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Complete and homologous pump characteristics for a reactor coolant pump

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A B S T R A C T

A reactor coolant pump is subjected to various abnormal operating modes, so the pump supplier has to provide all the transient pump characteristics to a user. Complete or homologous pump characteristics are the best forms including transient hydraulic information for an abnormally operating pump. Until now, there has been no consideration in the systematic test procedures to obtain the complete or homologous pump characteristics through a hydraulic test. No further research has been done on the relationships among the constant heads in complete pump characteristics. Likewise, no additional discussion has taken place on the direct transformation of the homologous pump characteristics into the complete pump characteristics. In present paper, a mathematical model is introduced to explain how the constant head curves in the complete pump domain are connected to each other. This means that other constant head curves can be obtained without additional hydraulic testing once a constant head curve is obtained for the full flow rate and speed range. It is also shown that the complete pump characteristics can be obtained from the homologous pump characteristics by another mathematical model. For homologous pump characteristics, even though differently enveloped test matrices that consist of different level sets of flow rate and speed are applied in hydraulic testing, the same homologous pump characteristics are obtained. These results indicate that a low-enveloped test matrix is sufficient to obtain the homologous pump characteristics.

1. Introduction

Due to nuclear power plant transients, the operating modes of a reactor coolant pump can be a positive flow with positive speed, a negative flow with positive speed, a negative flow with negative speed, and a positive flow with negative speed. These pump operating modes are categorized based on accident events in a nuclear power plant. In the pump transients, the flow rate of the pump is necessary information for the safety analysis of nuclear reactor systems. All the transient hydraulic characteristics are included in the homologous or complete pump characteristics from which we can find out the flow rate for any pump operation mode. For example, a loss of coolant accident caused by a pipe break leads to an abnormal pump operating condition. The flow rate passing through the reactor core is reduced so that melting of the core can occur. The safety analysis group has to know how much reactor coolant passes through the reactor core to evaluate the safety of the reactor systems. The complete or homologous pump characteristics themselves are the information that the safety analysis group requires.

Knapp and Pasadena (1937) investigated the complete pump characteristics of a centrifugal pump and explained their applications in the prediction of transient behavior. He used a 4-inch high-head high-efficiency pump to simulate all possible conditions of flow, head, and speed, both as a pump and as a turbine. His works are valuable for those who study complete pump characteristics. It is interesting that he tried to figure out the pump coastdown phenomena using the complete pump characteristics. He obtained the coastdown time duration in speed changes by calculating the area under the torque in the complete pump domain. Stepanoff (1957) explained special operating conditions of pumps beyond their normal head versus flow rate and speed range. He reported experimental results of the complete pump characteristics covering all possible cases or combinations of head, capacity, torque, and speed. In his test book, he referred to Swanson's (1953) results for the complete pump characteristics of a centrifugal pump, a mixed flow pump, and an axial pump. Gulich (2014, p. 861) called the complete pump characteristics "the general characteristics of a pump".

Gros et al. (2011) studied the complete characteristics of a centrifugal pump whose rated head, flow, and speed were 21 m, 787.5 m^3/h, and 1450 rpm, respectively. He obtained the complete pump characteristics through both hydraulic test and numerical calculation. A comparison of the calculated and experimental results showed that the numerical predictions are very accurate if unsteady computations are performed to simulate the domain for reverse speed. So far, it is known

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Nomenclature

D	Diameter (m)
g	Gravitational acceleration (m/s^2)
H	Head (m)
H_R	Rated head (m)
h	Normalized head (H/H_R)
N	Rotational speed, (rpm)
Q	Flow rate (m^3/s)
U	Fluid velocity (m/s)
H_c	Arbitrary head (m)
h_{loss}	Head loss (m)
h_m	Head of scale-down pump (m)
h_p	Head of full-scale pump (m)
H_{100}	100% head (m)
H_{200}	200% head (m)
N_s	Specific speed $\left(\frac{NQ^{0.5}}{H^{3/4}}\right)$
N_R	Rated speed (rpm)
Q_R	Rated flow (m^3/s)
T_h	Shaft torque (N m)
T_R	Rated torque (N m)
α	Normalized speed (N/N_R)
β	Homologous torque ratio (T_h/T_R)
ν	Normalized flow (Q/Q_R)
HAN	Forward flow and forward speed
HVN	Forward speed and forward flow
HVR	Reverse speed and forward flow
HAR	Forward flow and reverse speed
HAT	Reverse flow and reverse speed
HVT	Reverse speed and reverse flow
HVD	Forward speed and reverse flow
HAD	Reverse flow and forward speed

that the prediction of the complete pump characteristics from a numerical calculation is very difficult. However, his results may usher in a new way to predict the complete pump characteristics using computational fluid dynamics.

In the report of the Electric Power Research Institute (EPRI), Kennedy et al. (1980) described homologous pump characteristics based on fluid dynamic similarity. He experimentally obtained the single- and two-phase homologous head and torque curves for a pump whose rated head, flow, and speed were 76.7 m, 954.6 m^3/h, and 4500 rpm, respectively. The homologous pump characteristics are another way to express pump transients. The homologous pump characteristics are a closed curve in the flow versus speed axis whereas the complete pump characteristics are open curves. Todreas and Kazimi (1990) described reactor coolant pump transients and the application of homologous pump characteristics in a nuclear power plant. Choi et al. (2008) presented experimental results of homologous pump characteristics for a single phase. The hydraulic resistances for a locked rotor and a sheared shaft were described in his paper.

In the RELAP5/MOD3 Code Manual, NUREG/CR-5535 (1995), the homologous pump characteristics were obtained from the complete pump characteristics based on the pump similarities. Farman and Anderson (1973) explained the reactor flow rate during LOCA (loss of coolant accident) using the homologous pump characteristics. These two works presented the application of the homologous pump characteristics but did not explain the relationships between the constant heads in the complete pump characteristics. They did not discuss how the homologous pump characteristics were transformed into the complete pump characteristics.

Although many hydraulic tests are performed to determine the complete or homologous pump characteristics, no systematic way to experimentally obtain these two characteristics has been developed. The relationship between the two kinds of pump characteristics has not been explained yet. In the present, a basic mathematical model is described to convert the homologous pump data into the complete pump data. Another mathematical model is presented to explain the relationship among constant head curves in the complete pump characteristics. Through several homologous pump tests, we verified that using a low-enveloped test matrix is sufficient to obtain the homologous pump characteristics rather than using an over-enveloped test matrix.

2. Complete pump characteristics

Complete pump characteristics have been used to present pump transients, and many hydraulic tests have been performed to obtain them. Knapp and Pasadena (1937) and Swanson (1953) obtained the complete characteristics through hydraulic testing. However, they did not explain how the constant curves of the head and torque in the complete pump characteristics were connected to each other. They focused on getting the complete pump characteristics but did not try to understand the hydraulic features of the complete pump characteristics themselves. In this paper, the relationships among the constant head curves are determined by using hydraulic similarities. This information will be helpful in preparation of test facilities to get the complete pump characteristics.

From Swanson's hydraulic test results shown in Fig. 1, the selected point R belongs to the rated conditions, which are 100% of the flow rate and 100% of the speed of a testing pump. The slope (α/ν or ν/α) of the line OR is one. At any point on the line OR, the new pump head (H) is proportional to the square of the ratio of a new flow rate (ν_R') to the rated flow (ν_R):

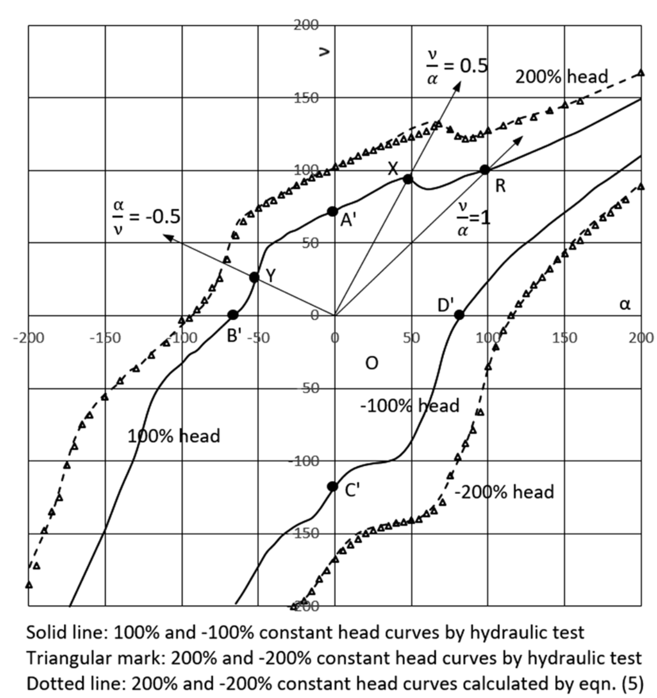

Fig. 1. Comparison of experimental and calculated complete pump characteristics. Data by Swanson (1953).