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CONF-831111--16

PREPRINT

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Tien-Hu Chen, Slawomir M. Modro

CONF-831111--16

November 13-18, 1983

DE84 005123

ASME Winter Annual Meeting

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EG&G Idaho
Idaho Falls, Idaho 83415

TRANSIENT TWO-PHASE PERFORMANCE OF LOFT REACTOR COOLANT PUMPS

Tien-Hu Chen,* Slawomir M. Modro**
LOFT Program Division
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

ABSTRACT

Performance characteristics of Loss-of-Fluid Test (LOFT) reactor coolant pumps under transient two-phase flow conditions were obtained based on the analysis of two large and small break loss-of-coolant experiments conducted at the LOFT facility. Emphasis is placed on the evaluation of the transient two-phase flow effects on the LOFT reactor coolant pump performance during the first quadrant operation. The measured pump characteristics are presented as functions of pump void fraction which was determined based on the measured density. The calculated pump characteristics such as pump head, torque (or hydraulic torque), and efficiency are also determined as functions of pump void fractions. The importance of accurate modeling of the reactor coolant pump performance under two-phase conditions is addressed. The analytical pump model, currently used in most reactor analysis codes to predict transient two-phase pump behavior, is assessed.

NOMENCLATURE

A	=	pump cross section area, m^2
H	=	head, m
h	=	homologous head ratio head/rated head, dimensionless
I	=	pump motor current, A
M_h	=	two-phase head multiplier, dimensionless
M_t	=	two-phase torque multiplier, dimensionless
N	=	rotor speed, rad/s
P	=	pump motor power, W
Q	=	volumetric flow rate, m^3/s
R_h	=	head ratio, dimensionless
T	=	pump torque, N-m
t	=	homologous torque ratio ≡ torque/rated torque, dimensionless
v	=	homologous flow ratio ≡ volumetric flow rate/rated volumetric flow rate, dimensionless
w	=	pump fluid velocity, m/s
α	=	void fraction, dimensionless
α_N	=	homologous speed ratio ≡ rotor speed/rated rotor speed, dimensionless
Δp	=	pump pressure-rise, Pa
η	=	pump efficiency
ρ	=	average density measured by three-beam gamma densitometer, kg/m^3
ρ_f	=	liquid density, kg/m^3
ρ_g	=	vapor density, kg/m^3
ϕ	=	pump energy dissipated into fluid, W

Subscripts

o	=	initial single phase value
1ϕ	=	single phase value
2ϕ	=	fully degraded two-phase value
f	=	saturated liquid condition
fr	=	friction
g	=	saturated vapor condition
hy	=	hydraulic
hl	=	hydraulic loss
m	=	pump motor
r	=	pump rated operating value
s	=	pump shaft

* Member, ASME
** Affiliated with Austrian Research Center, Seibersdorf.

INTRODUCTION

The LOFT program conducted by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory (INEL), is part of the overall reactor safety research program sponsored by the U.S. Nuclear Regulatory Commission (NRC) to investigate the behavior of pressurized water reactor (PWR) systems during a postulated loss-of-coolant accident (LOCA), and to provide data to assess and improve the reactor safety analysis computer codes used to predict PWR behavior.

The need to understand and predict the performance characteristics of reactor coolant pumps (RCPs) in transient two-phase flow stems from the necessity to accurately predict and analyze reactor thermal-hydraulic behavior during a postulated LOCA.

During a PWR LOCA, the performance of the RCP can influence the magnitude and direction of the core flow that critically controls the core heat transfer. In particular, one of the nuclear industry's concerns, since the Three Mile Island accident, has been the operation of RCPs during a small break LOCA. The important issue is controlling the primary system coolant mass inventory during a PWR small break LOCA. The LOFT small break pumps-on and pumps-off experiments showed that RCP operation during the transient significantly influenced the primary system coolant mass inventory. Therefore, a comprehensive understanding of typical RCP behavior under transient two-phase flow conditions is required before the thermal-hydraulic behavior of a PWR small or large break LOCA can be accurately analyzed.

The RCPs are generally modeled in the reactor analysis codes, such as RELAP4, RELAP5, and TRAC, with homologous relationships to derive the required pump head and torque. The two-phase head and torque degradation multipliers commonly used were based on the data from testing a small Semiscale radial-flow pump (1) which provides almost no head when the void fraction ranges from 20 to 90%. A review of RELAP4 predictions for LOFT large break LOCA Experiments L2-2 and L2-3, and RELAP5 prediction for LOFT small break LOCA Experiment L3-6 revealed that RELAP4 was unable to predict the early core quenching which occurred in L2-2 (2) and L2-3 (3), and RELAP5 failed to predict the core uncovery and fuel cladding temperature excursion which occurred in L3-6 (4). The disparity between the experiments and predictions can be attributed to the erroneous two-phase characteristics that have been used in these codes, because the LOFT pump is the mixed-flow type of centrifugal pump and has different specific speed and design characteristics from the Semiscale pump, which still develop a significant head at the intermediate void fractions.

LOFT pump performance characteristics should be obtained from the LOFT experimental data in order to provide a more realistic prediction of the LOFT experiments. This paper presents an analysis of transient two-phase performance characteristics of the LOFT reactor coolant pumps. Because the availability of experimental data on transient two-phase pump performance, especially of the reactor type mixed-flow pump is limited, results obtained from the LOFT experiments are an important contribution to understanding reactor coolant pump characteristics under actual transient conditions.

REVIEW OF PREVIOUS WORK

A detailed review of literature on centrifugal pump two-phase performance has been published by P. W. Runstadler (5) in 1976 and by D. G. Wilson (6) in 1979. A number of pump test programs have been carried out in the USA for improving and advancing the light water reactor safety technology. These included the General Electric (GE) Company high specific speed pump (7), the INEL Semiscale Mod-1 pump (8) and FAST (Full Area Steady-state Test) loop pump (9) Babcock and Wilcox (B & W) one-third scale pump (10) Combustion Engineering (CE) one-fifth scale pump (11) and Creare one-twentieth scale pump (12) test programs.

The GE pump data were limited to an inlet void fraction of 20%, which have only limited application under reactor blowdown conditions when the inlet void fraction can easily exceed 20%. The Semiscale Mod-1 pump was tested under steady-state, single-phase, and two-phase, steam-water conditions. The limited two-phase data were not adequate for defining the two-phase characteristics in all quadrants and the scatter in the data are too large to quantify the two-phase pump performance characteristics. The FAST loop pump was a mixed-flow pump with a specific speed of 4200 (in the dimension of gpm, rpm and ft) which was tested under steady-state, two-phase, nitrogen-water conditions, up to 35% pump inlet void fraction. The data indicated that this pump degraded much less than the Semiscale pump. The B & W one-third scale pump was tested at a relatively low pressure and the B & W pump showed similar degradation behavior to the Semiscale pump. The applicability of these data to reactor LOCA conditions is limited. The CE and Creare pump test programs were sponsored by Electric Power Research Institute (EPRI). The two pumps were similarly scaled to one-fifth and one-twentieth of a full scale CE reactor coolant pump. The CE test results indicated that the loss of head at intermediate void fractions is much less than for the Semiscale pump. The Creare pump was tested under two-phase air-water conditions at low pressure and under steam-water conditions at high pressure. The test data show that the head and torque degradation characteristics are functions of void fraction and flow rate.

LOFT FACILITY AND EQUIPMENT

LOFT Facility

The LOFT facility (13) is a 50-MW(t) experimental pressurized water nuclear reactor designed to simulate the major system and component responses of a commercial PWR during a hypothetical LOCA. It consists basically of the reactor vessel with the nuclear core, an operating loop with steam generator and two pumps in parallel, and a so-called "broken loop" that consists of hot and cold legs with pump and steam generator simulators. The cold and hot legs of the broken loop are connected via quick opening valves to a blowdown tank. The schematic of the LOFT facility is shown in Figure 1. The reactor coolant pump suctions are connected to the steam generator outlet. The pumps discharge to the reactor vessel is at the same elevation as the reactor vessel cold leg inlet.

LOFT Reactor Coolant Pumps

The LOFT RCPs are canned rotor, centrifugal pumps of the mixed-flow type. They are rated at a head of 96 m (315 ft), a discharge flow rate of 0.315 m^3/s (5000 gpm), and a rotational speed at 369 rad/s (3530 rpm). The dimensionless specific speed is approximately 1.2192 (or 3300 in the dimension of rpm $gpm^{0.5}$ $ft^{-0.75}$). The rated total torque is 1009 N-m (745 $ft\text{-}lb_f$) and the rated hydraulic torque is 500 N-m (369 $ft\text{-}lb_f$). The maximum overall efficiency is about 50%.

During two-phase steam-water operation, auxiliary cooling lubrication water is injected into the top bearing-cavity. This water supply cools the motor, lubricates all bearings, and prevents steam from forming inside the motor cavity while a two-phase mixture exists in the pump volute during a

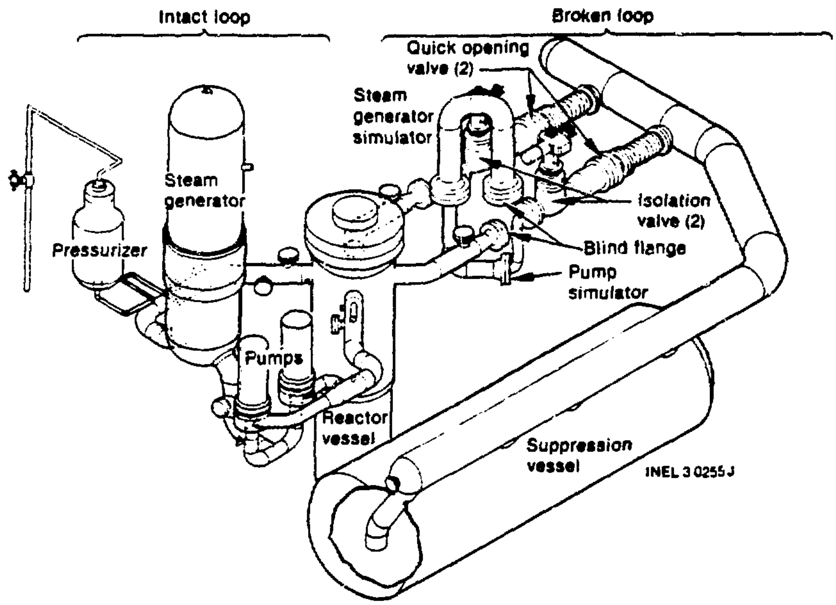

Fig.1 Axonometric projection of LOFT system

blowdown two-phase operation. Detailed information on LOFT reactor coolant pumps and instrumentation is given in Reference 14.

DESCRIPTION OF SELECTED LOFT EXPERIMENTS FOR PUMP PERFORMANCE ANALYSIS

Since 1976, over thirty experiments (large breaks, small breaks, and anticipated transients with and without scram) were conducted at the LOFT facility. None of these experiments was designed to directly address reactor coolant pump performance under transient two-phase conditions. Only in a few of the completed LOFT experiments were the pumps operated during the entire transient. Among these, the L1-5 (15) and L3-6 (16) had a fluid density measurement near the pumps inlet and outlet for determination of the void fraction at the pump. The pump performance characteristics data from these experiments are analyzed and reported in this paper.

Experiments conducted at the LOFT facility are designed to investigate overall reactor system response during postulated accident conditions. Therefore, the data presented and analyzed in this paper are limited, because they were obtained as part of a complete integral system experiments and were not directly addressed as an experiment objective. However, these data are of high value because they represent pump performance characteristics under realistic transient two-phase conditions.

Experiment L1-5 which simulated a double-ended break in a cold leg, was the fifth in the nonnuclear large LOCA experiment series. The nuclear core was installed in the reactor vessel, but the nuclear power was not generated during this experiment. One of the major experiment objectives was to provide data required to evaluate the adequacy and improve the analytical methods currently used to predict the LOCA response of LPWRs. Experiment L3-6 which simulated a 4-in. equivalent diameter cold leg break in a commercial PWR, was the fifth in a nuclear small break LOCA experiment series. The major experiment objective was to determine the effect of reactor coolant pump operation on plant response, and to provide data to analyze pump operation in transient two-phase flow. The initial conditions for these two experiments are summarized in Table 1. The detailed experiment results were given in References 15 and 16, respectively.

MEASURED PUMP PERFORMANCE CHARACTERISTICS

The operating loop of the LOFT reactor plant has two pumps in parallel. The individually measured pump speed and pressure-rise of these pumps show only slight differences. Since the mass flow rates and densities are not measured for each individual pump we assume equal distribution of the measured total mass flow rate between the two pumps and equal density in the pumps.

The normalized (to the values at zero void fraction) pump characteristics data versus the pump void

TABLE 1. INITIAL CONDITIONS FOR EXPERIMENTS L1-5 AND L3-6

Parameters	L1-5	L3-6
Power (MW)	0	50.0 ± 1
Pressure (MPa)	15.55 ± 0.20	14.70 ± 0.14
Hot leg temperature (K)	555.0 ± 5.1	577.1 ± 1.8
Cold leg temperature (K)	555.0 ± 5.1	557.9 ± 1.1
PMass flow rate (kg/s)	176.1 ± 4.4	4833.0 ± 2.6
Pump speed (rad/s)	118 ± 1.2	340.0 ± 1.2

fraction are shown for Experiments L1-5 and L3-6 in Figures 2 through 7.[a] The pump void fraction is determined by

$$\alpha = (\rho_f - \rho) / (\rho_f - \rho_g) \qquad (1)$$

where ρ is the pump average fluid density, ρ_f and ρ_g are the saturated liquid and vapor densities. The pump average fluid density is obtained by averaging the pump inlet and outlet densities which were measured respectively by two three-beam gamma densitometers near the pump inlet and outlet. Based on available instrumentation, the saturated liquid and vapor densities were determined from the measured pressure near the pump. The pressure-rise across the pumps are small compared with the system pressure; therefore, the variation of saturated liquid and vapor densities across the pumps are also small and negligible. Void fraction is calculated assuming homogeneous flow and equilibrium between the two phases. This assumption is reasonable because the data taken during the rapid subcooled blowdown and during emergency coolant (accumulator) injection are not used to evaluate the void fraction.

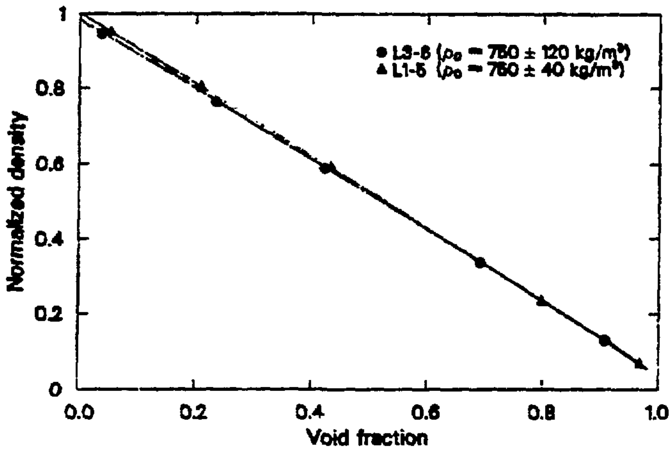

Fig. 2 Normalized pump fluid density

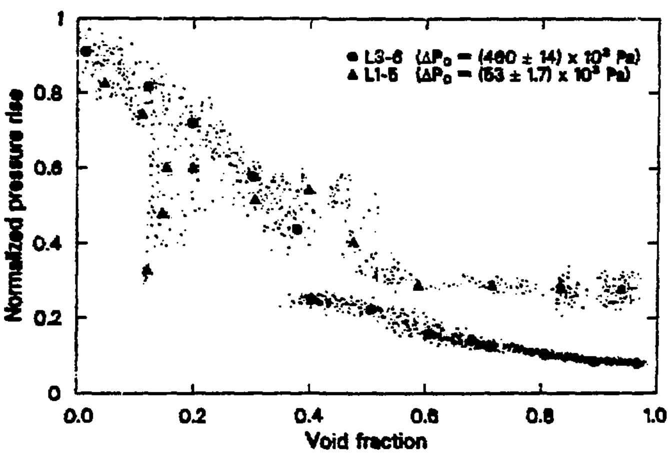

Fig. 3 Normalized pressure-rise across the pump

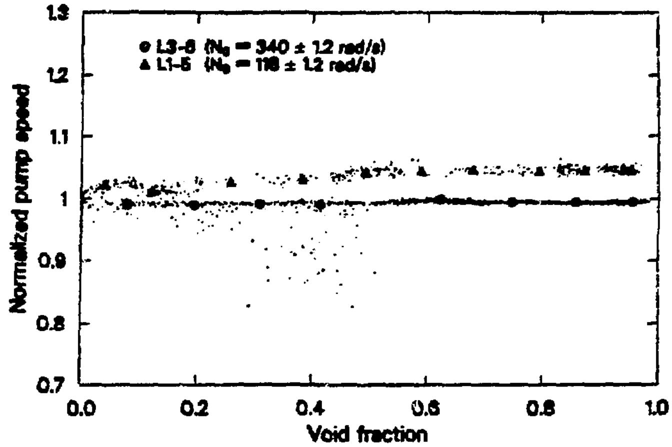

Fig. 4 Normalized pump rotational speed

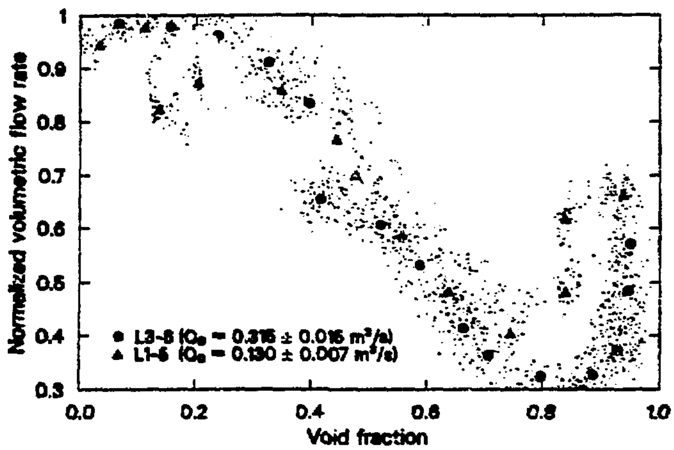

Fig. 5 Normalized pump volumetric flow rate

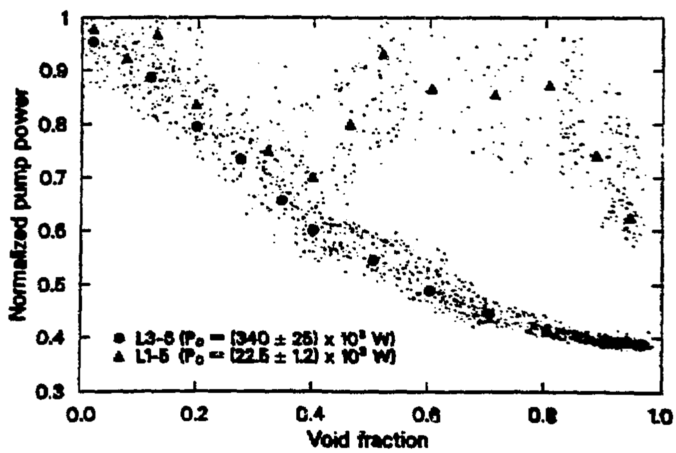

Fig. 6 Normalized pump motor power

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a. The LOFT data were collected at certain samples per second during the experiment. The pump void fraction calculated from the measured density has the same points as the density. When the time parameters are correlated, the resultant data are plotted against the corresponding void fraction values as the point plots. Each point in the figure represents the actual data point, and also represents temporal variations in the plotted parameters. The large symbols do not represent time-averaged values. They are plotted to distinguish the data from two different experiments.

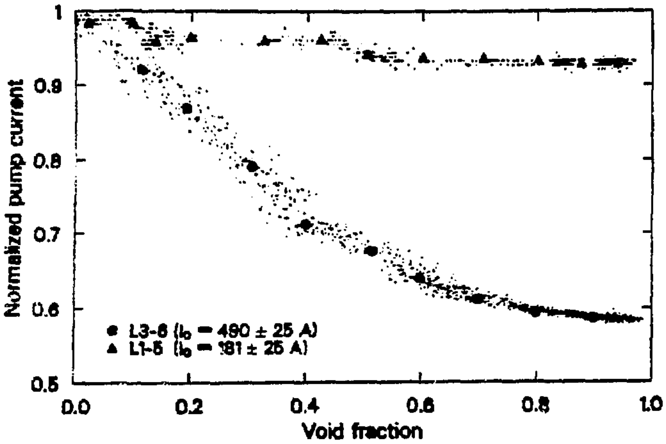

Fig. 7 Normalized pump motor current

Figure 2 shows how the pump fluid densities change with respect to the pump void fraction. The pump fluid density decreases linearly as the void fraction increases. The measured densities obtained from two different experiments closely match each other. The pressure-rise across the pump is presented in Figure 3. For Experiment L1-5, the pump pressure-rise decreases gradually to approximately 80% of the single-phase value around 13% void. Then, the pump pressure-rise suddenly drops to 30% and recovers to about 50 to 60% at about 20% void fraction. The pump pressure-rise again drops to approximately 30% when void fraction is greater than 45%. For Experiment L3-6, the pump pressure-rise decreases from its single-phase value to 50% and suddenly drops to 25% at approximately 35% void. Then, the pump pressure-rise continuously decreases to 10% at about 95% void. The reason for the earlier pump pressure-rise degradation in Experiment L1-5 is related to the lower initial pump operation efficiency and transient system effects.

The measured pump speed is presented in Figure 4. It shows that the LOFT reactor coolant pump was operating at nearly constant speed throughout both transients. The pump speed oscillations observed in Experiment L3-6 between 10 to 50% void are probably due to measurement noise since the pump speed cannot change that rapidly because of the large pump inertia and the measured pressure-rise and flow rate are not indicating changes corresponding to the speed oscillations. The measured pump pressure-rise is expressed in homologous form as $\Delta p' = \Delta p \times N_o^2 / N^2$, so that the effects of small speed changes can be removed from the analysis. Figure 5 shows the volumetric flow rate through the pump. Generally, the volumetric flow rate obtained from both experiments shows similar characteristics except for the sudden drop in value occurring at 13% void in L1-5 and 35% in L3-6, respectively. These sudden decreases in flow rates correspond to the drop in measured pump pressure-rise. The almost constant flow rate maintained between 13 to 40% void, is attributed to the recovery of pump pressure-rise (see Figure 3). The measured power and current are shown in Figures 6 and 7, respectively. The pump motor power and current show similar characteristics during the entire L3-6 transient, while they exhibit slightly oscillatory behavior during the L1-5 transient. It can be also seen that the current degradation is less than the power degradation in L1-5.

Figures 2 and 5 indicate that the LOFT RCPs operated in the first quadrant positive speed and flow condition (normal operation mode). The measured data indicate that the RCPs incurred no damage when subjected to a rapidly or slowly depressurizing two-phase environment.

CALCULATED PUMP PERFORMANCE CHARACTERISTICS

The pump head (Figure 8) is computed from the measured pressure-rise across the pump divided by the pump average fluid density multiplied by the gravitational acceleration:

$$H = \Delta p / \rho g \quad . \tag{2}$$

The heads show a response similar to the measured pressure-rises except that the heads start to recover when the void fraction is greater than 50% in L1-5 and 75% in L3-6. The measured pressure-rise in L1-5 is larger than that of L3-6 and the pump fluid densities are about the same. The pump head recovery is noted to occur earlier in L1-5 than for of L3-6. The pump head uncertainty may be larger at high void fractions due to the division of two small fluctuating quantities.

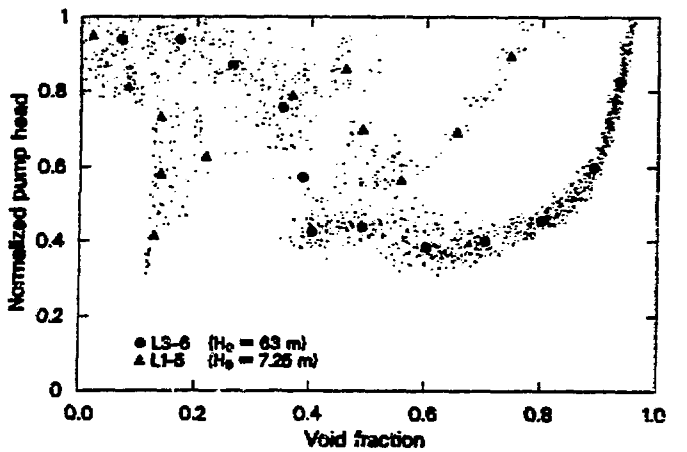

Fig. 8 Normalized pump head

The pump shaft torque (Figure 9) is computed from the measured pump motor power divided by the pump speed and multiplied by the pump motor efficiency:

$$T_s = (P / N) \times \eta_m \tag{3}$$

where η_m is the pump motor efficiency obtained from Reference 17 and is given as a function of pump speed and voltage to pump frequency ratio. The pump motor efficiency is about 68% for L1-5 and 74% for L3-6. The pump shaft torque shows response similar to the measured pump motor power (see Figure 6) because the measured pump speed and voltage are only slightly changed during the transients. The hydraulic torque (Figure 10) is obtained from

$$T_{hy} = \Delta p \times Q / N \quad . \tag{4}$$

The hydraulic torques show a response similar to that of the measured pump pressure-rises (Figure 3) except

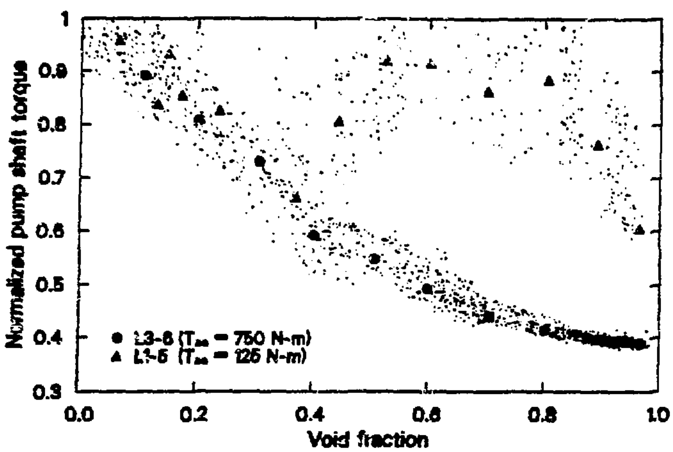

Fig. 9 Normalized pump shaft torque

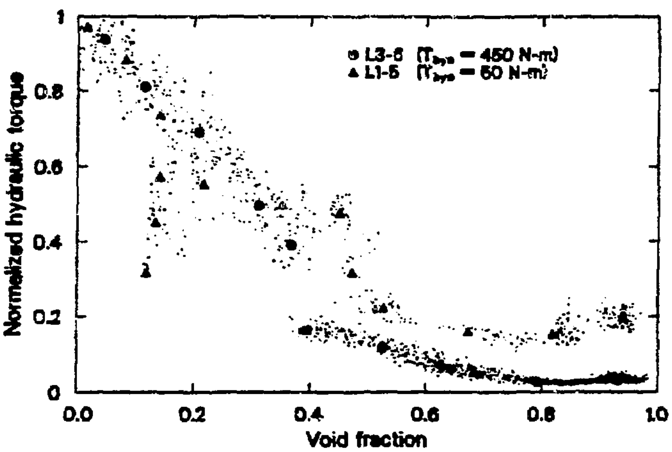

Fig. 10 Normalized pump hydraulic torque

slightly larger degradations are observed because the volumetric flow rates decrease as void fractions increase before 75% in L1-5 and 85% in L3-6.

The calculated pump efficiency (hydraulic torque/pump shaft torque) is shown in Figure 11. It can be seen that the pump efficiency is reduced substantially as void fraction increases. The LOFT RCPs were initially operated at a lower flow rate in L1-5 and were less efficient than in L3-6; therefore, the pump performance also degrades earlier. During the two-phase operation, a high percentage of the shaft power is lost in the pump impeller hydraulic loss, and friction losses of disc, seals, and bearings. This inefficiency of the pump during two-phase operation should be modeled as heat or energy dissipated into the fluid which may be a significant percentage of the reactor decay power during the small break LOCA and cannot be ignored.

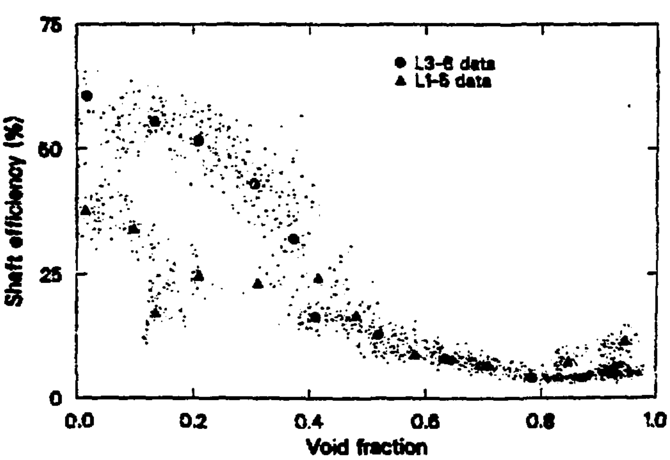

Fig. 11 Pump shaft efficiency

REACTOR COOLANT PUMP PERFORMANCE PREDICTIONS

The pump two-phase performance characteristics prediction model, used in the current reactor analysis computer codes (e.g., RELAP4, RELAP5, and TRAC) is based on an empirical rather than a mechanistic solution to the pump flow equations under two-phase conditions. These codes use homologous relationships to determine pump head and torque at a given speed and volumetric flow rate. When the pump operates under two-phase conditions, a two-phase head and a torque multiplier obtained from pump test data (usually Semiscale) are used to adjust the calculated pump head and torque as a function of void fraction. Two-sets of head and torque homologous curves are generally input in the code; one for single-phase condition and the other for the difference between the single-phase and fully degraded two-phase conditions (minimum two-phase performance). The two-phase head and torque are calculated as follows:

$$H(v, \alpha_N, \alpha) = H_{1\phi}(v, \alpha_N) - M_h(\alpha)\,[h_{1\phi}(v, \alpha_N) - h_{2\phi}(v, \alpha_N)] \times H_r \qquad (5)$$

$$T(v, \alpha_N, \alpha) = T_{1\phi}(v, \alpha_N) - M_t(\alpha)\,[t_{1\phi}(v, \alpha_N) - t_{2\phi}(v, \alpha_N)] \times T_r\,. \qquad (6)$$

The pressure-rise across the pump, used in the momentum equation, is obtained from Equation (5), and the torque obtained from Equation (6) is used to compute the pump inefficiency which is modeled as heat dissipation into the fluid in the energy equation. The torque is also used to calculate the change of pump speed during the pump coastdown. The detailed modeling of the RCPs in the reactor analysis code RELAP5 can be found in Reference 18.

To obtain a more representative momentum and energy balance for calculating the transient phenomena during LOCEs, the pump two-phase performance characteristics must be accurately predicted. Therefore, pump two-phase degradation data in terms of head and torque multipliers should be obtained from pump test data from a similar pump. The LOFT pump two-phase performance characteristics should be analyzed and used for predicting the LOFT experiments.

Figures 12 through 15 present the homologous two-phase head compared with the single-phase head (19) for L1-5 and L3-6 Experiments, respectively. In Experiment L1-5, in which the RCPs were initially operating at $\alpha_N/v = 0.75$, the head matches closely with the single-phase head curve. As void fraction increases, the volumetric flow rate decreases. However, the pump speed remains almost constant; therefore, α_N/v will increase. The pump head degrades to

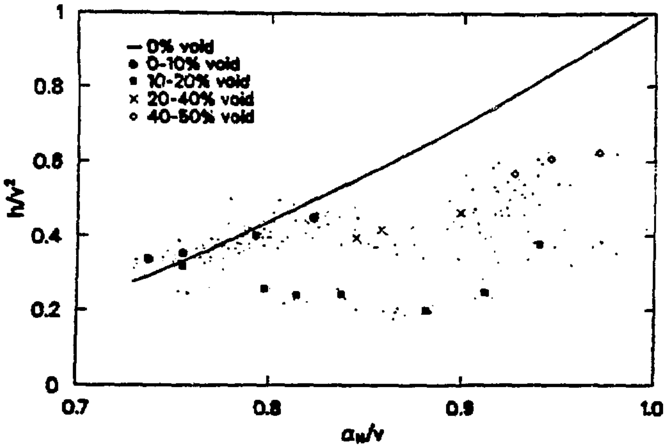

Fig. 12 L1-5 two-phase head vs. single-phase head (HVN)

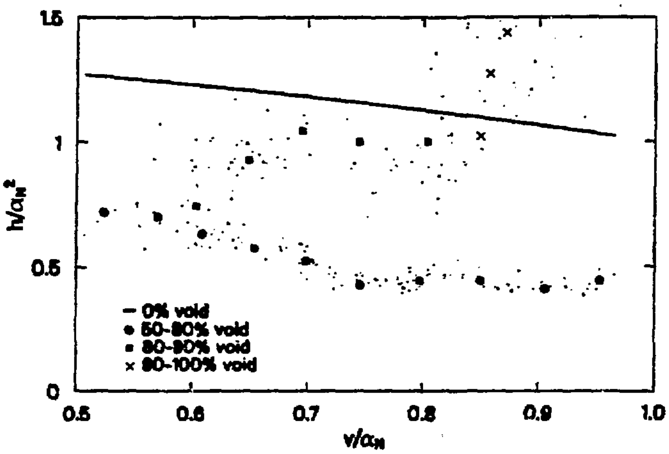

Fig. 13 L1-5 two-phase head vs. single-phase head (HAN)

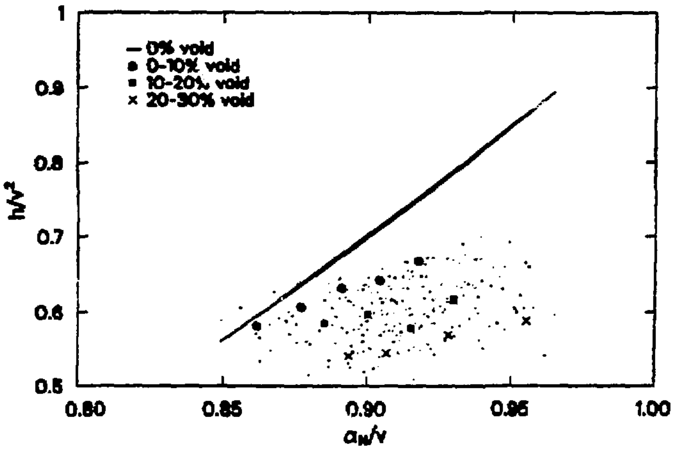

Fig. 14 L3-6 two-phase head vs. single-phase head (HVN)

about 50% of its single-phase head at $\alpha_N/v = 1.0$ (see Figure 12). The pump head indicates more degradation at 10 to 20% void than that at 20 to 50%, which is attributed to the pump pressure-rise recovery

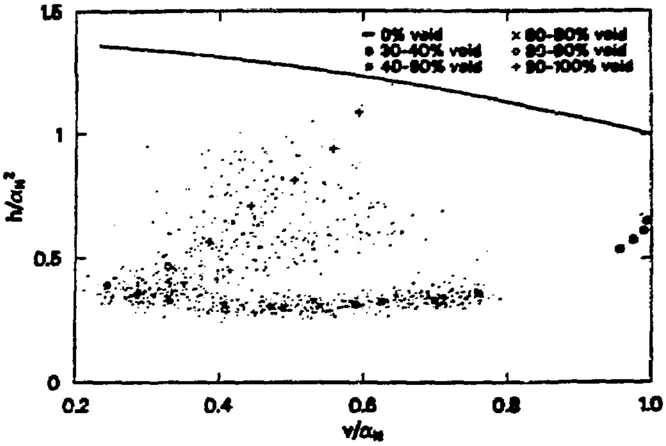

Fig. 15 L3-6 two-phase head vs. single-phase head (HAN)

after the initial drop, and smaller fluid density. This behavior is due to transient system effects on the pump performance. When $\alpha_N/v \geq 1.0$ (i.e., $v/\alpha_N \leq 1.0$), increasing the void fraction results in a decrease in flow rate and v/α_N starts to decrease (Figure 13). The head remains at about 50% of the single-phase value. When the void fraction reaches about 75%, the volumetric flow rate increases because more steam exists in the pump. The head starts to recover and reaches the single-phase head at about 80% void. Beyond this void fraction, the calculated head exceeds its single-phase value, which may be due to the larger uncertainty in the measurement of pump pressure-rise at the higher void fractions. Figures 14 and 15 show similar pump performance characteristics in Experiment L3-6. Similar performance characteristics can also be obtained for pump torques.

Generally, the pump two-phase performance characteristics depend on both void fraction and homologous independent variables (either α_N/v or v/α_N). Homologous independent variables should be kept the same (namely, the two-phase head to single-phase head ratio should be obtained at the same flow conditions) in order to compare the pump two-phase performance with its single-phase performance. The head ratio is defined as

$$R_h(\alpha) = \frac{H(v, \alpha_N, \alpha)}{H(v, \alpha_N, \alpha = 0)} . \quad (7)$$

The head ratios obtained in accordance with Equation 7 for Experiments L1-5 and L3-6 are shown in Figure 16. The results clearly indicate that the minimum two-phase head (i.e., fully degraded head) is about 25 to 30% of its single-phase values. The loss of head at intermediate void fractions (13% to 60% for L1-5, and 35 to 80% for L3-6) is much less for the LOFT pump than for the Semiscale pump that develops almost no head in these void fraction ranges. The LOFT pump two-phase head performance characteristics obtained from L3-6 data show close similarity with the CE/EPRI steady state pump test results (11), while that from L1-5 data show different response. The critical void fraction in which the pump performance suddenly degrades to the minimum performance varies with the initial operating conditions (i.e., pump initial operating efficiency).

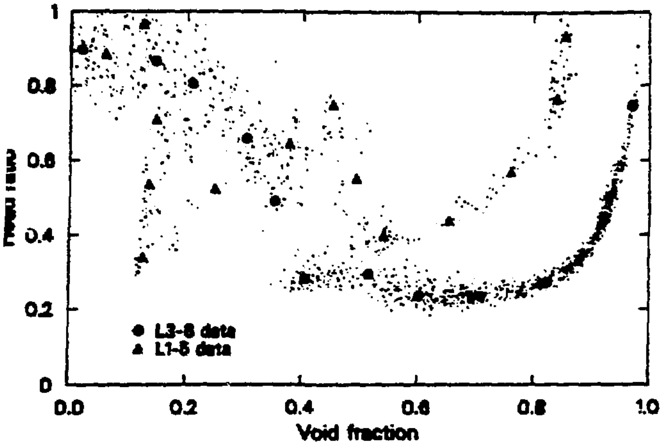

Fig. 16 Two-phase head to single-phase head ratio

Similar results were also identified by the Creare pump test results (12) that indicate that the initial degradation of pump head performance is a function of both void fraction and flow rate.

The differences between the homologous single-phase and fully degraded two-phase heads is simply equal to the homologous single-phase head if the fully degraded two-phase head is zero. The head multiplier can be related to the head ratio simply as:

$$M_h(\alpha) \approx 1 - R_h(\alpha) \quad . \qquad (8)$$

The LOFT data indicate that $M_h(\alpha)$ varies with void fraction as well as pump initial operating conditions; however, the pump performance prediction model used in the current reactor analysis codes incorrectly assumed $M_h(\alpha)$ is only a function of the void fractions. Similar multipliers can also be developed in terms of the actual fully degraded two-phase head.

The pump inefficiency is modeled as energy dissipation into the fluid, that is:

$$\Phi = (T_s - T_{hy}) \times N$$

$$= T_s N - \Delta p \times A \, [\alpha \rho_g w_g + (1-\alpha) \rho_f w_f] / \rho \qquad (9)$$

where $T_s = T_{hy} + T_{hl} + T_{fr}$.

T_{hl} is the torque due to the hydraulic loss of the pump impeller; T_{fr} is the torque due to friction losses of pump disc, seals, and bearing.

In computer codes such as RELAP5, the pump inefficiency modeling as energy dissipation is incomplete because the hydraulic loss through the pump impeller, which may be significant during two-phase operation, is not accounted for in the computation. The power losses due to various frictions are not computed until the pump coastdown and also the input requirement for shaft torque or impeller torque is incorrectly referred to as hydraulic torque.

Therefore, no hydraulic and friction losses are accounted for, and either no heat is added into the pump fluid for positive Δp or too much heat is added into the fluid for negative Δp. The deficient modeling of pump energy dissipation in RELAP5 is evident and was reported in Reference 20.

It is believed that the current pump performance prediction model used in the RELAP5 code needs improvements before pump characteristics can be well predicted. No data for torque multiplier are presented in this paper because, despite correct multipliers, the energy dissipation into the fluid will not be computed properly.

CONCLUSION

LOFT experiments have provided valuable information about pump characteristics under transient two-phase flow conditions even though the facility was not designed to investigate pump performance in particular but integral reactor system behavior. Based on experimental pump performance data two-phase head multipliers were developed to allow proper code simulation of experiments such as L3-6. The LOFT experiments indicated that two-phase pump head degradation for the LOFT pumps is not as strong as degradation of the Semiscale pumps. The LOFT pumps can provide primary coolant flow through the core even with significant system void fractions. It is believed that this property of the LOFT pumps is similar to the two-phase characteristics that should be expected for reactor coolant pumps in large commercial power plants. The data presented in this paper showed significant influence of transient system effects on pump performance in large break LOCAs, which, together with the pump data obtained during small break LOCA, should be useful for transient two-phase model development. Because the pump two-phase flow performance depends strongly on initial operating conditions and transient flow rates, the pump performance degradation characteristics in future models should depend on single-phase operating efficiency and be represented as a function of void fraction and flow rates. In most of today's codes, pump energy dissipation models also need to be improved.

REFERENCES

1. Loomis, G. G., "Intact Loop Pump Performance During the Semiscale MOD-1 Isothermal Test Series," TID-4500, R63, October 1975, Aerojet Nuclear Co., Idaho Falls, Idaho.

2. Batt, D. L., "Quick Look Report on LOFT Nuclear Experiment L2-2," LOFT-TR-103, December 1978, EG&G Idaho, Inc., Idaho Falls, Idaho.

3. Reeder, D. L., "Quick Look Report on LOFT Nuclear Experiment L2-3," QLR-L2-3, May 1979, EG&G Idaho, Inc., Idaho Falls, Idaho.

4. McCreery, G. E., "Quick Look Report on LOFT Nuclear Experiment L3-6/L8-1," EGG-LOFT-5318, December 1980, EG&G Idaho, Inc., Idaho Falls, Idaho.

5. Runstadler, P. W., "Review and Analysis of State-of-the-Art of Multiphase Pump Performance," EPRI Report RP 347, February 1976, Creare R&D Inc., Hanover, New Hampshire.

6. Wilson, D. G., et al., "Analytical Model and Experimental Studies of Centrifugal Pump Performance in Two-Phase Flow," EPRI Report NP-677, California 1979.

7. Sozzi, G. L., and Burnette, G. W., "Two-Phase Pump Performance During a Simulated LOCA Blowdown," Report NEDE-13239, Class 1, 1971, General Electric, San Jose, California.

8. Olson, D. J., "Single- and Two-Phase Performance Characteristics of the Mod-1 Semiscale Pump Under Steady-State Conditions," ANCR-1165, 1974, Aerojet Nuclear Co., Idaho Falls, Idaho.

9. Chen, T. H., and Quapp, W. J., "Centrifugal Pump Performance Under Simulated Two-Phase Flow Conditions," Polyphase Flow and Transport Technology, ASME H00158, pp. 175-184.

10. Cudlin, J. J., "One-Third Scale Air-Water Pump Program, Analytical Pump Performance Model," EPRI Report NP-160, October 1977, Babcock and Wilcox, Lynchburg, Virginia.

11. Kennedy, W. G., et al., "Pump Two-Phase Performance Program," EPRI Report NP-1556, September 1980, Combustion Engineering, Inc., Windsor, Connecticut.

12. Runstadler, P. W., and Dolan, F. X., "Two-Phase Pump Data for a Scale Model NSSS Pump," Polyphase Flow in Turbomachinery, ASME H00123, 1978, pp. 65-77.

13. Reeder, D. L., "LOFT System and Test Description (5.5-ft Nuclear Core 1 LOCES), TREE-1208, July 1978, EG&G Idaho, Inc., Idaho Falls, Idaho.

14. Hunter, J. A., and Harris, P. A., "Performance of Small Nuclear Reactor Primary Coolant Pumps Under Blowdown Conditions," Polyphase Flow in Turbomachinery, ASME H00123, 1978, pp. 157-170.

15. Jacoby, M. J., "Experiment Data Report for LOFT Nonnuclear Test L1-5," TREE-NUREG-1215, June 1978, EG&G Idaho, Inc., Idaho Falls, Idaho.

16. Bayless, P. D., and Carpenter, J. M., "Experiment Data Report for LOFT Nuclear Small Break Experi- ment L3-6 and Severe Core Transient Experi- ment L8-1," NUREG/CR-1868, January 1981, EG&G Idaho, Inc., Idaho Falls, Idaho.

17. Roth, F. S., and Maday, G. S., "Analytical Study of LOFT Coolant Pump Electrical System for EG&G Idaho, Inc.," GE Report 433-97543, December 1977, General Electric, Schenectady, New York.

18. Ransom, V. H., "RELAP5/MOD1 Code Manual Volume 1: Systems Models and Numerical Methods," NUREG/CR-1826, March 1982, EG&G Idaho, Inc., Idaho Falls, Idaho.

19. Payne, H. M., and Klebauskas, J. J., "LOFT Primary Coolant Pump Tests," KDL-74-M-36, June 1974, Combustion Engineering, Inc., Windsor, Connecticut.

20. Riemke, R. A., et al., "RELAP5/MOD1 Code Manual Volume 3: Checkout Problems Summary," EG&G-NSMD-6182, February 1983, EG&G Idaho, Inc., Idaho Falls, Idaho.