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DYNAMIC MODELING OF STARTING AERODYNAMICS AND STAGE MATCHING IN AN AXI-CENTRIFUGAL COMPRESSOR

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ABSTRACT

A DYNamic Turbine Engine Compressor Code (DYNTECC) has been modified to model speed transients from 0-100% of compressor design speed. The impetus for this enhancement was to investigate stage matching and stalling behavior during a start sequence as compared to rotating stall events above ground idle. The model can simulate speed and throttle excursions simultaneously as well as time varying bleed flow schedules. Results of a start simulation are presented and compared to experimental data obtained from an axi-centrifugal turboshaft engine and companion compressor rig. Stage by stage comparisons reveal the front stages to be operating in or near rotating stall through most of the start sequence. The model matches the starting operating line quite well in the forward stages with deviations appearing in the rearward stages near the start bleed. Overall, the performance of the model is very promising and adds significantly to the dynamic simulation capabilities of DYNTECC.

NOMENCLATURE

A	Flow Area
e	Internal Energy
F	Blade Force
H	Total Enthalpy
M	Mach Number
P	Pressure
Q	Heat Addition
R	Ideal Gas Constant
S	Shaft Work
T	Temperature
t	Time
U	Axial Flow Velocity
W	Mass Flow Rate
x	Axial Coordinate
ρ	Density
γ	Specific Heat Ratio

Subscripts

B	Bleed Flow
s	Static Property
t	Total (Stagnation) Property
x	Axial Direction

INTRODUCTION

The development of reliable high performance gas turbine engines continues to be one of the most challenging engineering endeavors of the 20th century. In today's competitive market, engine designers rely increasingly on the ability to numerically simulate engine performance throughout the entire region of operation. To this end, considerable effort has been devoted to modeling the compression system of gas turbines with particular attention to multistage axial compressors for aircraft applications. The work presented here stems from a consortium of government, industrial, and academic members known as the Joint Dynamic Airbreathing Propulsion Simulations (JDAPS) partnership whose mission is to advance the state of the art in numerical modeling of gas turbine engine components (Davis et al., 1995).

BACKGROUND

Numerous publications in the past two decades have been devoted to understanding the phenomenon of surge and rotating stall in axial flow multistage compressors. Numerical models capable of predicting post stall behavior generally gained acceptance with the lumped volume approach of Greitzer (1976) and have evolved into finite difference control volume methods which can isolate aerodynamic behavior of an individual stage. One widely accepted and validated model known as DYNTECC was developed by Davis and O'Brien (1986,1991) and has become the cornerstone of the JDAPS modeling effort.

An application of this model by O'Brien and Boyer (1989) was able to identify the critical stages in a 10 stage high performance compressor which exhibited a rotating stall problem at mid speeds. One conclusion of their results was that stall recovery problems at mid-range speeds can be identified as an extension of the starting problems typically encountered from zero speed to ground idle. This "extended starting" theory postulated that methods which provide for aerodynamic starting at low speeds will produce recovery at higher

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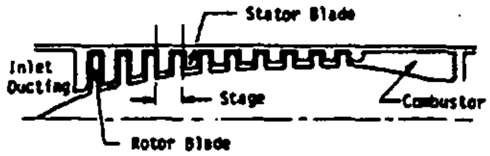
speeds if properly applied. The work presented here was originally undertaken to investigate this extended starting theory from the perspective of a dynamic model. The T55-L-712 turboshaft engine was chosen as the validation vehicle for this model because of a timely start testing program begun in 1993 which included interstage data from 20%-100% of design speed (Owen and Davis, 1994). The availability of complete interstage data in the starting region was crucial to the model development.

The investigation of starting problems and the development of full speed range models has been given some attention in current literature. Chappell and McLaughlin (1993) developed an approach for modeling continuous turbine engine operation which was an extension of a component matching technique already in use. Agrawal and Yunis (1982) presented a similar approach based on generalized component maps in the starting region. These models generally depend on table lookup or "map reading" schemes and do not have the inherent ability to look at post stall and interstage behavior. Some Navier-Stokes calculations have been undertaken for starting flows in a compressor cascade (Outa et al., 1993) but the computing time and memory requirements presently make this method impractical for modeling a multistage compressor with post stall behavior. The utility of the DYNTECC starting model lies in its ability to look at compressor behavior for any foreseeable operating condition based on fundamental flow physics with reasonable computing time.

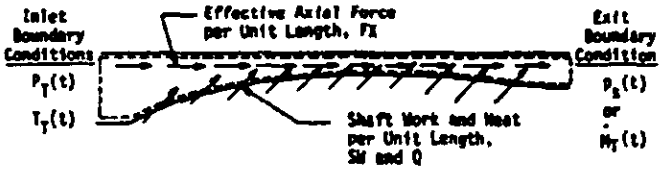
STARTING MODEL

DYNTECC is a one-dimensional stage-by-stage compression system model which is able to analyze generic compression systems as illustrated in Fig. 1. The inlet ducting, compressor, and combustor volumes are modeled as a series of elemental control volumes with mass, work, and heat fluxes across the control volume surfaces. The equations governing the flow are those for mass, momentum, and energy transfer for a non-viscous fluid with turbomachinery source terms, commonly referred to as the Euler equations (Eq.1).

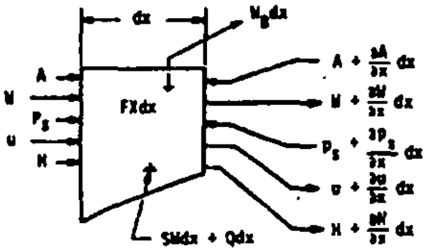
The source terms for compressor stages are given in the form of pressure and temperature coefficients vs. mass flow coefficient for each stage. The stage characteristics are defined for all performance possibilities, which are generally divided into three distinct regions as shown in Fig. 2. The pre-stall region is the normal stable operating regime where the pressure rise characteristic has a negative slope. The rotating stall region is modeled as a continuous characteristic along a throttle line with positive slope down to the zero flow condition, and the reversed flow region represents performance associated with full annulus reversed flow. The results presented here are concerned primarily with normal operation up to the inception of rotating stall. This is the region in which experimental stage characteristics were available from the T-55 test program. A full complement of spanwise pressure and temperature probes for each stage was used to measure stage performance from 20%-100% of design corrected speed, with ground idle occurring at approximately 61%. It should be noted that the flow blockage due to boundary layer effects will be inherent in the stage characteristics, thus blockage effects are not handled explicitly inside the framework of DYNTECC.



a) Compressor and ducting system



b) Overall control volume



c) Elemental control volume

Figure 1. DYNTECC Control Volume Technique.

$$\frac{\partial}{\partial t}\left(\overline{Q}A\right)+\frac{\partial}{\partial x}\left(\overline{F}A\right)=\overline{S}$$

$$\overline{Q}=\begin{bmatrix}\rho\\ \rho U\\ \rho\left(e+\frac{U^2}{2}\right)\end{bmatrix}$$

$$\overline{F}=\begin{bmatrix}\rho U\\ \rho U^2+P\\ \rho U\left(e+\frac{P}{\rho}+\frac{U^2}{2}\right)\end{bmatrix}$$

$$\overline{S}=\begin{bmatrix}-W_{Bx}\\ F_x\\ Q_x+S_x-H_{Bx}\end{bmatrix} \tag{1}$$

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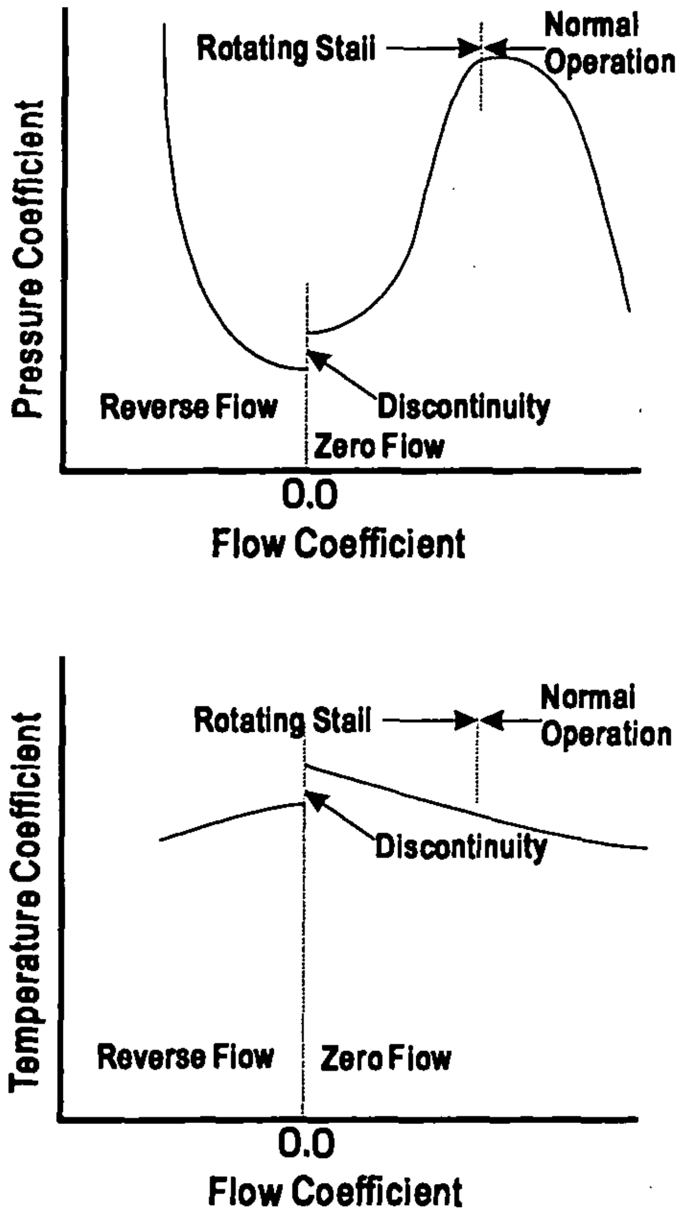

Figure 2. Typical Stage Characteristics

BOUNDARY CONDITIONS

Some changes to the model have been implemented in order to simulate a start sequence from 0% - 100% design corrected speed. The most critical of these was the development of a uniform pressure/area boundary condition which can be applied to both choked and unchoked exit flow. This allowed the model to run at variable speeds over the entire range of operability. The same principle was applied to develop a start bleed model based on bleed flow area and bleed dump pressure. This allowed simulation of actual start bleed schedules and significantly enhanced the ability to model interstage behavior during a start.

The inflow boundary condition during normal forward flow is the specification of total pressure and temperature. The exit boundary condition has traditionally been the specification of exit mass flow parameter or static pressure. The specification of exit mass flow parameter makes the implicit assumption of a choked downstream throttle area, while specification of static pressure assumes unchoked conditions. This set of boundary conditions works well at constant speed as DYNTECC was originally developed, but proved to be cumbersome when varying speeds from 0%-100% of design speed, since it is unknown a priori at what point the exit flow will become choked as speed increases.

To model starting behavior over a wide range of speeds, a uniform set of boundary conditions was developed based on the exit flow area and exit static pressure. This provides a logical model since the actual flowfield is also governed by these two physical properties. The pressure / area boundary condition provides all the information for closure of the governing equations and remains valid over the entire operating region. The exit mass flow parameter is still employed within the framework of DYNTECC, after being derived from the pressure area conditions by Eqs. 2 & 3. The exit Mach number is determined from the given static pressure and calculated total pressure by Eq. 2. This is then used to calculate an exit mass flow parameter, which incorporates the given exit flow area in Eq. 3. This technique allows for speed and throttle transients over the entire compressor performance map with a smooth transition through the starting region.

$$M=\sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_t}{P_s}\right)^{\frac{\gamma-1}{\gamma}}-1\right]} \tag{2}$$

$$\frac{W\sqrt{T_t}}{AP_t}=\sqrt{\frac{\gamma}{R}}M\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(1-\gamma)}} \tag{3}$$

START BLEED MODEL

The same procedure used for determining the exit mass flow was also used to develop a dynamic bleed flow model. Given the bleed flow area and dump static pressure, the mass flow through the bleed is determined for each time step. For the T55 model, the ratio of static pressure at the sixth stage start bleed to the bleed dump static pressure determines the bleed mass flow rate for a given bleed area. This allows a bleed flow schedule to be modeled based on the actual bleed flow area as indicated by the position of the bleed band during a start sequence. Bleed flow blockage and pressure losses through the bleed band and piping are not modeled explicitly, but are included implicitly in the selection of bleed flow area and bleed dump pressure. The combination of exit boundary conditions and bleed flow boundary conditions determine the internal stage matching in the model.

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ENGINE DATA ACQUISITION

In 1990, the U.S. Army Vehicle Propulsion Directorate (VPD) initiated its non-recoverable stall program. One goal of this broad program looking at dynamic engine events is the study of the AlliedSignal T55-L-712 turboshaft engine and to report to the U.S. Army Aviation and Troop Command (ATCOM) on this engine's start sequence. To accomplish this, the VPD's program included extensive rig testing which defined the individual stage characteristics and engine testing to characterize the engine start sequence.

Engine testing began in November of 1994 and start testing ended on March 27, 1995. During that time, 127 engine starts were accomplished with high response data acquired during 74 of those starts. The engine was started at altitudes up to approximately 4.5 km, with varying fuel schedule, starter torque and disengagement point, turbine inlet temperature (warm restarts), and bleed flow. Owen (1995) presents in detail the T55-L-712 engine, instrumentation locations, data acquisition procedures, and provides some preliminary results. Data from this program is available, under appropriate proprietary constraints, to the United States turbomachinery community.

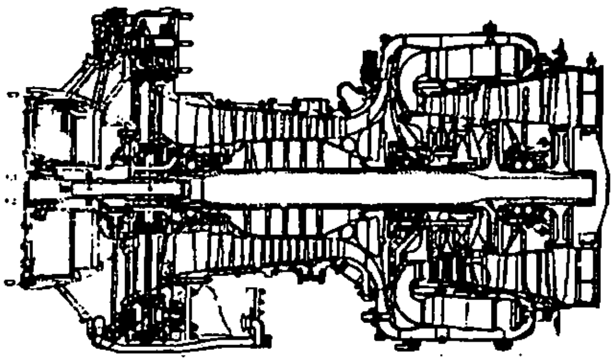

Figure 3. T55-L-712 Turboshaft Engine

THE T55-L-712 ENGINE

The T55-L-712 turboshaft engine (Fig.3) is a gas turbine engine in the 12 kg/s class. The transonic compressor consists of seven axial stages and one centrifugal stage. It uses no variable geometry but uses a single start bleed over the sixth stage stator. The compressor operates at a design point of about 12 kg/s mass flow with a pressure ratio of about 8.0. The combustor is a reverse flow annular combustor. For these start tests, the engine power turbine was locked. Figure 4 shows the meridional flowpath of the engine as it was implemented in the DYNTECC model.

Steady state instrumentation included total pressure and temperature rakes in the bellmouth region upstream of the engine inlet for use in calculating engine mass flow. Pressure and temperature rakes were integrated to provide overall stage pressure and temperature rise characteristics. High response instrumentation included, but was not limited to, a string of high response pressure transducers located on the shroud in front of the first rotor, and on the hub at the exit of the first two stators.

Steady state pressure is sensed using an electrically scanned pressure (ESP) system which scans and updates the readings every second. Start data was continuously acquired for a maximum of 60 seconds after the initiation of data acquisition to capture the entire start sequence. The total pressure and temperature measurements experienced a time lag of up to one second behind the rotor speed measurements, but this did not affect the synchronization of mass flow calculations which are independent of rotor speed.

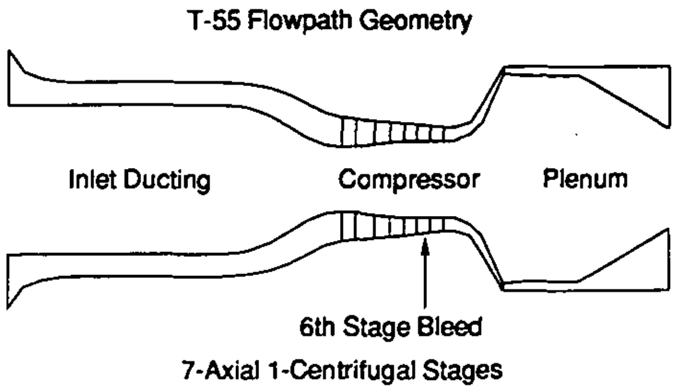

Figure 4. T-55 DYNTECC Flowpath Model.

RESULTS

Figure 5 shows a simulated start sequence from 0%-80% design corrected speed plotted with test results from a successful cold start and warm start. Axis scales are omitted since all data has been non-dimensionalized. The speedlines in this plot were generated from the model based on stage characteristics from rig test data. This plot shows overall compressor performance from compressor inlet to the combustor inlet. The test data goes up to ground idle speed, which is approximately 61% of design corrected speed. The two experimental starts follow essentially the same path on the overall plot. The most obvious feature of the start sequence is that the engine appears to be operating on the stall line through most of the start. The simulated start sequence follows a slightly lower overall operating line but closely matches the ground idle point. The effect of closing the start bleed can be clearly seen in the simulation. The point at which the exit flow becomes choked has been labeled on the plot to emphasize the smooth transition which the model is able to make. This is a direct result of the pressure / area boundary condition and represents a significant enhancement to the modeling capabilities of DYNTECC.

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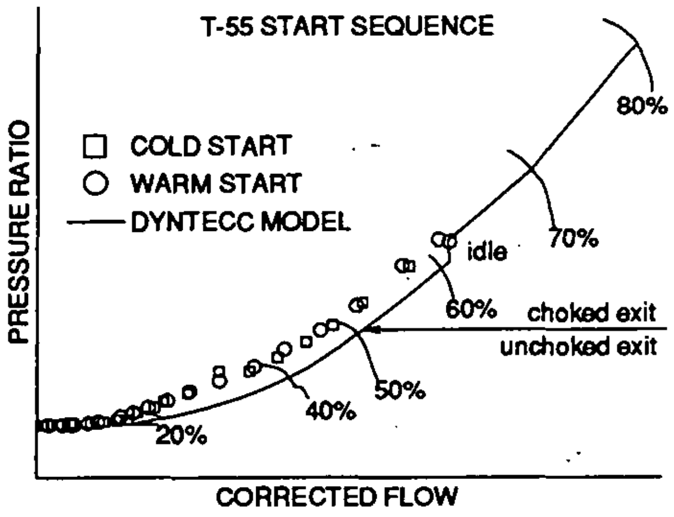

Figure 5. Full Start Simulation vs. T-55 data.

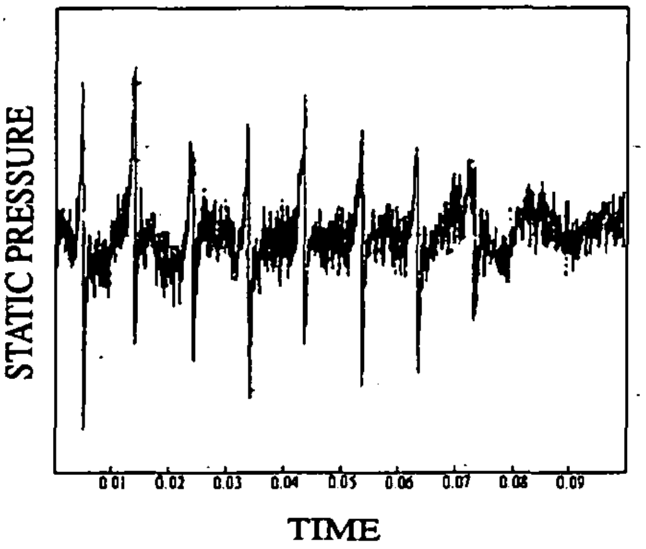

Figure 6. High Response Static Pressure Trace

Figure 6 supports the observation that the compressor is indeed operating in rotating stall during much of the start sequence. It shows the high frequency response of a flush mounted shroud pressure transducer taken when the engine was at 52% of design corrected speed. This was one of eight circumferentially mounted transducers at the same axial location approximately one chord length upstream of the first stage rotor. As can be seen, this sharp pressure rise occurs with a frequency of about 100 Hz, roughly 60% of the ground idle compressor speed. Further, it appears approximately 1.25 ms later in the transducer mounted 45° in the direction of rotation. This pattern continues for all eight of the transducers in the array in front of the compressor. It seems logical to assume that this pressure variation is moving circumferentially about the front face. Transducers located in an axial string indicate a pressure drop behind the first stage that moves with this pulse. A study of the entire transducer pressure trace indicates this pattern exists from the beginning of the start sequence with up to four of these rotating pressure events occurring early in the start sequence. That number gradually declines until the event disappears at 52% of design speed. This apparently rotating pressure phenomenon moves circumferentially at between 40% and 60% of the rotor speed throughout the sequence.

Figures 7-12 show the start sequence on a stage-by-stage basis for stages 1-6 respectively. The background speedlines for these plots are the pre-stall stage characteristics used by DYNTECC which were derived from experimental rig test data. Axis scales have been omitted since all parameters have been non-dimensionalized. The experimental data for stages 1-3 lies on or near the stall line for most of the start sequence. This supports the observation that the front stages are operating in or near rotating stall throughout most of the start sequence. The model closely matches this behavior and matches the ground idle point quite well for all stages. The tendency of the model to follow a lower operating line than the test data in the aft stages is not clearly understood at this time. Aerodynamic blockage is inherent in the stage characteristics, but these are only valid for the bleed schedule which was used during data acquisition on the test rig. It has been postulated that an explicit treatment of flow blockage, rather than accounting for blockage in the stage characteristics, may improve the match.

A point of interest is how the model is able to run at speeds below 20% of design, since stage characteristics were not available below 20% speed. A zero speed characteristic was input to the model with the assumption that the pressure and temperature rise characteristics would be zero at zero speed. The model uses an interpolation scheme to calculate characteristics at intermediate speeds, hence it interpolates between the assumed zero speed condition and the nearest speedline (20%) for the very low speed calculations.

CONCLUSIONS

The DYNamic Turbine Engine Compressor Code (DYNTECC) supported by JDAPS has been modified to incorporate speed transients with pressure / area boundary conditions allowing dynamic simulation of compressor events throughout the entire operating regime. The enhanced starting model has been configured to simulate starting behavior in the AlliedSignal T55-L-712 axi-centrifugal compressor and compares favorably with start test data from this engine. The T55 compressor normally operates in rotating stall until it reaches approximately 50% of design speed (ground idle is about 61%). This is near the starter disengagement point for the start sequence. During the start sequence, the first and third stages of the compressor are the most highly loaded axial stages. Stage 3 is most highly loaded between about 20% and 43% of design speed and stage 1 is loaded more highly elsewhere. Comparison of interstage data with the model shows a tendency of the model to follow a lower operating line as the flow approaches the start bleed location. It is believed that an explicit treatment of flow blockage may improve these results. The model represents a significant investigative tool which can be used to simulate changes in start bleed schedules and stage matching during dynamic events "all over the map".

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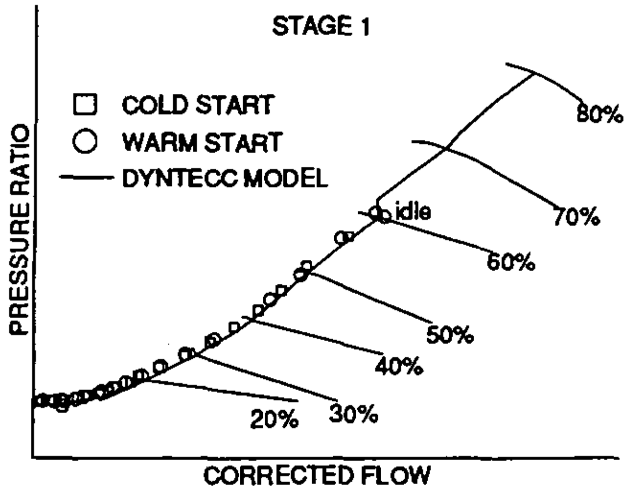

Figure 7. Stage 1 Start Sequence

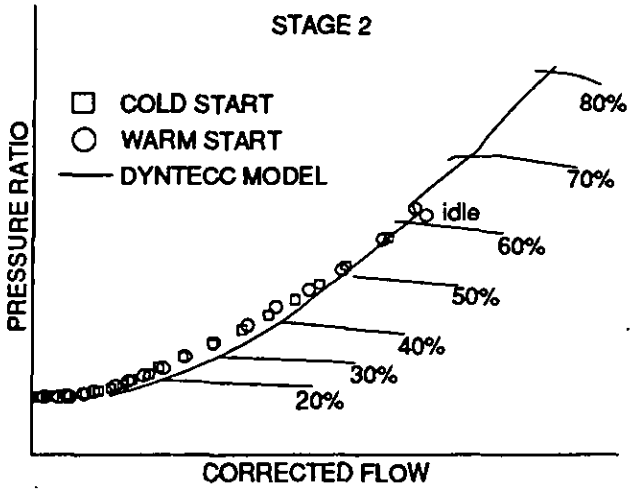

Figure 8. Stage 2 Start Sequence

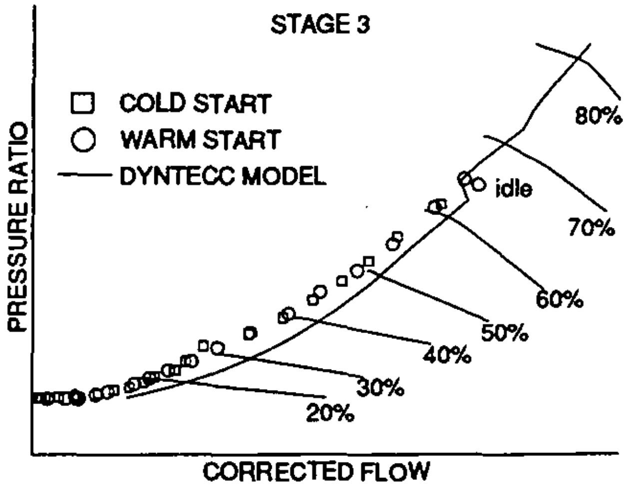

Figure 9. Stage 3 Start Sequence

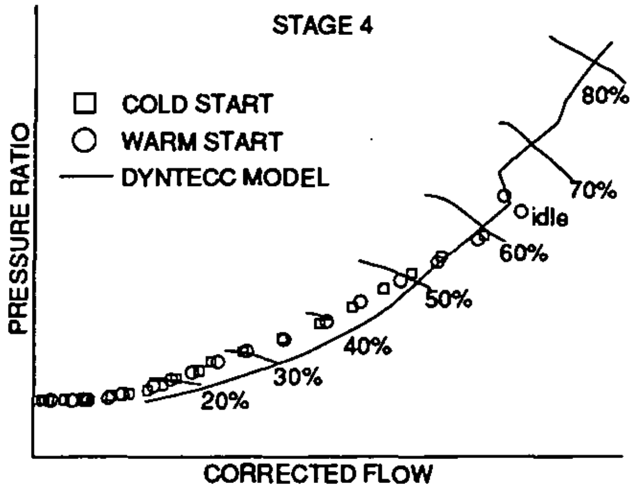

Figure 10. Stage 4 Start Sequence

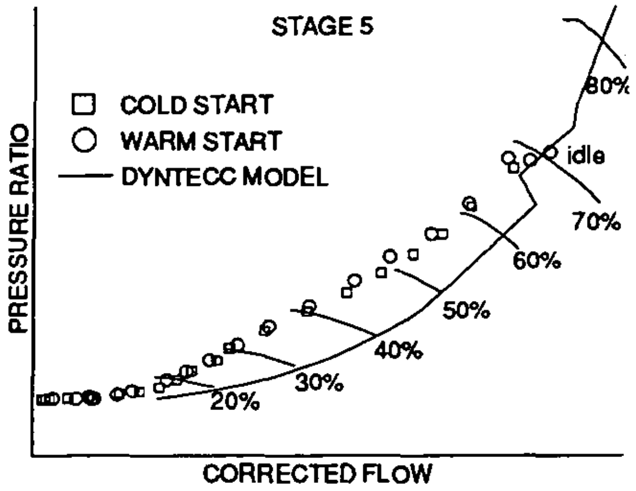

Figure 11. Stage 5 Start Sequence

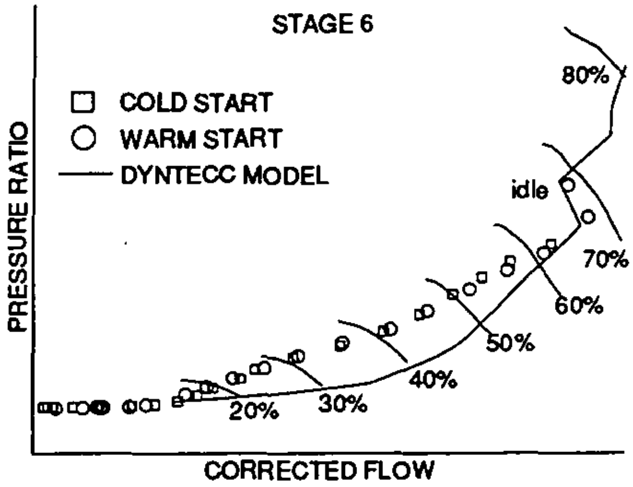

Figure 12. Stage 6 Start Sequence

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