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AXIAL AND CENTRIFUGAL PUMP MEANLINE PERFORMANCE ANALYSIS

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SUMMARY

A meanline pump flow modeling method has been developed to provide a fast capability for modeling pumps of cryogenic rocket engines. Based on this method, a meanline pump flow code (PUMPA) has been written that can predict the performance of pumps at off-design operating conditions, given the loss of the diffusion system at the design point. The design point rotor efficiency is obtained from empirically derived correlations of loss to rotor specific speed. The rapid input setup and computer run time for the meanline pump flow code makes it an effective analysis and conceptual design tool. The map generation capabilities of the PUMPA code provides the information needed for interfacing with a rocket engine system modeling code.

DISCUSSION

The pump meanline flow modeling code (PUMPA) has been written to provide a rapid evaluation of pump design concepts. Once the design operating performance is established, the code can estimates the off-design performance. The ability to predict pump off-design performance is necessary for evaluating turbopumps for rocket engine systems. During the conceptual design phase of new liquid propellant rocket engine systems, the performance of the turbopumps at off-design operating conditions can influence the design of the pump. The pump code is based on the Euler equation coupled with empirical relations for rotor efficiency. The diffusion system loss at the design point is input and varied at off-design by an empirical relation. The code provides the capability to predict pump performance at all operating conditions encountered during engine throttling. PUMPA provides an estimate of flow incidences, pump stall, losses and cavitation inception at off-design operating conditions. In the design process of pumps, a single operating point for which to optimize the geometry may not be adequate because of often conflicting system requirements. By knowledge of the flow-physics at off-design conditions, the designer can optimize the pump configuration to provide acceptable pump and system performance during engine throttling. The match between the pump rotor and the diffusion system influences the slope of the pump map and can effect the location of the stall and cavitation inception lines. The flow along a speedline where the static pressure is equal to the vapor pressure determines the cavitation inception point. The suction performance at off-design conditions is based on empirical correlations to the suction performance at design. The pump configuration, flowpath and number of stages that will result in an acceptable system performance can be quickly determined by the use of this meanline flow modeling method.

The meanline pump flow modeling method can be used to model inducers, mixed-flow, and centrifugal pumps. The flow code has multi-stage capability with up to four stages in series. The code has empirically derived rotor loss correlations to specific speed based on tests of several rocket engine turbopump and research rigs. The predicted values of rotor efficiency.and slip factor can be modified by correction factors which have a default value of 1.0. The default values of rotor efficiency correction, slip factor correction and diffusion system loss at the design point enable the pump code to estimate the stage performance at the design point, as well as at off-design operating conditions. For a given inlet pressure and temperature, the code can generate a pump map. Fluid options are liquid hydrogen, liquid oxygen, liquid nitrogen JP-4, water, and air. Fluid properties are obtained from GASPLUS (1).

A minimal number of dimensions can adequately describe the rotor and the diffusion system for each stage. Figure 1 shows the locations of some of the key parameters required to specify the dimensions of the rotor and the diffuser. The flowpath radii and the blade angles are input at the leading and trailing edges at both the hub and tip. The diffusion system dimensions are specified in terms of inlet and exit axial widths, radii, volute or diffuser throat area, volute tongue or diffuser leading edge angle and exit flange area. Pump inlet fluid conditions are specified in terms of design rotational speed, fluid flowrate, pressure, temperature and inlet swirl.

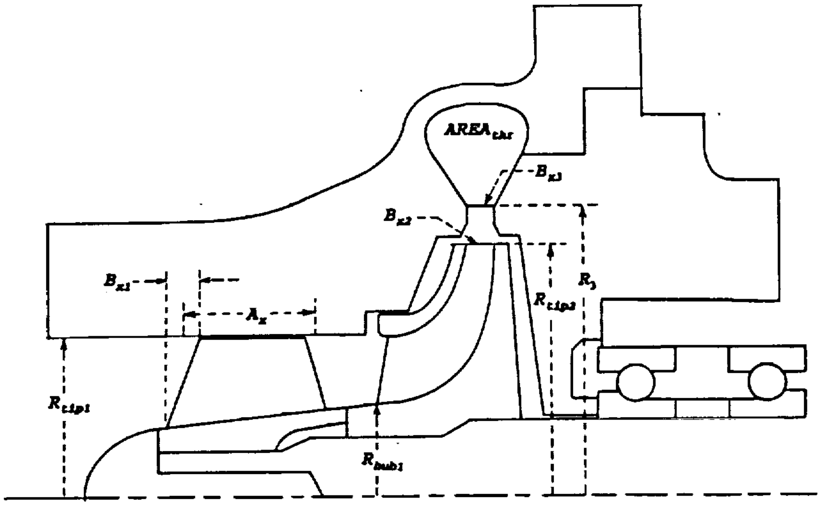

Figure 1. Pump Stage with Axial Inducer and Centrifugal Impeller.

The PUMPA code output consists of flow conditions at the rotor leading and trailing edges, as well as the diffusion system inlet and outlet. The output describes the flow conditions in terms of velocities, flow angles, pressures and temperatures. Velocities and flow angles are calculated in both the relative and the absolute frames of reference. Static and total pressures and temperatures are calculated at the discharge of the rotor and stage. The total head rise, horsepower and efficiency are summarized and plotted (2) for each stage and the overall pump.

Rotor Work

The work performed by the rotor is calculated from the Euler equation and is reflected by the inlet and exit velocity triangles and the rotor efficiency. The flow area at the rotor inlet is calculated from the input flowpath dimensions. The available flow area is compensated for the effects due to metal blockage of the rotor blade and the boundary layer blockage. The blade blockage is included in the inlet velocity triangle calculations. The meridional velocity of the fluid at the rotor leading edge root-mean-square (RMS) diameter is calculated from the mass flow and the available flow area. Figures 2, 3 show the absolute and relative components of velocity at the inlet and exit.

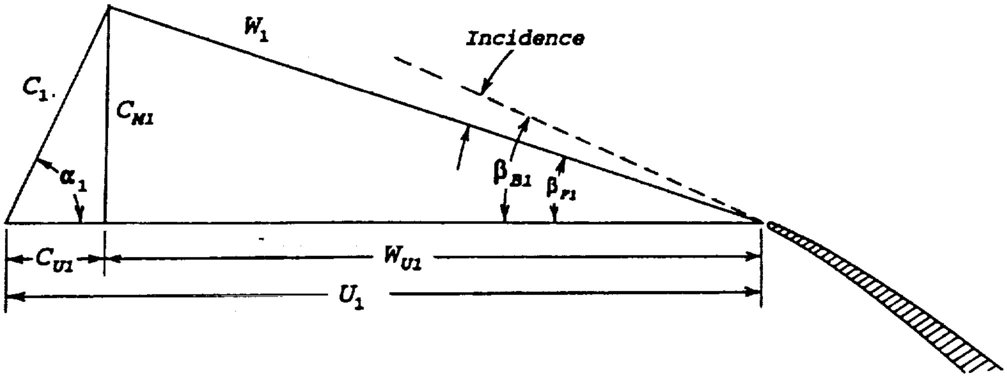

Figure 2. Rotor Inlet Velocity Triangle

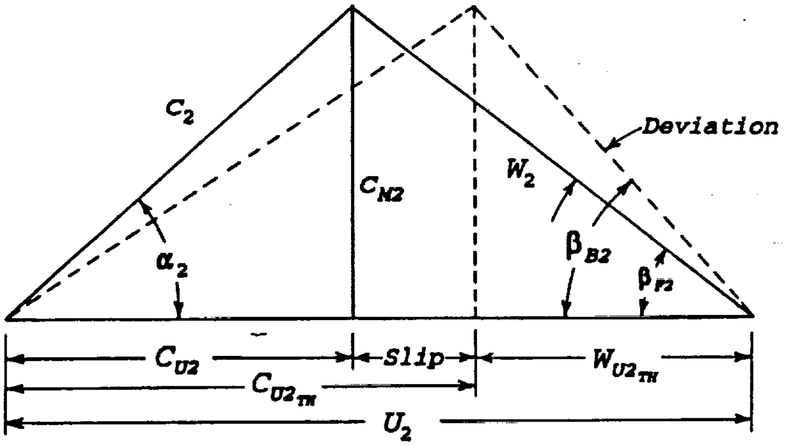

Figure 3. Rotor Exit Velocity Triangle

Rotor Efficiency

The best efficiency point (BEP) rotor efficiency in terms of total-to-total conditions is determined from empirical correlations (3). Figure 4 shows the rotor best efficiency point (BEP) polytropic efficiency database as a function of rotor dimensionless specific speed. The figure shows the relative location and expected efficiency levels for three basic types of pumps: centrifugal, mixed-flow and axial, or inducer.

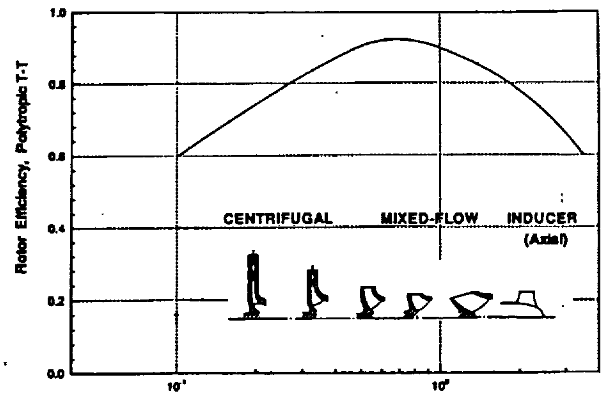

Figure 4. Rotor Efficiency at the BEP vs. Specific Speed

The off-design variation of rotor efficiency has been empirically derived from pump data. A plot showing the efficiency variation is shown in Figure 5.

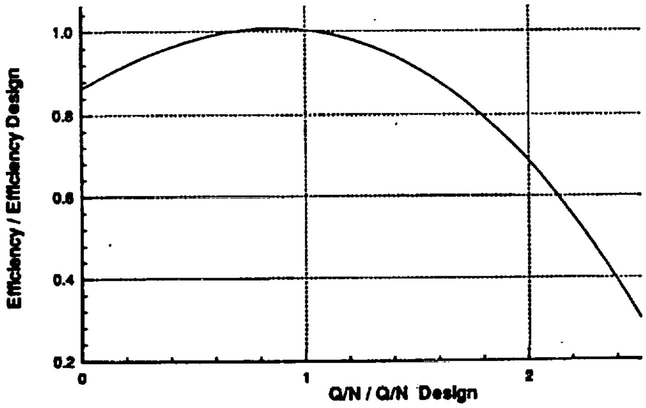

Figure 5. Rotor Efficiency at Off-Design Flow-Speed Parameter (Q/N)

Suction Performance

The net positive suction head of a pump is a function of the inlet total pressure and the vapor pressure of the fluid. Rotor suction performance is estimated by comparing the static pressure at the rotor tip (throat) region to the local vapor pressure. Typically, the highest relative fluid velocity is at the blade tip near the throat region. The high velocity causes a local reduction of static pressure and reaches a value equal to the vapor pressure at the onset of cavitation. The suction performance capability at off-design operating conditions is lower than at the design condition due in part to increased levels of incidence that result in separations and reduced flow area at the rotor leading edge (4). The suction performance at off-design flow conditions is estimated using an empirically derived map in Figure 6.

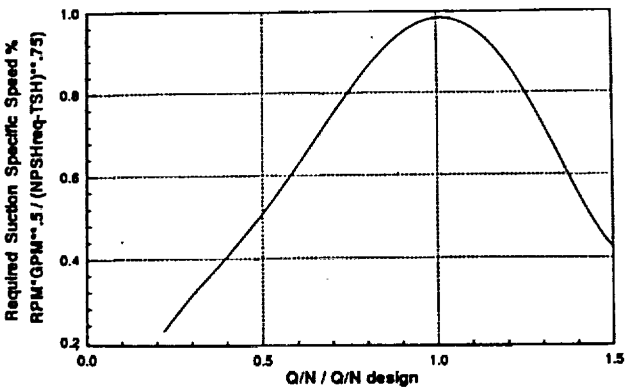

Figure 6. Suction Performance at Off-Design Flow-Speed Parameters (Q/N).

Diffusion System: Static Pressure Recovery; Total Pressure Loss

The design point total pressure loss coefficient of the diffusion system is assumed to be known and is input in terms of a normalized loss coefficient. The loading parameter is defined in terms of the velocities at the vaneless diffuser exit and the velocity at the diffusion system throat. The diffusion system pressure loss at off-design conditions is varied by empirical correlations to loading (Figure 7).

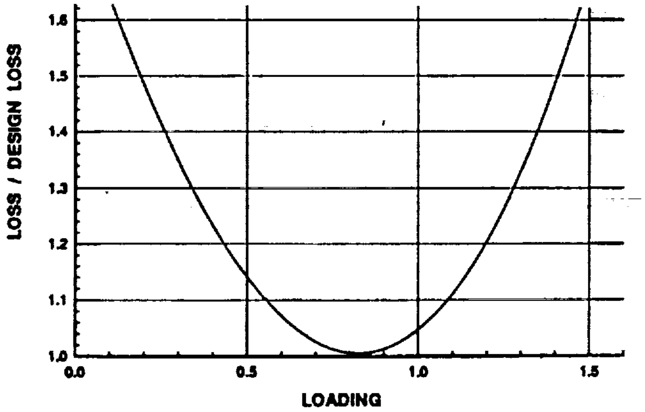

Figure 7. Diffusion System Pressure Loss Coefficient vs. Loading.

SAMPLE PUMP ANALYSIS

The PUMPA flow code can be used as an analysis tool in the conceptual design phase of new pumps since it requires minimal input and has fast setup and computer run times. The performance of candidate pump configurations can be assessed with reasonable accuracy. The code can predict the shape of the pump off-design head-flow characteristic performance map and can provide pump maps for system evaluation of the complete rocket engine. Figure 8a shows the cross-section of a pump (Ref. 5). A PUMPA flow model of the pump resulted in the performance map shown in Figure 8b. The test data is superimposed for comparison.

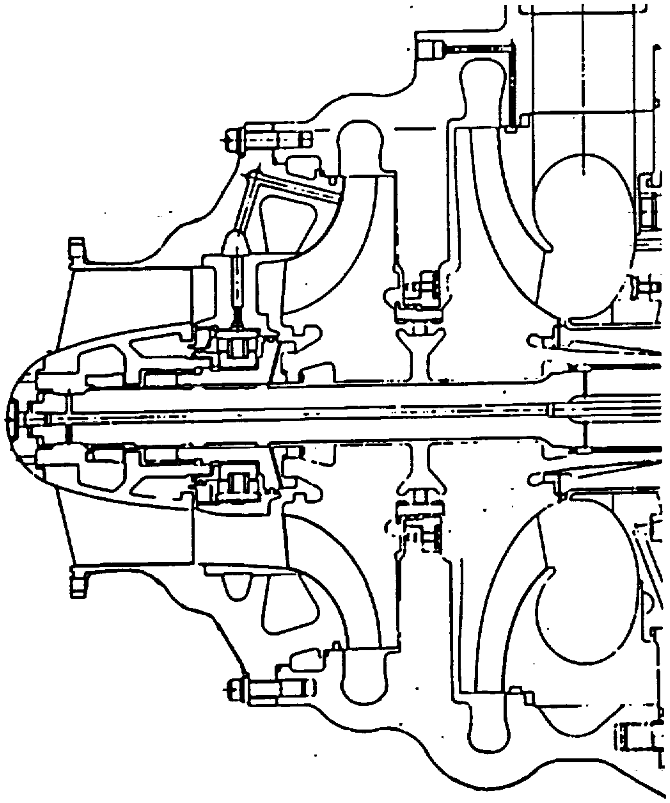

Figure 8a. XLR-129 Liquid Hydrogen Turbopump

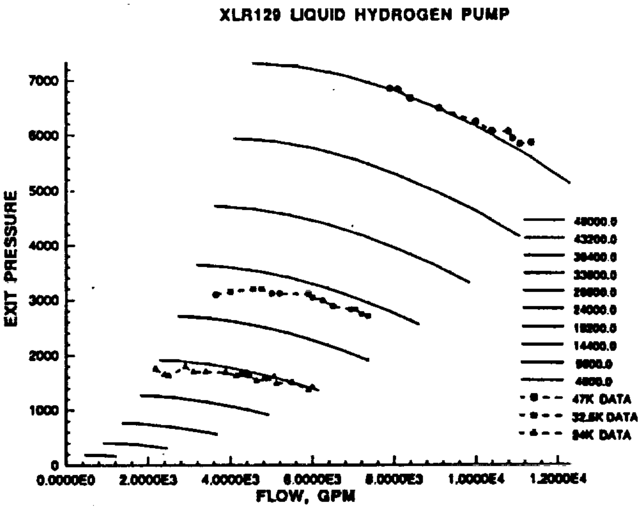

Figure 8b. Pump map with test data

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