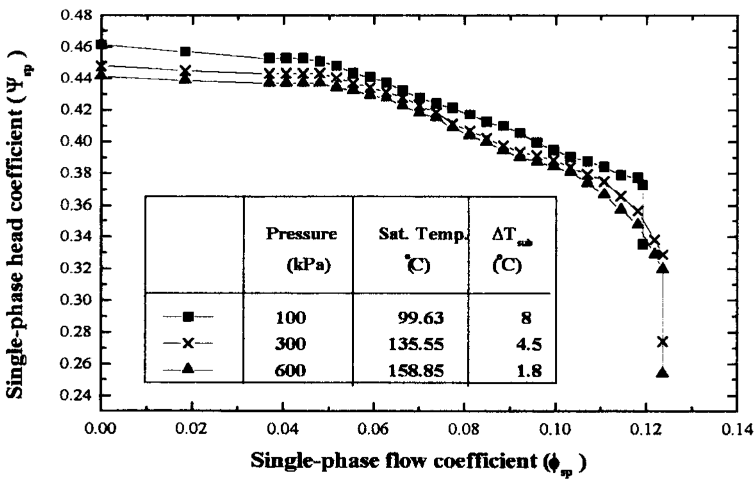

Fig. 5. The Pump Characteristics Near the Saturation Temperature

system pressure 100, 300, 600kPa. Therefore, it was found that the cavitation number of model pump was about 1.0~1.7.

5. Conclusions

Experiments were carried out with a 1/10 scale RCP model pump of Y.G.N #3 & 4 to obtain head performance near saturation. We predicted the subcooled temperature(cavitation occurring temperature) for RCP of Y.G.N # 3 & 4 in near-saturation. Following conclusions were obtained :

1) In single phase flow experiment, the actual head coefficient was about 67% with respect to theoretical value near 0.1 flow coefficient.
2) The pump behavior around the saturated temperature almost consists with the single phase behavior until the cavitation occurs.
3) ΔT_{sub} decreases as the pressure of the system increases.
4) When the cavitation occurs, pump-head rapidly drops degrades about 70% of single phase one and gradually decreases as the flow rate increases further.
5) In real RCP, subcooled temperature (cavitation occurring temperature) was predicted about 7~12℃ for pressure of RCS.

Acknowledgments

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