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The WINCOF-I Code: Detailed Description

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Executive Summary

The performance of an axial-flow fan-compressor unit is basically unsteady when there is ingestion of water along with the gas phase. The gas phase is a mixture of air and water vapor in the case of a bypass fan engine that provides thrust power to an aircraft. The liquid water may be in the form of droplets and film at entry to the fan. The unsteadiness is then associated with the relative motion between the gas phase and water, at entry and within the machine, while the water undergoes impact on material surfaces, centriguging, heat and mass transfer processes, and reingestion in blade wakes, following peal off from blade surfaces. The unsteadiness may be caused by changes in atmospheric conditions, and at entry into and exit from rain storms while the aircraft is in flight. In a multi-stage machine, with an uneven distribution of blade tip clearance, the combined effect of various processes in the presence of steady or time-dependent ingestion is such as to make the performance of a fan and a compressor unit time-dependent from the start of ingestion up to a short time following termination of ingestion.

The original WINCOF code was developed without accounting for the relative motion between gas and liquid phases in the ingested fluid. A modification of the WINCOF code has now been developed, named the WINCOF-I, which can provide the transient performance of a fan-compressor unit under a variety of input conditions.

A complete description of the modifications introduced in the WINCOF-I code is provided. Along with the documentation on the WINCOF code, the current description provides the documentation on the WINCOF-I code.

In order to illustrate the use of the WINCOF-I code for determining the performance of a multi-stage compressor, a test case with two stages has been calculated, and the details of the input and the output have been presented.

Finally, a methodology for incorporating the output of the WINCOF-I code in a code for the determination of transient performance of a bypass fan engine is described.

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CHAPTER 1
INTRODUCTION

Ingestion of water into jet engines during aircraft flight operations in rain storms (and also, during take-off over rough runways with puddles of water) has been known to cause changes in engine performance, and difficulties in flight operations. A knowledge of such performance changes is essential not only to improve flight quality and safety but also to enable advanced design, and engine testing and certification procedures.

An approach to developing methods of predicting engine performance is to include in an engine transient performance code elements or codes for determining the performance of individual components of the engine with water ingestion. Over several years, attempts have been made to model axial-flow fan-compressor units of fan jet engines operating with air-water mixture flow, and to develop a performance code. The output of the code has then been included in an engine transient performance code. The fan-compressor performance code with water ingestion has been named WINCOF, and References 1-6 provide a bibliography of publication that describe the WINCOF code and it application.

The WINCOF code was developed to provide a tool for determining the steady state performance of fan-compressor units with steady ingestion of an air-water mixture of fixed quality. Water in the mixture could be in the form of a film or in part in film and the rest in droplet form. When determining transient engine performance changes, the steady state output of the WINCOF code was utilized while the engine performance was time-dependent for other reasons.

It has since been realized that the performance of an axial-flow fan-compressor unit is basically time-dependent whenever there is an ingestion of air-water mixture into it. The time-dependence is a consequence of the presence of a relative velocity between air (and water vapor, or the gas phase, in general) and water at entry and in the flowpath of the mixture in the machine. It is also a fact that the blade geometry, the stage performance, and the blade clearance height do not follow any systematic variation in relation to the velocity of flow in the blade passages in a multi-stage machine. Therefore, the combination of various processes in the fan-compressor unit, such as impact of water on material surfaces, centrifugal action, heat and mass transfer, and reingestion of water following peal-off from blade surfaces into wakes, lead to a time-dependent performance of the unit. Such time-dependent performance extends from the instant of start of ingestion up to a short time following termination of ingestion.

The performance of a fan-compressor unit can also be time-dependent for two additional reasons: (i) Due to changes in atmospheric conditions, causing changes in the characteristics of the ingested fluid mixture; and, (ii) due to such events as entry into and exit from rain storms during flight.

The WINCOF code has been modified so as to permit taking into account the relative velocities between the two phases (water being in film and droplet form), and thus obtaining the transient performance of a fan-compressor unit. The modified code has been named the WINCOF-I code, and a brief description with an illustrative example has been provided for the modified code in Ref. 7.

The current report provides a more complete documentation of the WINCOF-I code with necessary explanations. It also includes the methodology for utilizing the results obtained with the WINCOF-I code in determining the transient performance of a fan engine. A generic bypass fan engine was chosen for illustrative purposes in Ref. 8.

1.1 Outline of Report

The methodology for determining the time-dependent performance of a fan-compressor unit is described in Chapter 2. The method of incorporating the results generated by utilizing the WINCOF-I code in an engine transient performance code is given in Chapter 3. A general discussion on the methodology is included in Chapter 4. Various details related to the WINCOF-I code are given in a series of five appendices, which are referred to appropriately in various chapters.

CHAPTER 2
FAN-COMPRESSOR UNIT PERFORMANCE WITH WATER INGESTION: METHODOLOGY

The performance of an axial-flow fan-compressor unit under discussion in this chapter is that obtained for the unit when it is operated in isolation by means of independent drives as necessary. Most of the discussion pertains to a multi-stage compressor unit, while some of it is devoted to the combined fan-compressor unit driven by two independent drives, one for the supercharger with the fan and the other for the core compressor, at different speeds.

The operational parameters for a fan or a compressor unit are (a) the operating speeds, (b) the total mass flow at entry, (c) the bypass ratio and (d) water ingestion parameters, in addition to the ambient conditions of pressure, temperature and degree of saturation with respect to humidity. The mass flow at a specified value of rotational speed at the radius (in blade span) under consideration may be specified in terms of a flow coefficient value. The flow coefficient is defined as the ratio of axial flow velocity of air to the rotational velocity of the rotor blade row (or stage), both at the same spanwise radius under consideration. The range of operating speed of the supercharger, as also that of the flow coefficient, differs from that of the core unit by design. The bypass ratio is a function of operating speeds of the two units and the power demand.

The water ingestion parameters are mass fraction of water taking into account the scoop factor, droplet size distribution, difference in velocity between air and large droplets and temperature.

The performance parameters of interest in the case of a fan or a compressor unit at specified speed of operation, flow coefficient and water ingestion conditions are the following at the outlet of the compressor.

(i) Pressure ratio, temperature ratio and efficiency (usually adiabatic efficiency based on output obtained for given input of work based on conservation of energy);

(ii) mass fraction of water in the air-water mixture;

(iii) temperature of water in span; and

(iv) volumetric mean droplet size.

(v) mass fraction of vapor in the air-water mixture;

(vi) thickness and mass flux of water in film form in the compressor clearance.

The foregoing may be of interest in any stage of a fan or a compressor or for a multistage unit as a whole.

In the case of operation of a unit with air, it is common practice, in simplified approaches, to specify the performances of a compressor in terms of one or both of the following: (i) Performance of the unit with reference to a specified radius of the unit; and (ii) performance of the unit based on a weighted-average of performance data at several chosen radii to encompass the span of the unit. In the alternative, one can undertake fully three-dimensional predictions for the unit over its entire span. However, for the purposes of specifying representative performance parameters, especially for use in engine simulation codes, it is again necessary to determine, through some form of weighted averaging, the overall performance of the unit.

In the current investigation, the performance of an axial-flow fan or compressor unit is determined utilizing a modified version of the so-called WINCOF code (References 1), developed at Purdue University some years ago. A brief description of the WINCOF code follows in Section 2.1. That code has been modified in several respects (Reference 7) and the modified code is named WINCOF-I code, and is described in Section 2.2.

In both of these codes, the performance of a fan or a compressor is determined with respect to a chosen streamtube. Figure 2.1 shows a set of six streamtubes that are illustrative of the type of streamtubes of interest in a fan-compressor unit. Among those streamtubes 2 and 5 are considered as mean streamtubes and the performance of various units calculated with respect to them are utilized as representative for the units.

The WINCOF-I code has been utilized, for illustrative purposes, to determine the performance of various units in the fan-compressor unit of the generic engine referred to in Chapter I.

2.1. Description of WINCOF Code

The objective in the development of the original WINCOF code has been to obtain a means of predicting the steady state performance of an axial-flow compression system (single or multi-stage fan, compressor or combination) with water ingestion. The WINCOF code was developed to calculate, as stated earlier, the performance with respect to a designated streamtube of a single stage of a fan or compressor. Thus no account is taken of the radial component of velocity in the three-dimensional flowfield that is usually generated in an axial-flow turbomachine. The calculation procedure of the WINCOF code is, therefore, referred to as "one-dimensional", implying that the flux of fluid is assumed to be in the axial direction along the designated streamtube. However, the input of work absorbed by the fluid is obviously related to the change in moment of angular momentum of the fluid; the rotor tangential speed determines the angular momentum. The WINCOF code can be utilized for determining the performance of a multi-stage machine by the stage-stacking procedure with respect to a streamtube passing continuously through the machine. Typical streamtubes for such calculation are presented, as referred to earlier, in figure 2.1. A streamtube is specified by means of its (a) area of cross-section and (b) radius of location in each stage, with necessary attention to continuity and smooth transition from stage to stage.

The WINCOF code can be utilized to determine the performance of a single- or multi-staged unit under (i) design conditions for operation with air and (ii) off-design conditions with (a) air or (b) air-water mixture. For design point calculation of performance during operation with air, the following geometrical and aerodynamic details of design are required for the unit.

i) Hub and casing diameters;

ii) spanwise distribution of chord and thickness-chord ratio;

iii) spacing between blade rows; and

iv) spanwise distribution of metal angles, incidence, deviation, inlet Mach number and maximum boundary layer momentum thickness along chord for inlet guide vane, rotor and stator, as appropriate, at the design point of the unit.

For the calculation of performance at an off-design point, the following procedure is adopted.

(a) *Operation with air*: Various rules are incorporated in the code for obtaining, based on design point information, the necessary aerodynamic performance parameters corresponding, for example, to the specified value of rotational speed, ambient conditions and flow coefficient at the designated streamtube location. A typical set of such rules can be found Reference 1, and they have been incorporated into the code. Details are repeated for convenience in Appendix I. It may be pointed out that another set of rules can be easily substituted in place of the set of rules currently adopted.

(b) *Operation with air-water mixture*: The air-water mixture modifies the aerodynamic parameters as well as introduces several new features that are a direct consequence of the two-phase nature of the mixture. They are described briefly in Section 2.1.1. along with the procedure for taking into account those two-phase fluid-related processes.

2.1.1. Processes Included for Consideration

The air-water mixture entering the fan or the compressor unit is characterized by (a) composition of air-water mixture and (b) velocities of air and water droplets. Regarding (a), further details are of interest concerning (i) mass fraction of vapor and water and (ii) droplet size distribution. The latter is of critical importance in determining drag, velocity of motion and interphase heat and mass transfer processes. However, in the current investigation, some simplification is introduced as follows.

Droplets are considered to be in two categories based on size, namely large and small, the latter under 20 microns in mean-volumetric diameter. Small droplets are assumed to follow the gas path, while large droplets move independently. Also, small droplets absorb work input, while large droplets do not. Work is absorbed by water in the course of pealing off from a rotor by shearing action. Both sizes of droplets undergo size adjustment based on mass transfer and critical Weber number consideration, and both undergo heat and mass transfer processes.

Both the composition and the velocities may vary radially and circumferentially across the plane of ingestion. Radial variation can be accounted for by specifying the relevant values in various streamtubes chosen for calculation. However, circumferential variation requires consideration of a nonaxisymmetric flowfield, and this feature has not been included in the current investigation.

The main two-phase flow processes that are considered to have significant effect on the performance of an axial-flow fan or compressor are the following.

i) Ingestion of water at the machine face,

ii) droplet impact and rebound from blade surfaces,

iii) film formation and flow over blade surfaces,

iv) flowfield and boundary layer modifications based on deviation, diffusion factor, and momentum thickness,

v) centrifugal action on droplets and film over blade surface, and corresponding radial movement,

vi) heat and mass transfer processes between liquid and gas phases,

vii) reingestion of water into wakes of blades from film flow over surfaces,

viii) droplet size and breakup based on the attainment of a critical value for the Weber number,

ix) the total of work input and its division of work input between the two phases, and

x) film formation and movement at the casing wall.

In accounting for these processes, several assumptions are introduced as follows.

(a) Ingestion occurs at a specific plane immediately upstream of the unit or the stage under consideration. Initial conditions of air-water mixture, including composition and velocities, are specified at that plane.

(b) Processes (ii), (iii) and (iv) are accounted for in establishing work done on the mixture and related losses.

(c) Processes (v) through (viii) are taken into account at the exit plane of a blade row although they occur everywhere along the flow in the blade passage.

(d) Regarding processes (v) and (vi), which are time rate-governed, it is necessary to determine a duration of time for the occurrence of the processes. This is done based on characteristic length and velocity scales, namely the chord of blades and axial velocity of mean air-water mixture flow through the relevant blade passage or stage width..

(e) The liquid phase may absorb work input only when the droplets are small and follow the gas path or when water is splashed off a blade surface. In general, the amount of work done on the liquid phase can be assumed to be small.

(f) Finally, film formation and movement at the casing wall result from centrifugal action on droplets and film over blade surfaces, accumulation of water at the casing wall and shearing action due to adjoining air-water mixture flow. In the WINCOF code, it has been assumed that the film moves at the same speed as the adjoining air-water mixture.

2.1.2 Single Stage Machine

To apply the WINCOF code to a stage of a fan or compressor, a specific streamtube must be chosen, along which the performance calculations are performed. A streamtube is designated by its location along the span, and with a specified cross-sectional area. A small value of cross-section area is chosen based on local design point mass flow and density and axial velocity data pertaining to the chosen radius of location. But the performance of a blade row at the design point is also a function of blade metal angle, incidence angle, and deviation angle. Also a stage consists of two or three blade rows. Therefore it becomes necessary to use some trial and error in choosing the location and cross-section area such that it is compatible with design point data available at discrete locations along the stage.

2.1.3 Multi-Stage Machine

As mentioned previously, the overall performance of a compressor is established by extending the single stage calculation through a "stage-stacking" procedure. In this connection, it is worthwhile discussing the manner in which centrifugal action on water is determined in various stages. In the WINCOF code, in order to calculate centrifugal action on water in a blade row or stage, the span of the blade row or stage has been divided into a finite number (ten, for example) of streamtubes of equal cross-sectional area. The centrifugal action and the resulting displacement of water towards the casing wall are calculated at the exit plane of the blade row or stage under consideration over the period of time equal to the residence time of the air-water mixture therein. All of the water displaced is assumed to accumulate in the casing and not in any of the streamtubes themselves. Heat and mass transfer processes as well as droplet size adjustment processes are also taken into account at the same exit plane. When the calculation proceeds from one row or stage to the next, the water and the water vapor contained in any one of these streamtubes is considered to reside in the streamtube of the same number in the next stage. The water film at the casing wall is also considered to move from one row or stage to the next at the same speed as the adjoining air-water mixture. However, in the WINCOF code no account is taken of either (a) the casing clearance space or (b) relative motion between film and air-water mixture.

2.1.4 Weaknesses in the WINCOF Code

In recent years a detailed examination has been undertaken of the assumptions and methodology employed in developing the WINCOF code. A number of weaknesses have been recognized in the WINCOF code as follows.

(i) The WINCOF code was developed and utilized as a code for the determination of the steady state performance of both single and multiple stage axial-flow machines. In accounting for time-rate-dependent processes such as centrifugal action on water droplets and film and inter-phase heat and mass transfer processes, a time scale was chosen equal to an estimated value of residence time of air-water mixture flow in the blade row under consideration. The residence time was defined as the ratio of mean width of a blade row or a stage to the mean axial velocity of flow in it. Since such processes were accounted for at the exit of a blade row or a stage, the performance so calculated was assumed to be the steady state performance of the stage with the given water ingestion and other inputs to the stage.

(ii) Centrifugal action on water droplets and film (over blade surfaces or in blade passages) was considered only to establish the amount of ingested water that became removed in film form at the casing wall and hence to determine the balance of amount of water that remained within the span of the blade row. No account was taken of the motion of water film at the casing wall due to the shearing action exerted by the adjoining air-water mixture and the time-dependent nature of build-up and motion of the film at the casing wall. In other words, it was assumed in the WINCOF code, that the blade row or stage had attained a state of "equilibrium" or a steady state at the end of the (somewhat arbitrarily selected) step time of calculation. In fact, taking into account the nature of centrifugal action over the blade span and the growth and motion of the clearance film, the distribution of water in the blade span would become time-dependent. This was left out of account as well as the resulting time-dependent changes in the aerodynamic performance of the unit under consideration.

(iii) Heat and mass transfer processes were accounted for in the WINCOF code at the exit of a blade row or a stage utilizing the residence time of air-water mixture as the time interval for the processes to occur. The interactive time-dependent changes in the composition and state of air-water mixture between centrifugal action, film formation and motion in casing wall on the one hand and heat and mass transfer processes on the other were again left out of account.

(iv) No account was taken of the possible difference in velocity between water droplets and air at entry to a compressor. While small droplets were assumed (correctly) to move with air, large droplets were considered also as entering the machine with the same velocity as that of air. Thus the relative velocity between air and (all of) the droplets was assumed to be zero at entry to a fan or a compressor.

(v) At entry to a fan or a compressor, two other features of air-water mixture that are of interest are (a) nonuniformities due to scoop factor and other causes and (b) presence of a film at the casing wall, for example, due to flow over the inlet wall. Neither of these was included in the utilization of the WINCOF code.

(vi) Finally, interphase heat and mass transfer processes in a conglomeration of droplets are strong functions of the size distribution and number density of droplets. There are not enough reliable data for including the details of shielding of heat and mass transfer processes in a cloud of large droplets; however, a parametric study could be conducted to determine the effect of shielding. This was not included in the WINCOF code.

There are several implications of (i) to (v) in the use of the WINCOF code for determining the performance of a multistage machine. In actual calculation, a single sweep was made through a fan or a compressor, over all of its stages. In determining centrifugal action and heat and mass transfer, a calculation time was introduced for each stage equal, as stated earlier, to the residence time of air-water mixture in the blade row or stage under consideration. Then the performance of the machine obtained at the end of the single calculation sweep of time was assumed to be the steady state performance of the unit. The performance determined for any chosen streamtube pertained to the air-water mixture in it, taking into account centrifugal action and heat and mass transfer processes. Meanwhile, no further account was taken of the water at the casing wall or the consequences of its motion relative to the air-water mixture in the span.

2.2 The WINCOF-I Code

The WINCOF-I code has been developed with the objective of removing some of the aforementioned weaknesses and limitations in the WINCOF code. The modifications introduced pertain to the following.

i) Time-dependent nature of performance of axial-flow fans and compressors during water ingestion (Section 2.2.1.);

ii) modeling centrifugal action and film formation and flow as a function of time (Section 2.2.2.);

iii) modeling heat and mass transfer (Section 2.2.3);

iv) accounting for droplet-relative velocity with respect to air velocity (Section 2.2.4); and

v) accounting for desired entry conditions to the machine with respect to air temperature and thickness of film at the casing wall.

Each of these is discussed in some detail in the following.

2.2.1. Time-Dependence in the Performance of a Fan or a Compressor

A single or multiple stage fan or compressor cannot be expected to operate under steady state conditions with water ingestion may be shown as follows.

Water entering a stage and moving over the surface of a blade or in the passage between blades becomes centrifuged to the casing wall on account of the rotational field. At the casing wall, a film is formed. The film moves along the casing wall due to the shearing force exerted on it by the adjoining air-water mixture in relatively high speed motion. The shearing force is obviously small and there arises a large difference between the velocities of the film and the air-water mixture. Since water is being centrifuged continuously, one can expect a net growth in the thickness of the film at any blade row location, while some of it moves along the casing wall to the exit or a following blade row location. This is equivalent to an accumulation of water in the clearance at any blade row. The accumulation ceases only when (a) the local, instantaneous clearance between the blade row and the casing wall becomes filled up with water or (b) the film thickness is such that the adjoining air-water mixture flow is no longer able to shear it to a recognizable velocity. In either case, any water centrifuged subsequently may only be splashed back into the span of the blade row. Such a state of operation of any blade row (or a stage, when a complete stage is under consideration) is named the "equilibrium" state of operation. Beginning with the instant of ingestion, the first or any other stage of a machine and also the entire machine may reach "equilibrium", if only instantaneously. It corresponds to a limiting condition of operation beyond which any water centrifuged may only be splashed back into the span and cannot accumulate in the local clearance space. The performance of the stage or the machine is time-dependent during the attainment of equilibrium condition. It turns out that it will continue to be time-dependent, perhaps periodic, beyond that instant of time.

In discussing redistribution of water due to centrifugal action, it is necessary to distinguish and to treat individually the following: (i) a stage, whether it is the first or a subsequent stage in a multistage machine, and (ii) the nature of ingestion, whether (a) steady, uniform, (b) steady, nonuniform, or (c) nonsteady uniform or nonuniform. The case of steady, uniform ingestion is considered first, and some remarks are added about the other cases at the end.

The reasons for time-dependent performance during water ingestion may be summarized as follows.

(i) Considering first a single stage machine or the first stage of a multi-stage machine and steady ingestion of water, one can then visualize a period of time-dependent performance during which the film at the casing wall is growing steadily and also moving downstream from the stage. Finally, at the end of a certain number of calculation time step intervals, an equilibrium state is reached. In the next calculation time step interval, any water centrifuged becomes splashed back into the span. If it is assumed that the water splashed back into the span becomes uniformly distributed over all of the calculation streamtubes in the span, the one or more streamtubes at the hub of the row that had originally been depleted of water due to centrifugal action would now again contain water due to the splash back just described. Meanwhile the steady, uniform ingestion at the front of the stage continues to bring in air-water mixture across the entire span. Hence the process in the blade row remains time-dependent so long as there is water ingestion.

(ii) During such a period of time, the effects of heat and mass transfer processes - in fact, the processes themselves - become time-dependent. Thus there arises a further time-dependent effect.

(iii) Considering next the second or any subsequent stage of a multi-stage fan or compressor, there are two inputs of water at the casing wall, one from the previous stage and the other due to centrifugal action in its own span. Both of those are time-dependent. Along with the influence of heat and mass transfer, the processes in any but the first stage of a multi-stage machine remain time-dependent.

One can next ask, if steady state conditions are ever likely to be reached in a multi-stage machine. A multi-stage machine has a reducing area of cross-section from inlet to outlet in view of pressure and density increases along the compressor. Individual stages, in general, have different values of casing clearances, blade-heights, geometrical features and aerodynamic characteristics. In any practical machine, in general, those quantities do not vary according to any organized, simple, functional relationship from stage to stage. On the other hand, it is clear that, in order that a steady state may be attained, at least the following quantities must vary linearly with respect to each other along the compressor: (a) residence time of air-water mixture, equal to stage width divided by mean axial velocity over the stage, (b) span height, hub radius and blade clearance, (c) aerodynamic performance, (d) heat and mass transfer and (e) droplet break-up and reforming characteristics. Such an occurrence is extremely unlikely, if not impossible, in any practical machine. Thus, for a steady, uniform ingestion of a given type of water ingestion, one invariably obtains a time-dependent performance for a multistage fan or compressor.

There is one other feature of a multistage fan or compressor that must also be recognized in regard to its time-dependent performance with water ingestion.

This relates to the fact that in a given multistage machine, succeeding stages may not necessarily reach their "limiting" conditions one after the other, that is in the same order as they appear, the third after the second, the (n-1)th after the (n-2)th stage. By "limiting" conditions, it is implied that a steady set of conditions has come into existence with respect to performance of the stage including the growth and motion of water film in the local casing clearance. If such a state is not reached in succeeding stages in succession, then the conditions at the exit plane of the machine will definitely have a time-dependent character. However, at the end of a sufficiently long period of time, all of the stages will have attained limiting conditions for an instant of time. But at the very next instant of time, further ingestion (of the same steady type and rate) will cause a change in some of the stages, while not in others, and therefore the time dependence will persist although with a long-time, periodic behavior or pattern.

The foregoing applies to steady, uniform ingestion of water. If the ingestion is steady but nonuniform, the extent to which different calculation streamtubes of the stage receive water becomes different. This leads to changes, compared to the case of uniform ingestion, in (a) the distribution of water across the span at the end of each calculation step, (b) the interval of time required for the attainment of equilibrium conditions for the first time and (c) the periodic nature of nonsteady performance.

In the case of nonsteady ingestion of water, the processes become further complicated depending upon whether ingestion is (a) continuously or discretely nonsteady and (b) simultaneously, uniform or nonuniform. No general statements can be made in regard to such situations, especially because of the complicated influence of stage aerodynamic characteristics and because of the presence of various values of clearance in different stages.

In summary, the time-dependent nature of performance of the first or any other stage of an axial-flow compression machine or of the machine as a whole depends upon the following.

(a) Type of water ingestion;

(b) geometry of various stages including the casing clearance;

(c) aerodynamic characteristics; and

(d) heat and mass transfer processes.

It can be stated that it is extremely unlikely that steady state performance becomes possible in any machine with water ingestion.

2.2.2 Model for Centrifugal Action and Film Formation and Flow

The WINCOF code does not take into account the motion of the film due to the shearing action of the adjoining air-water mixture, the relative motion between the film and the air-water mixture, and the resulting time-dependent processes until equilibrium conditions become set up in the stage. In order to account for these, the following procedure is adopted in the WINCOF-I code.

(a) Single stage machine or the first stage of a multi-stage machine.

(i) Calculation of centrifugal action: The blade span is divided into a finite number of parts, for example 10, based on (a) size of droplets present, (b) increment in thickness of film at casing wall resulting from radially displaced water during a calculation step in time and (c) depletion in film thickness on account of motion of water in the film caused by the shearing action of the adjoining air-water mixture, again in the same calculation step in time. The number of parts into which the span is divided has to be chosen by a trial-and-error procedure. Taking the local rotational component of motion into account, the amount of water displaced from each calculation streamtube to the next is determined as well as the net water content in itself.

(ii) Film formation and motion: Water displaced from the calculation streamtube in the tip region of the blade is allowed to accumulate in the casing clearance. The film so formed becomes subject to the shearing action of the adjoining air-water mixture. Based on the momentum transferred to the film, its velocity is determined.

(iii) Net state of film: By knowing the velocity of film motion and the resulting depletion of mass of water in the film, the final thickness of the film is determined.

(b) The second or other stage of a multi-stage machine.

In carrying out a sweep of calculation across the machine, each stage of the machine is dealt with assuming the following inputs.

(i) The state of air-water mixture at the exit of the previous stage after all of the processes in that stage have been taken into account;

(ii) the state of air-water mixture across the span in the various calculation streamtubes at the exit of the previous stage taking into account any depletion that has occurred in water in any of the streamtubes, including the one near the hub; and

(iii) the state of the film in the clearance that is entering the current stage from the exit of the previous stage.

The rest of the procedure for the calculation of centrifugal action and film formation and motion is the same as for the first stage.

Details of the analysis and procedure are given in Appendix II. There are also some implications of the foregoing discussion that are of interest in the numerical procedure adopted. These are discussed in Sections 2.2.6 and 2.3.

2.2.3 Model for Heat and Mass Transfer

In the WINCOF code, interphase heat and mass transfer was calculated based on (a) fixed coefficients of heat and mass transfer and (b) a time interval equal to the width of a blade row or a stage divided by the mean axial velocity therein. These calculations were preformed at the exit of a stage as a correction to the aerodynamic performance obtained for the stage.

In the WINCOF-I code two modifications have been introduced as follows.

(i) Shielding of heat and mass transfer processes due to multiplicity of droplets: In a conglomeration of droplets, heat and mass transfer are affected, along with other parameters, by (a) the number density, (b) the size distribution, and (c) the vapor clouds around the droplets, which grow in size with time. In order to take these into account in a parametric form, it is assumed that (a) there is a maximum separation of droplet clouds beyond which droplets do not interact with each other; for example, 10 volumetric mean diameters, and (b) there is a minimum separation of droplets less than which no heat and mass transfer is possible; for example, 2 volumetric mean diameters. Figure 2.2 illustrates schematically the nature of the assumptions. Based on such conditions, a linear curve has been constructed to relate a so-called heat and mass transfer weighting parameter, z, to the mean separation between droplets utilizing mean volumetric droplet diameter as an additional parameter. The curve is presented in figure 2.3 It is then possible to utilize this parameter in the calculation of heat and mass transfer at any location when droplets of a given mean volumetric diameter are present therein at a specified number density.

(ii) Characteristic length of time for heat and mass transfer processes: The residence time of droplets in a blade passage depends upon the velocity of droplets therein. In general, the residence time of droplets should be several times larger than the residence time of the gas phase. In order to take this into account parametrically, a time factor has been introduced in WINCOF-I, whose value may vary over the range 1 - 100. The length of residence time of air-water mixture in a blade row or a stage is then multiplied by the time factor and the resulting time utilized in the calculation of interphase heat and mass transfer.

Details concerning the calculation of heat and mass transfer in the WINCOF-I code are given in Appendix III.

It may be pointed out here that heat and mass transfer processes are confined entirely to the span region of a compressor unit. Thus no heat and mass transport are included for the film in the casing clearance space; this is based on the reasoning that the film, growing continuously in thickness with centrifuged water, does not undergo transport processes.

2.2.4 Relative Velocity of Droplet with Respect to Air

There are two situations where the relative velocity between the droplets and the air become of interest: (i) at entry to a turbomachine and (ii) between two blade rows. In case (i), as stated earlier, the velocities of large droplets may be quite independent of the velocity of air. Regarding (ii), water droplets are present in the blade passage, and are also generated from water pealed off from blade surfaces into blade wakes. In either case, the attainment of mechanical equilibrium and, thereby, a particular size distribution requires a length of time and distance. In other words, there is a lapse time of residence in which water is essentially in an indefinite state and, therefore, during this time water can be assumed to be moving at a substantially lower velocity compared to the velocity anywhere else.

The difference in velocity between droplets and air was entirely neglected in the WINCOF code. In the WINCOF-I code it has been taken into account parametrically by introducing a so-called relative velocity factor, ξ. The relative velocity factor is defined by writing

$$\xi = (V_a - V_D) / V_a$$

where V_a and V_D denote velocities of air and droplet, respectively. Thus $\xi=1$ represents the condition $V_D = 0$; and $\xi=0$ corresponds to $V_D = V_a$.

2.2.5 Other Parameters

Other quantities that have been taken into account as parameters in the WINCOF-I code are as follows.

(i) Ambient water temperature: The effects of large differences in temperature between air and water have been explored.

(ii) Film thickness at entry to the machine: The effects of the presence of a film of finite thickness at entry to the machine have been explored in addition to nonuniformities in water ingestion parameters.

(iii) Ingestion as a function of time: The mass fraction of water ingested may vary as a function of time in the form of a series of telegraphic signals of varying magnitude. It is then of interest to investigate the nature of changes in performance as a function of the manner in which the mass fraction of ingested water changes with time, both on short time and long time basis.

2.2.6 Numerical Procedure and Modifications Introduced in WINCOF-I Code

No modifications of the WINCOF code have been required in regard to the parameters mentioned in Section 2.2.5. The initial conditions are specified as necessary at entrance to the first stage of the machine under consideration.

Modifications and additions made in various subroutines, in the WINCOF-I code, relative to those in the WINCOF code, are discussed in Appendix IV.

Concerning the numerical procedure, the main parameter of interest is the set of calculation times in determining the transient performance of the machine. The problem is formulated as follows: air-water mixture at given state conditions and composition enters the machine at the instant of time $t = t_0$. The residence time of the air-water mixture in a blade row or a stage is assumed, as stated earlier, to be equal to the width of the element of machine divided by the mean axial velocity therein, Δt_{RS} secs. Centrifugal action and film build-up and motion are calculated over the interval of time Δt_{RS} secs. At the exit of the element of machine under consideration, one obtains (a) the state conditions of air-water-vapor mixture in the calculation streamtube under consideration, (b) the extent of span from the hub over which water has become depleted due to centrifugal action, and, therefore, the extent of span over which water remains up to the tip of the blades, (c) the extent of clearance that has become filled up with water film in the element of machine under consideration and (d) the film flow conditions. Utilizing those as entry conditions to the next element of machine (blade row or stage) the calculations are repeated. In this way, the entire machine is swept once over an internal of time that is equal to the sum of the residence times of air-water mixture in all of the elements of machine, the so-called sweep time, Δt_{RM}. The calculation must now be repeated utilizing given ingestion conditions and starting with the entry section of the machine in order to obtain "equilibrium" conditions of film formation and flow in all of the stages. This requires, in general, a large number of sweeps across the machine until, at the end of an interval of time, Δt_{EM}, all of the stages indicate operation under equilibrium conditions.

It may be useful to recall here that, depending upon the geometrical and aerodynamic characteristics of the machine under design and off-design conditions, various successive stages may not attain equilibrium in succeeding order. Then at the end of time $t = t_o + \Delta t_{EM}$, there arises equilibrium in all of the stages at the end of a calculation sweep time equal to Δt_{SM}; however, when the calculation is extended further in time, starting with entry to the machine, one again observes time-dependence in the exit conditions from the machine. The exit conditions of interest are the same for any stage, including the last stage, as those given for the first stage. When the calculation is carried out over an interval of time equal to several times the Δt_{EM}, one obtains a periodic pattern of performance with equilibrium conditions arising instantly at the end of various successive values of Δt_{EM} . It must be pointed out here that the foregoing calculation intervals of time and the resulting performance estimates may vary substantially in different machines of differing aerodynamic and geometrical design, rotational speed, and physical size and also, with different air-water-vapor mixture conditions and their distribution with respect to span at entry to the machine.

In summary, the calculation of transient performance of a multistage machine involves several characteristic calculation times, namely Δt_{RS} , Δt_{RM} , Δt_{EM} . In any machine three types of performance of a stage may be found even under equilibrium conditions: (i) clearance partially filled but film unable to be sheared by the adjoining air-water mixture flow, (ii) clearance completely filled and film itself able to be sheared, and (iii) clearance completely filled and film also unable to be sheared. In each case, any water centrifuged beyond setting in of that state is splashed back and redistributed uniformly across the span of blading, by assumption. The manner in which various stages with different kinds of performance as described happen to become stacked in a given machine under a particular set of operating and ingestion conditions determines how Δt_{EM} varies in the long time as calculations are continued in time. Such variation is affected further when there is radial nonuniformity in ingested water and also when ingestion itself involves an unsteadiness.

An important observation here pertains to the calculation procedure based on using a finite difference approach in the calculation of transient performance. The discrete intervals involved in introducing Δt_{RS} and Δt_{SM} lead to changes in performance of various stages and the machine with a periodicity corresponding to those intervals. Such periodicity or unsteadiness is entirely due to the finite difference-based calculation procedure and has no physical significance. The periodicity of interest is only that associated with the instantaneous attainment of equilibrium, at the end of Δt_{EM}, in all of the stages during a long time operation of the machine with water ingestion. The machine operates, (even) with a steady set of conditions at entry to it, in a time-dependent manner with a periodic behavior in the long time, the periods being of the order of Δt_{EM}.

Finally, the procedure and the nature of results described in the preceding pertain to the case of steady conditions of air-water ingestion into the machine. There are various situations in practice in which the conditions may vary as a function of time, either continuously or, more often, over discrete intervals of time, in telegraphic signal form. It is then necessary to introduce changes in the entry conditions at the appropriate time and proceed as before. Such changes will invariably give rise to changes in all of the three characteristic calculation time intervals and also, in the long time performance of the machine. For example, Δt_{RS} is a function of mean axial velocity in the element of machine under consideration and therefore, is a function of local aerodynamic performance which, in turn, is influenced by the local state of air-water vapor mixture composition. Once there is a change in Δt_{RS} in any part of the machine, there also arise changes in Δt_{RM} and Δt_{EM}.

2.3 Prediction Methodology

The methodology employed in determining the transient performance of an axial-flow compression machine may be summarized as follows for a given set of input and operational data. It may be recalled that (a) the WINCOF-I code is operated in the transient mode considering a series of successive, discrete intervals of time; (b) centrifugal action, heat and mass transfer processes and droplet size adjustment are considered at the exit plane of a blade row or a stage following the determination of aerodynamic performance through the element of machine; and (c) performance of a multi-stage unit is obtained by adopting a stage-stacking procedure.

(i) The streamtube for which the calculation has to be carried out is identified and its area of cross-section and radius of location are selected through the element of machine under consideration.

(ii) The WINCOF-I code is utilized to determine the aerodynamic performance of the element of machine with respect to the chosen streamtube.

(iii) In order to determine the effects of centrifugal action, the span of the blading is divided into a finite number of parts, each part being sufficiently small in order to obtain the desired levels of accuracy and, at the same time, adequately large with respect to the largest droplet size and radial displacement of water expected. The selection of the number of parts into which the blading is divided involves a certain amount of trial-and-error. However, in most of the problems dealt with to date in relation to the generic engine unit, division into 10 parts have proved adequate.

(iv) A time interval is chosen for the calculation of the effect of centrifugal action. As stated earlier, this interval of time has been chosen as equal to Δt_{RS} , the residence time of air-water mixture in the element of machine. Centrifugal action is calculated over this interval of time in all of the ten parts of the span. As a result, a part of the water in the element of span closest to the casing moves into the casing clearance space. At the same time, in each of the elements of span starting from the hub, one obtains values for the next amount of water taking into account what is removed from it into the adjoining element towards the tip and what is added on to it from the adjoining element on the other side towards the hub. Insofar as the streamtube under consideration is concerned, one obtains the net amount of water present in it following centrifugal action.

(v) Utilizing the same interval of time and taking into account the net amount of water present following centrifugal action, the heat and mass transfer processes are calculated.

(vi) Finally, the size of droplets that can be present in equilibrium with the local state of gas phase is determined for the streamtube under consideration at the exit plane of the element of machine. At this stage, one has all of the data that are needed as input for the determination of the performance of the succeeding element of the machine.

(vii) The one remaining parameter of interest is the net amount of water that is present in film form in the casing clearance. One can establish this taking into account the amount of water centrifuged into that space from the nearest element of span and the amount of that water which is sheared by the adjoining air-water mixture over the same period of time, namely Δt_{RS}. When the clearance space at the start of calculation is already filled up to the extent that (a) shearing of the film is no longer possible or (b) the clearance space itself is filled up by the film, then any centrifuged water must become splashed back into the span and the thickness of the film remains the same as the input value. At the same time the excess amount of water that is splashed back is assumed to be redistributed uniformly across the span. This affects the value of (a) the mass of water that is calculated as present in the streamtube (b) the interphase heat and mass transfer and (c) the droplet size adjustment, calculated according to (iv), (v) and (vi) above, respectively. Thus, some iteration is indicated in establishing the final state of air-water-vapor mixture in the streamtube at the exit of the element of the machine.

(viii) One can then proceed to calculations for other elements of the machine through a simple stage-stacking procedure for the streamtube under consideration. The streamtube must be located in each element of the machine in terms of its area of cross-section and its radius of location. When, according to this procedure, one has reached the exit plane, one has, by definition, completed a sweep over a period of time equal to Δt_{RM}.

(ix) The next step is to repeat the sweep starting from entry into the machine utilizing the input data concerning ingestion and operating conditions, but taking into account the current state of the air-water mixture in the machine in various elements of it, as given by the results from the previous calculation sweep. The sweeps are continued until all elements of the machine reach equilibrium condition.

(x) A long time calculation is now initiated over a period of time equal to several times the period Δt_{RM} , in order to determine the periodic nature of the time-dependent performance of the machine. It may be pointed out that this calculation may be of interest for certain selected stages of the machine or for the machine as a whole. In practice, mainly in order to reduce computational costs, calculations have been performed in the current calculation ranging over 100 -

1,000 Δt_{RM}. Generally calculations over 500 - 3,000 sweeps have proved adequate to uncover the periodic nature of performance in most of the cases investigated. It may be pointed out that in the multistage compressor chosen for illustration the period of time for 500 sweeps corresponds to about 3 seconds of actual operation time at rotational speed of 100 per cent of design speed, flow coefficient of 0.450 and ingestion of 4.0 per cent mass fraction of water in saturated air.

(xi) When it is desired to take into account a non-zero value of velocity between water and the gas phase (air-vapor mixture) at entry to the first or any other element of the machine, the input as utilized in (i) above needs to be modified.

(xii) When it is desired to take into account modifications in heat and mass transfer coefficients based on number density of droplets, the calculation scheme as given in (v) above needs to be modified taking into account the heat and mass transfer weighting factor.

(xiii) If the entry input conditions to the machine vary as a function of time, such changes are taken into account in the input as utilized in (i) above at the instant of time of appropriate step advance in time.

2.4. Application of WINCOF-I Code

The application of the WINCOF-I code for the determination of a compressor performance with water ingestion is illustrated in Appendix V of the current report.

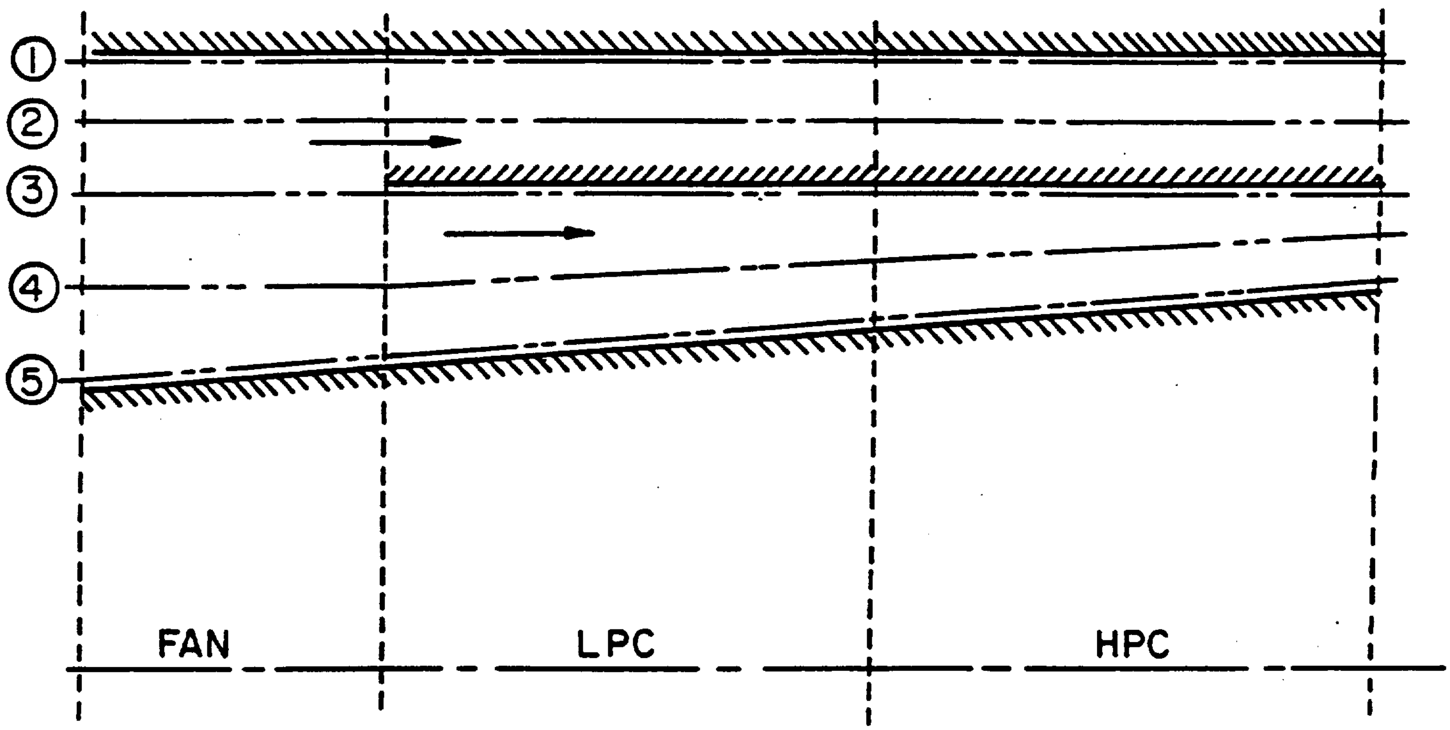


Figure 2.1. Streamtubes chosen in a fan-compressor unit.

* **DROPLET GROUP HEAT/MASS TRANSFER**

  - PROBABLY UNSTEADY
  - PROBABLY GOVERNED BY D, ND

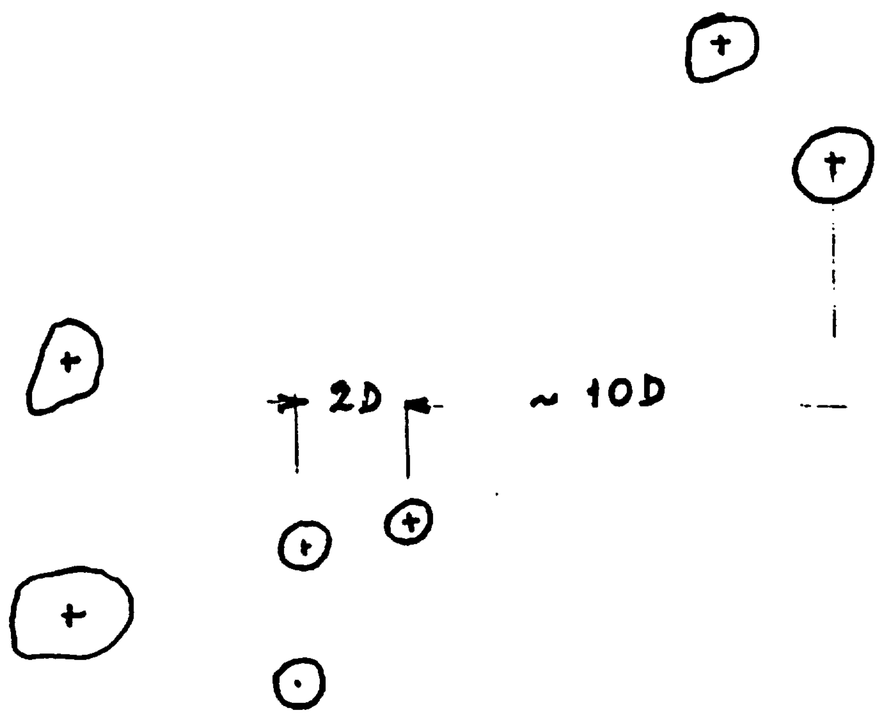


Figure 2.2. Schematic of a conglomeration of droplets.

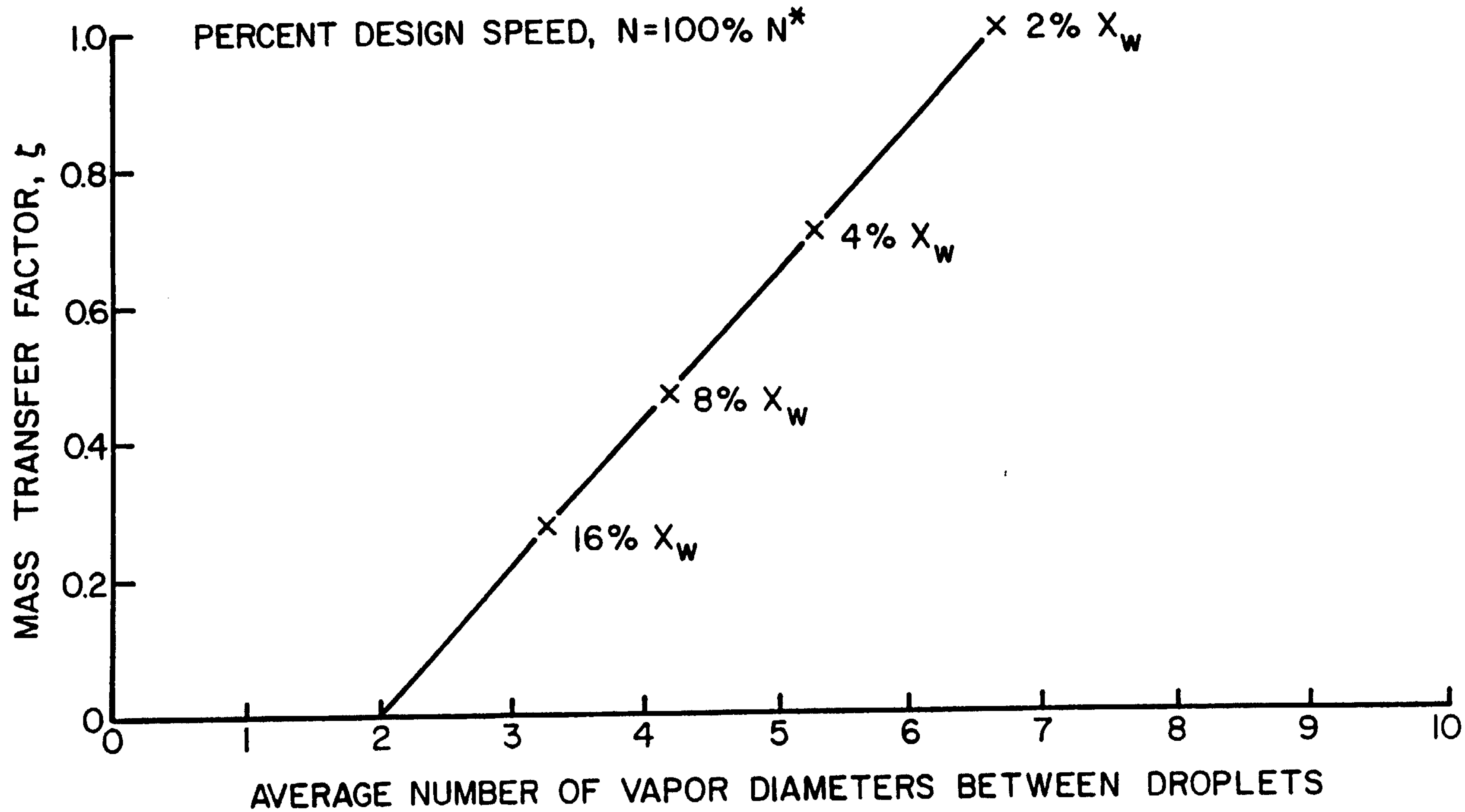


Figure 2.3. Relation between mass transfer parameter (ζ) and mean separation between droplets.

CHAPTER 3

BYPASS ENGINE PERFORMANCE WITH WATER INGESTION: METHODOLOGY

The transient performance of engines is of great interest in all cases when operational conditions are a function of time. It is also of interest when the input conditions to the engine are substantially different from those assumed in the design of the engine. During water ingestion the input conditions become different from those for which most engines are designed, namely operation with air. Water ingestion may occur under various steady and changing operating conditions, the latter in ambient conditions, and power demand as a function of time. Water ingestion parameters themselves may become affected by such changes through modification of scoop factor, for example. Finally water ingestion may be a function of time in certain cases due to changes in atmospheric conditions. In all such cases, it is of importance to determine the extent to which the performance, operation and handling characteristics become affected as a function of time. The setting-in of critical and unstable conditions needs attention. The surge margin and the margin in combustor performance with respect to the occurrence of flame-out are examples of critical conditions. Instability may lead to such and other undesirable situations.

Early work on simulation of bypass engine performance under a variety of water ingestion conditions has been discussed in References 4 and 5. It was undertaken to determine the influence of several parameters related to water ingestion on the transient performance of a typical bypass engine, illustrated in figure 3.1. The parameters pertained to (a) compressor performance with water ingestion, determined utilizing the WINCOF code, (b) combustor performance and (c) instrument response during flooding with ingested water. An engine performance simulation code was utilized to determine the transient performance of a generic bypass fan engine.

In the following, the manner in which the output from the WINCOF-I code can be incorporated into the engine performance code is discussed briefly.

3.1. Generation of Parameterized Compressor Maps for Use in an Engine Simulation Code

The engine simulation code has provision to incorporate the performance of the fan-compressor unit (fan, lower pressure (supercharger) compressor and high pressure (core) compressor) in the form of a set of parameterized maps. The maps consist of the following for each component unit.

(i) Loss as a function of work coefficient;

(ii) minimum loss and minimum loss work coefficient as functions of rotational speed of machine;

(iii) (loss - minimum loss) as a function of (work coefficient - minimum loss work coefficient) squared;

(iv) minimum loss coefficient as a function of rotational speed of machine; and

(v) pseudo-Mach number of flow as a function of (work coefficient - minimum loss work coefficient).

The first three maps provide a representation of efficiency and the latter two, a representative of mass flow. Thus mass flow, work done and efficiency are represented as functions of speed in a combined fashion such that (iii) and (v) become available in a multi-linear form. This makes it relatively simple to introduce and to use the maps in the engine simulation code. Those maps and the methodology for determining them have been described in detail in References 4 and 5 and in summary form in Appendix VI. It may be pointed out that the engine performance characteristics presented in References 6 and 8 are based on the use of performance results for the fan-compressor unit that were obtained utilizing the WINCOF code.

3.1.1 Use of Fan-Compressor Unit Performance Maps in the Engine Simulation Code

In generating performance of a fan-compressor unit for use in engine simulation with water ingestion, it is necessary to cover a sufficiently wide range of operating speeds and mass flows. In general, it is not feasible to determine *a priori* the ranges required since ingestion may cause the engine to operate in unusual ranges of operation parameters. Some guidance may be obtained from calculations performed for operation with air, and this is the basis employed in generating maps in the current investigation.

Typical parameterized performance maps for a multi-stage compressor unit with water ingestion are illustrated in figures 3.2. It may be observed therein that the performance is given for a series of discrete values of mass fraction of water entering the unit. It is clear that engine simulation is feasible only for steady or discretely changing (from one value to another) amount of water ingestion at the front of the fan-compressor unit. In view of the nonlinear changes in performance with water ingestion, no simple interpolation is possible between performance values calculated for even closely separate values of ingested parameters.

There arises yet another important consideration in the use of performance maps for the fan-compressor unit, namely that they refer to quasi-steady state operation during water ingestion. As stated earlier, at the end of a certain interval of time beginning with the inception of ingestion, a quasi-steady is reached in which the aerodynamic performance of the unit (as a whole) remains nearly steady. However, it is necessary to recognize two features in regard to performance: (i) the distribution of water across the span and in the casing clearance continues to vary with a periodic feature and (ii) during the time required to attain quasi-steady state the performance of the fan-compressor unit can be appreciably worse than on reaching that state.

On one hand, the periodic variation of water distribution has to be taken into account in the prediffuser, and combustor and also, if necessary, in the turbine and the thrust nozzle.

On the other hand, the variation of performance during the attainment of quasi-steady state is not available in the performance maps corresponding to the quasi-steady state. In determining the transient performance of an engine, the use of "constant" (or non-time variant) quasi-steady maps, therefore, does not account for the variation of performance during the setting-in of the quasi-steady state. This method of determining performance becomes questionable in, at least, two cases considered in the current investigation as follows: (i) prediction of engine performance desired from the instant of commencement of ingestion; and (ii) prediction of engine performance from the instant of a change in the amount of water being ingested. In both of those cases, it is clear that the fan-compressor unit is in a non-steady mode of operation over an initial period of time during which conditions are tending towards the setting-in of a quasi-steady state.

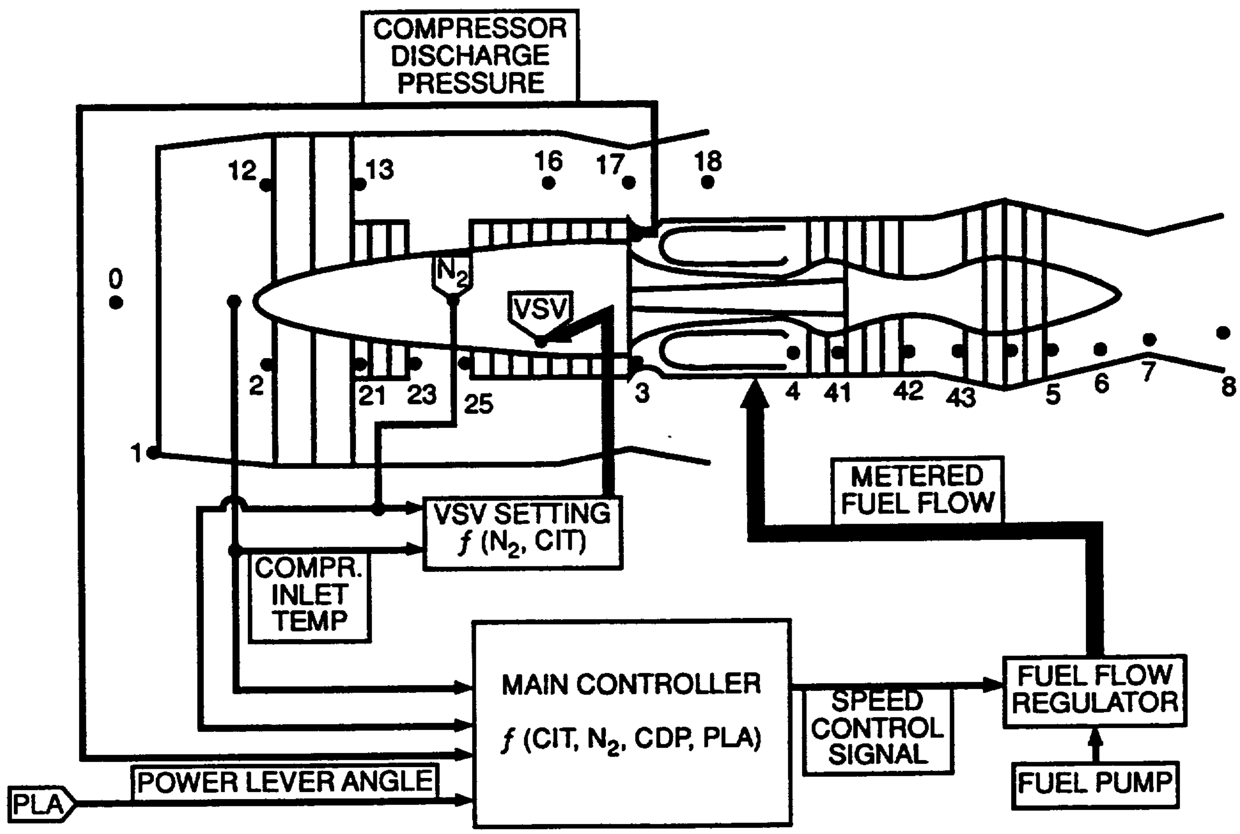
The performance of a fan-compressor unit with water ingestion is, unfortunately, highly nonlinear. It is, therefore, not possible to rationalize changes in performance during the period required for attaining the quasi-steady state in the form of functional relationship governing performance with respect to time even for a single unit. Even for a single unit, it is necessary to take into account rotational speed of operation, mass flow of air and mass fraction of water being ingested as three (primary) variables governing performance; each of them has effects intimately intertwined with the other two.

Two ways of overcoming this difficulty may be considered: (i) to introduce transient performance of the fan-compressor unit directly into the calculation of transient performance of the engine; and (ii) introducing some form of approximation for the performance over the initial period of time beginning with ingestion or change in amount of ingestion. Concerning (i), it has already been stated that current computer capability does not make it practicable. In fact, the setting up of quasi-steady performance maps is in itself a consequence of such limitations. Regarding (ii), the following method has been adopted in the current investigation.

The change in performance with water ingestion, relative to the base performance for operation with air, is expressed in terms of adders in the engine simulation program. They are called in as necessary with reference to the mass fraction of water entering the compressor. The adders are obtained from performance maps of the type illustrated in figures 3.2 - 3.4. In using the adders for calculations immediately following the start of ingestion or a change in it, the following assumption is introduced: for any value of water ingestion, the adder becomes double the value varying linearly over an interval of time of about one minute and then, the original value applies. This is based entirely on trends in the results of various performance calculations conducted on a multi-stage compressor unit operating with several types of air-water mixtures. It is possible that other assumptions, not proposed here, may be preferred in different engines.

3.2 Predicted Results

The methodology for predictions of performance for a bypass engine under various conditions of ingestion and operation, and specific results pertaining to an example engine are presented in Reference 8.



PRIMARY GAS STREAM

STATION	DESCRIPTION
0	AMBIENT
1	INLET/ENGINE INTERFACE
2	FAN FRONT FACE
21	FAN DISCHARGE AT HUB
23	BOOSTER DISCHARGE (STATOR EXIT)
25	HIGH PRESSURE COMPRESSOR INLET
3	HIGH PRESSURE COMPRESSOR DISCHARGE
4	BURNER DISCHARGE
41	HIGHE PRESSURE TURBINE ROTOR INLET
42	HIGH PRESSURE TURBINE EXIT
43	LOW PRESSURE TURBINE ROTOR INLET
5	TUTBINE DISCHARGE
6	EXHAUST NOZZLE/ENGINE INTERFACE
7	EXHAUST NOZZLE THROAT
8	EXHAUST NOZZLE DISCHARGE

PRIMARY GAS STREAM

STATION	DESCRIPTION
12	FAN INLET AT TIP
13	FAN DISCHARGE
16	DUCT EXHAUST NOZZLE/ ENGINE INTERFACE
17	DUCT EXHAUST NOZZLE THROAT
18	DUCT EXHAUST NOZZLE EXIT

Figure 3.1. Schematic representation of a generic bypass fan engine.

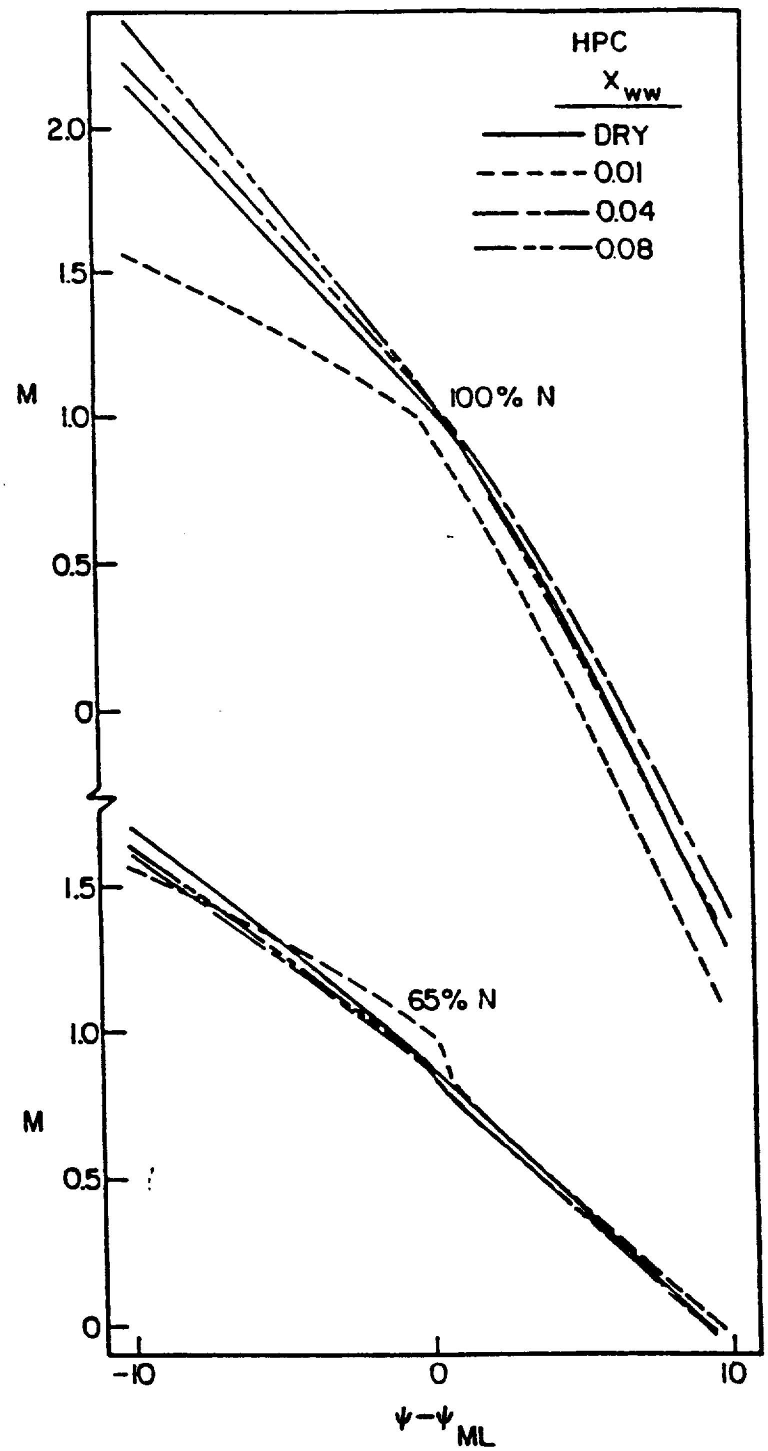


Figure 3.2. Parameterized performance maps for a multi-stage compressor unit.

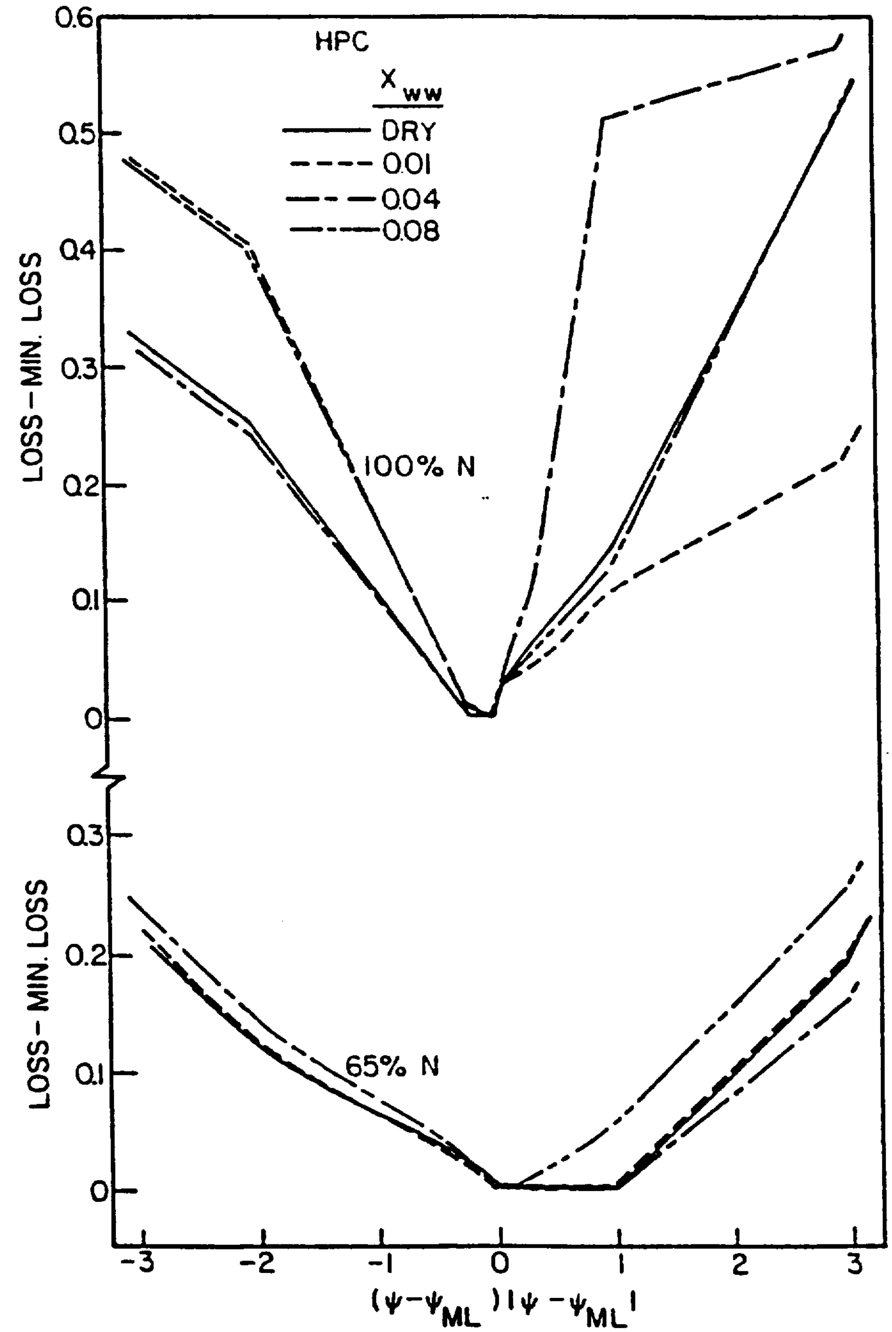


Figure 3.2. (continued)

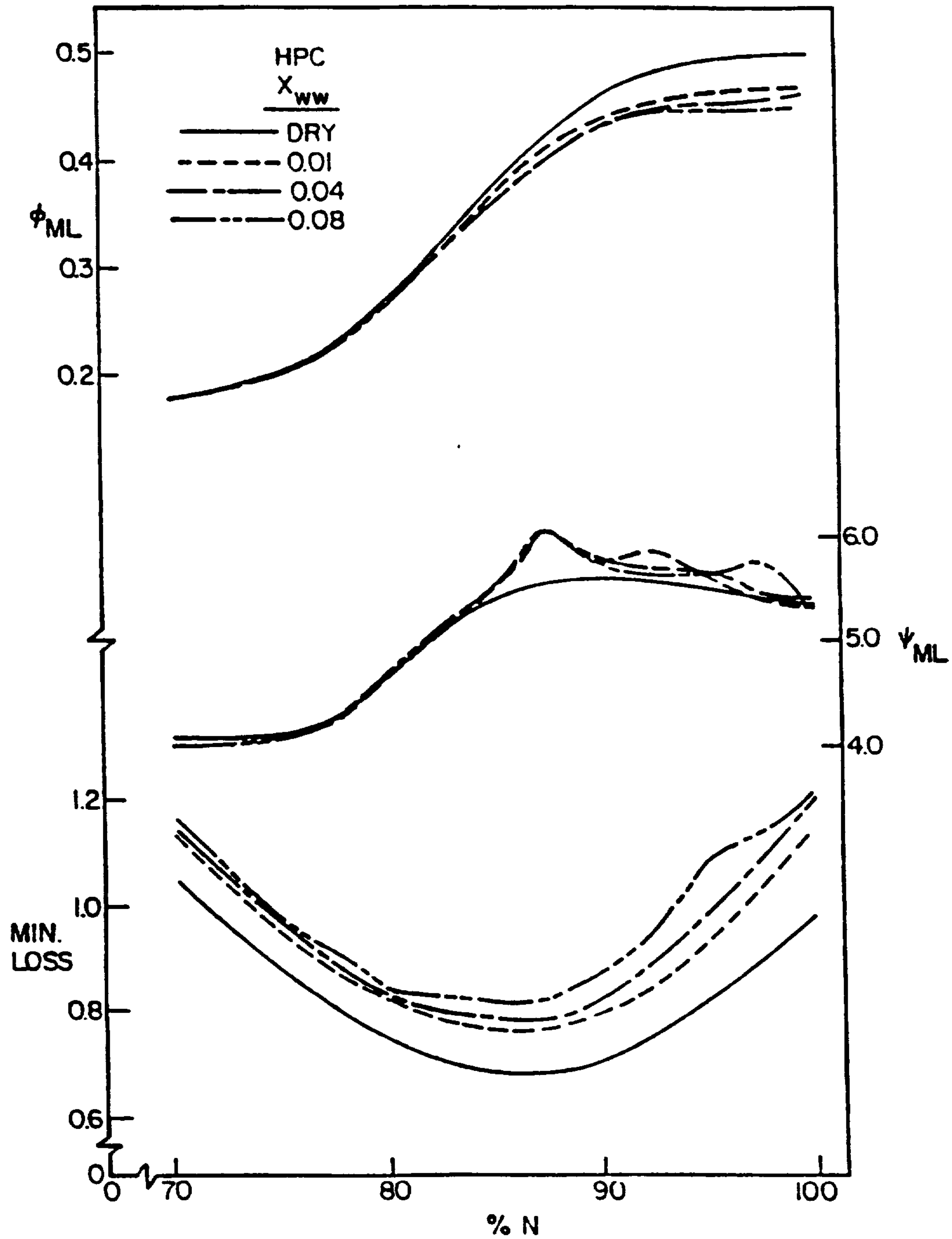


Figure 3.2. (continued)

CHAPTER 4
DISCUSSION

The methodology developed in the WINCOF-I code can be utilized for the prediction of performance of an axial-flow fan or axial-flow compressor in a variety of cases of steady and varying ingestion of water. The type of cases that are significant in practice are discussed in Section 4.1. The WINCOF-I code can be incorporated into an engine performance code for the determination of the transient performance of an engine. Various cases of practical interest are discussed in Section 4.2. Finally, several recommendations for the manner in which the WINCOF-I code can be adapted for the improvement of design and operation of turbomachinery as well as a complete engine are presented in Section 4.3.

4.1 Application of WINCOF-I Code

The WINCOF-I code provides a means of determining the performance of an axial-flow fan or axial-flow compressor given (a) the geometry of the turbomachinery, (b) the aerodynamic rules governing the performance, and (c) the initial conditions of flow immediately upstream of the machine. The latter, namely the entry conditions, may vary in a variety of ways, and also differ substantially from one case to another of water ingestion into engines.

The entry conditions may be characterized by the following parameters:

(i) the variation of temperature and velocity of air as a function of blade radius (or height) and time;

(ii) the mass fraction of water in air as a function of blade radius (or height) and time;

(iii) the ratios of water in film, droplet, and vapor form in different parts of the annulus formed by the blade height, including the casing and the hub walls, and their variation with respect to time;

(iv) the droplet size distribution in the annulus as a function of time; and

(v) the velocity of film and droplets across the annulus height as a function of time.

In practice, the foregoing parameters are likely to vary on account of the following:

(i) distortion introduced due to atmospheric conditions;

(ii) distortion introduced due to inlet, spinner, and splitter plate geometry, or, equivalently, the scoop factor, as a function of time;

(iii) film formation over inlet, spinner, and splitter plate;

(iv) engine demand for air flow;

(v) entry into and exit from environmental conditions giving rise to water ingestion; and

(vi) changes in rainfall, atmospheric conditions, and engine demand in various combinations giving rise to modifications in ingestion as a function of time.

In each of the foregoing cases, the WINCOF-I code can be utilized for determining turbomachinery performance.

4.2 Applications in Engine Performance Estimation

The WINCOF-I code can be readily incorporated into a code for the determination of the transient performance of an engine, as described in Chapter 3. The engine performance is a function of the following parameters:

(i) the basic design and matching of various components of the engine;

(ii) the atmospheric conditions in the environment of operation; and

(iii) the thrust power demand from the engine with a given fuel flow control system.

In practice, the latter two sets of parameters, (ii) and (iii), may vary for the same (practical) reasons as stated in section 4.1. These include time-dependent power demand changes during acceleration and deceleration of a flight vehicle with possible concurrent changes in flight altitude. In all such cases, the engine performance changes, relative to design point performance, can be established taking into account changes in turbomachinery performance utilizing the results of performance calculations performed with the WINCOF-I code. In addition, combustion performance changes also may be taken into account on a parametric basis, as stated in Chapter 3.

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10. General Electric Company, Extended Parametric Representation of Compressor Fans and Turbines, NASA Contractor Report 174645, March, 1984.

APPENDIX I

RULES FOR ESTIMATION OF OFF-DESIGN PERFORMANCE OF COMPRESSORS

The problem of determining the off-design performance of a multistage compressor may be stated as follows: Given the geometric details of the compressor, including the metal angles at inlet and outlet, and the aerodynamic design of the stages at the design point, to determine the performance of the compressor under conditions of operation away from the design point. The design point and, therefore, also off-design points for a stage may be designated by specifying the rotational angular speed of the rotor and the axial velocity or mass flux, as as function of radius across the span of the rotor in the stage, and the ambient conditions. For a multistage compressor, the axial velocity in the first stage may be specified as the reference value for the machine as a whole so long as there is no change in mass flux across the compressor.

The main performance parameters of a compressor stage are pressure ratio and efficiency as functions of the operating rotational speed, and the axial velocity at entry to the stage. In the case of a multistage unit the pressure ratio and efficiency for the unit as a whole are functions of the operating rotational speed and the axial velocity at entry to the first stage, so long as the mass flux remains constant everywhere along the compressor. The axial velocity at entry to each stage succeeding the first is determined by the performance of the preceding stage. Thus, one can proceed to determine the performance of each stage. Then the performance of the multistage unit can be obtained by a stage stacking procedure, as done in the current case, or some other means of matching successive stages.

It may be noted here that, as far as ambient conditions are concerned, the operational parameters of a compressor stage may be specified in terms of angular speed and mass flux that are normalized with respect to reference values (for example, standard temperature and pressure). In the alternative, the performance of a stage can be given in a form that does not involve ambient conditions; this alternative procedure is discussed further in Appendix IV.

Figure I.1 provides a schematic representation of a part of a blade row, wherein various relevant parameters are shown.

The geometry of a compressor stage is usually fixed. However, there are cases in which the stage setting (or its stagger angle) and the casing clearance are adjustable for various reasons. In such cases, one knows a priori, as part of design information, the manner in which blade geometry varies with off-design conditions of operation.

The problem of predicting the performance of a compressor stage under off-design conditions thus becomes one of establishing the aerodynamic parameters that, in turn, can be utilized to calculate the performance corresponding to the given off-design operating conditions.

The aerodynamic parameters may be chosen, for example, as the incidence angle, the deviation angle and a parameter by means of which the losses in the flow over the blades in the blade rows of the stage under consideration can be estimated (References 1 and 9). It is then necessary to evolve a set of functional relations, rules, as called here, between the changes in the aerodynamic parameters and the changes in the operating conditions, both with respect to design point conditions.

The rules currently utilized are a modification of the rules given in Reference. They are provided in the following.

(1) Diffusion factor

A key parameter in the estimation of aerodynamic performance of a compressor stage is the so called diffusion factor (Reference 9). Briefly, it denotes the diffusion of air as a function of momentum diffusion and the inlet and outlet air angles of the blade row. The diffusion factor has been based on equivalent diffusion ratio, defined as follows in the current investigation.

$$D_{eq} = \frac{V_{Z1}}{V_{Z2}} \cdot \frac{\cos \beta_2}{\cos \beta_1} \left[1.12 + k\,(i - i^*)^{1.43} + 0.61\, \frac{\cos^2 \beta_1}{\sigma}\, k \right] \cdot AK3 \qquad (I.1)$$

Here V_Z is the axial velocity, β the blade metal angle, i incidence angle, σ solidity of blade and k, a coefficient that is specific to a blade form. The subscripts 1 and 2 refer to blade inlet and outlet conditions, while i^* denotes design value. The numerical values may be treated as constants pertaining to a typical blade in a class of blades designed with a particular level of technology. The parameter AK3 then is of the nature of an adjustable factor by means of which the equivalent diffusion ratio for another blade (of the same class) can be obtained. Thus, at design, noting that $(i - i^*)$ is equal to zero, one can find D_{eq} and adjust it with respect to a measured or otherwise determined value by means of a suitable value for the AK3 factor. The expression (I.1) itself can then be used for determining D_{eq} corresponding to an off-design value for the angle of incidence.

(2) Deviation angle

The deviation angle is a measure of the departure of the air exit angle in a given blade row compared to the metal exit angle of a blade for given entry conditions of air flow including the incidence angle. Its value may be positive or negative, a large positive value indicating separation of flow over the blade surface somewhere along the chord. While the metal turning angle over a blade is given by the metal inlet and outlet angles, the deflection of air over the blade is obtained by including the incidence and the deviation angles with the inlet and the outlet metal angles, respectively. The deflection of air is a parameter in the determination of the change in angular momentum and hence of the work absorbed by the air in a rotor.

The deviation angle is defined as follows in the current investigation.

$$\delta = \delta^* + 6.40 - 9.45 \, (M_1 - 0.6)(D_{eq} - D^*_{eq}) \cdot AK1 \qquad (I.2)$$

where M_1 is the Mach number at inlet to blade row and AK1 is an adjustable factor with the same status as the factor AK3. The expression (I.2) contains the factor (M_1 - 0.6) and therefore needs further adjustment when the inlet Mach number is over 0.6.

(3) Nondimensional Wake Momentum Thickness

The total pressure increases across a compressor stage, by design, due to input of work. However there are losses due to various causes, including frictional losses, over the surface of a blade. The losses are denoted by a total pressure loss factor and defined, according to Reference 9, as follows.

$$\overline{\omega} = \left(\frac{\theta}{c}\right) \frac{2\sigma}{\cos \beta_2} \left(\frac{\cos \beta_1}{\cos \beta_2}\right)^2 \qquad (I.3)$$

Here (θ / c) denotes the wake momentum thickness, θ, non-dimensionalized with respect to chord c. It is calculated in the current investigation according to the following rule.

(i) For $D_{eq} > D_{eq}^*$:

$$\left(\frac{\theta}{c}\right) = \left(\frac{\theta}{c}\right)^* + \left(0.827M_1 - 2.69\ M_1^2 + 2.675M_1^3\right)\left(D_{eq} - D_{eq}^*\right)^2 \cdot AK2 \qquad (I.4)$$

(ii) For $D_{eq} < D_{eq}^*$:

$$\left(\frac{\theta}{c}\right) = \left(\frac{\theta}{c}\right) + \left(0.89\ M_1 - 8.71\ M_1^2 + 9.36\ M_1^3\right)\left(D_{eq} - D_{eq}^* \cdot AK2\right) \qquad (I.5)$$

Here AK2 has the same status as AK1 and AK3 earlier.

I.1. Method of Application

The relations I.1 - I.5 involve three adjustable factors AK1, AK2 and AK3. In determining those factors at the design point such that the design pressure ratio and efficiency are obtained with the aerodynamic parameters and operating conditions of the design point, some trial-and-error, as well as iteration with respect to blade exit flow conditions, are involved. The reason is that the three adjustable factors themselves are not related to one another through an independent set of relations.

Once a set of adjustable factors is chosen such that the design point performance is recovered at the design point operating conditions, the relations I.1 - I.5 can be utilized with the chosen values of adjustable factors for determining performance under off-design operating conditions.

It may be noted that in the case of a multistage machine the set of rules must be "tuned" with appropriate values of adjustable factors in each stage. As a consequence, following stage stacking, it is possible that an accumulation of small differences in performance of individual stages may lead to a noticeable change in overall machine performance. Some ingenuity is required in the final evolution of rules with acceptable, adjustable factors.

It may also be pointed out that the rules including the adjustable factors are specific to the local station along the span. Thus, referring to figure 2.1, for the case of a multistage machine, a separate set of rules for use in various stages is required along each of the calculation streamtubes through the machine. In the current investigation, the performance of the fan and the compressor has been obtained along streamtubes 2 and 5.

I.2. Extension to the Case of Water Ingestion

In applying the rules to the case of water ingestion in the WINCOF and the WINCOF-I codes, the following methodology is utilized.

(i) The angle of incidence is based on the velocities calculated with respect to air-water mixture, without taking into account any differences in velocities of air and small and large droplets. The velocities involved in determining the entry angle are the axial velocity of air-water mixture and the rotational speed at entry, the latter unaffected by the flowfield.

(ii) The angle of deviation is based on the blade surface with any film formed due to droplet impact.

(iii) Finally, the inlet Mach number is based on acoustic speed in the local state of air-water incidence.

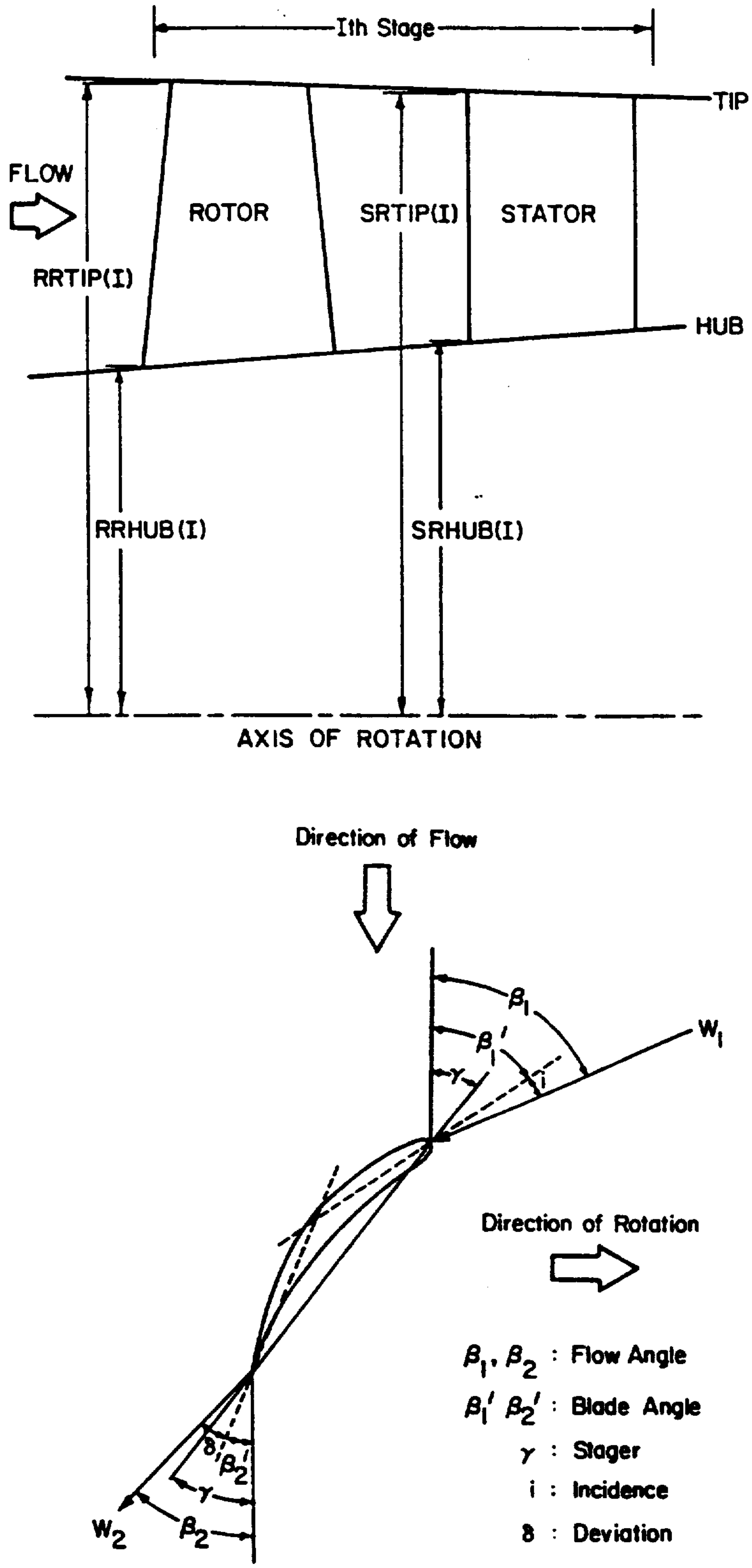

Figure I.1. Schematic representation of a blade row.

APPENDIX II

ANALYSIS OF CENTRIFUGAL ACTION AND FILM FORMATION

An important change introduced in the WINCOF-I code, relative to the WINCOF code (Reference 1), is the method of including film formation and motion in the casing clearance continuous with the determination of centrifugal action on water in the air-water mixture flowing through the stage of a compressor.

The details on the calculation of motion of water due to centrifugal action over blade surfaces and in blade passages has been discussed in detail in reference 1. The method of calculation remains the same in the WINCOF-I code. In essence, centrifugal force is balanced with change in radial momentum of water. Gravitational action, drag and buoyancy are neglected since they have been shown to have little effect on the motion.

Details regarding film formation and motion are given in section II.1. The manner in which film growth and motion on the one hand and radial motion of water due to centrifugal action are coupled in a time-dependent calculation scheme is described in section II.2.

II.1 Film Formation, Growth and Motion

The casing film may have its origin on the inlet surface, in which case the presence of film becomes a part of the initial conditions of water distribution at entry to a fan or compressor stage.

In any case, a film can become formed in a stage in the casing clearance space as water is displaced radially outwards towards the casing wall. The film suffers a motion along the gas path due to the shearing action of the adjoining air-water mixture flow. The velocity of film motion is affected, although to an unknown extent, due to the continuous deposition of water and the mixing losses between the original film (at any instant of time) and the new deposit.

In order to calculate the growth and motion of film over a finite, but short duration of time, the following assumptions are introduced.

(i) The film as well as the air-water mixture consist of incompressible, viscous fluids.

(ii) The air-water mixture is saturated with water vapor at all times.

(iii) Surface tension and gravity effects are small and therefore, a continuous film exists.

(iv) the film is in laminar motion while the air-water mixture is in turbulent motion. Suitable velocity profiles may be assumed (Reference 7) at the wall and the interface on the film and the air-water mixture sides.

Regarding the velocity profiles, they are described as follows.

laminar profile

$$\frac{u}{u_I} = C_i + C_2 \frac{u}{\delta_1} + C_3 \frac{u^2}{\delta_1^2} + C_4 \frac{u^3}{\delta_1^3} \qquad \text{(II.1)}$$

The velocity boundary conditions for film flow are given by:

$y = o$: $u = o$; and

$y = \delta_I$: $u = u_I$

Here the u represents velocity, u_I the velocity at interference, δ_I the thickness of film and y the coordinate direction normal to the wall. The shear stress at any location y is given by $\tau = \mu \ (\partial u / \partial y)$, where μ is the molecular viscosity of water.

turbulent profile

$$\frac{u}{u_\infty} = (1 - \frac{u}{u_\infty}) \quad (\frac{u}{\delta g})^{1/7} \qquad \text{(II.2)}$$

The velocity boundary conditions for the air-water mixture flow are given by:

$$y = \delta_I : \qquad u = u_I \qquad \text{and}$$
$$y = \delta_I + \delta_g : \quad u = u_\infty$$

Here δ_g is the thickness of the viscous layer of the air-water mixture at the interface and u_∞ the velocity of the air-water mixture outside the viscous layer. The shear stress at the interface may be written as follows.

$$\tau_o = \delta\, u_I^2 \frac{d\theta}{dx}$$

where θ is the momentum thickness of the air-water mixture viscous layer and x the direction of air-water mixture and film motion, parallel to the axis of the machine.

The film motion can be analyzed based on a control volume, as shown in figure III.1, and invoking the laws of conservation of mass and momentum. The film gains momentum transferred across the interface from the air-water mixture due to the difference in kinematic viscosity between the two fluids, influenced further by the turbulent nature of air-water mixture flow. A gain in momentum gives rise to a velocity to the water centrifuged to the casing clearance. By conservation of mass, the film becomes thinner at the exit plane of the control volume. If the length of the control volume along the direction of flow is set equal to a row of blades, one thus obtains the thickness and the velocity of film provided one knows the value of interfacial velocity; that velocity, u_1, is common to the film and the air-water mixture.

Referring to figure III.1, the transfer of momentum can be represented by the following equation.

$$\delta_g \, u_\infty^2 \, \delta_g - \int_{\delta_1}^{\delta_g} \delta_g \, u_g^2 \, dy = \int_0^{\delta_1} \delta_w \, u^2 \, dy \qquad \text{(II.3)}$$

where δ_g represents the density of the air-water mixture.

The transfer of mass into the film due to centrifugal action may be written as follows.

$$\dot{m}_y + \delta_w \, \delta_1 \, u_1 = \dot{m}_y \, \delta_2 \, u_2 \qquad \text{(II.4)}$$

where $(u_2 - u_1)$ is the gain in velocity due to shearing action.

Equations (II.3) and (II.4) can be solved by guessing the interfacial velocity and using the so-called shooting method.

II.2. Coupling of Centrifugal Action and Film Motion

Entry conditions to a stage are assumed to be given with respect to distribution of water in the air-water mixture in the span of the blade row and the casing clearance space. It is then the objective to determine the distribution of air-water mixture at the stage exit, for given values of rotational speed and flow coefficient, as a result of centrifugal action and film formation and motion in the clearance space. There are two possibilities of interest with respect to the condition of film at entry to a stage: its thickness is equal to or less than the casing clearance height. In the former case, any centrifuged water must be splashed back into the span. Thus the result of centrifugal action is a redistribution of water in the span. In the second case, with a partially filled casing clearance space, centrifugal action adds to the film thickness. In both cases, the film, with the given value of initial velocity of motion, undergoes shear (locally in the blade row) by the air adjoining air-water mixture and therefore attains a new value of velocity of motion at the stage exit. It is the combination of film growth and the velocity of its motion due to shear that determines the gradual attainment (in time) of quasi-equilibrium condition in the stage, as stated earlier.

The span of blading is divided into a certain number, e.g. ten, of streamtubes. The number depends on local droplet size and also, the amount of water in air. All streamtubes should be larger than the diameter of drops and the largest expected separation distance between drops. The width of the streamtubes need not be equal. The casing clearance width is treated as a single streamtube whether it is partially or fully filled.

In order to perform calculation of centrifugal action on water droplets and the film growth in successive discrete time intervals, an interval of time must be chosen. The mean residence time of air-water mixture in the blade row, equal to chord distance divided by axial velocity of flow is generally short enough in duration for obtaining an accurate solution. If the changes of film thickness and velocity of motion are not gradual during calculation, then the duration of time step may be the main cause and needs to be reduced. We denote the calculation step interval of time in a stage by Δt_{RS} .

Centrifugal action on water droplets in each streamtube is calculated over the interval of time equal to Δt_{TS} divided by the number of streamtubes in the span. Accounting for accumulation and displacement of water, starting from the hub towards the tip of the blade, one can establish the addition to the casing clearance space. The shearing action on the film is calculated over the same interval of time. The calculation is repeated the number of times equal to the number of streamtubes chosen for the blading; thus, at the end of the set of repeated calculations, the total length of time covered is Δt_{RS} . The results of the calculation yield the distribution of water in the span and the casing clearance space as well on the velocity of film motion.

In a single stage machine, utilizing the initial conditions at entry one can calculate the distribution of water in the blade passage taking into account droplet impact and rebound processes. The resulting distribution provides the distribution in the blade passage for starting the calculation.

In a single stage machine, Δt_{RS} is obviously equal to the length of time to cover the length of the machine and, therefore, can be set equal to δt_{RS} , the sweep time over the machine. In view of the fact that in the first sweep quasi-equilibrium conditions may not necessarily have been attained, additional sweeps are required. At the initiation of each succeeding step, one has to recognize the entry conditions and the local conditions in the stage with respect to water distribution. Regarding the latter, a part of a streamtube towards the hub may have become depleted in the first sweep while all other streamtubes have a small change (generally addition) in the amount of water.

After a certain number of sweeps, one attains the quasi-equilibrium condition. For a single stage machine, the performance becomes periodic in time as calculations are continued.

In a multi-stage machine the foregoing procedure is repeated over all of the stages in an interval of time that is designated as the sweep time, Δt_{RM} . All of the data is each of the stages pertaining to water distribution must be saved as part of the initial conditions for the next sweep of calculation.

The entry conditions to the first stage give rise, in the next sweep to a set of new conditions in the first stage blade passage taking into account the result of calculation over the first time interval Δt_{RS} . The balance of the calculation procedure during the second and succeeding sweeps, then, is the same as in the first sweep.

At the end of a certain number of sweeps all of the stages in the multi-stage machine can be expected to have attained quasi-equilibrium conditions. At that instant of time, a second cycle of changes begins and thus, a periodic change occurs in time.

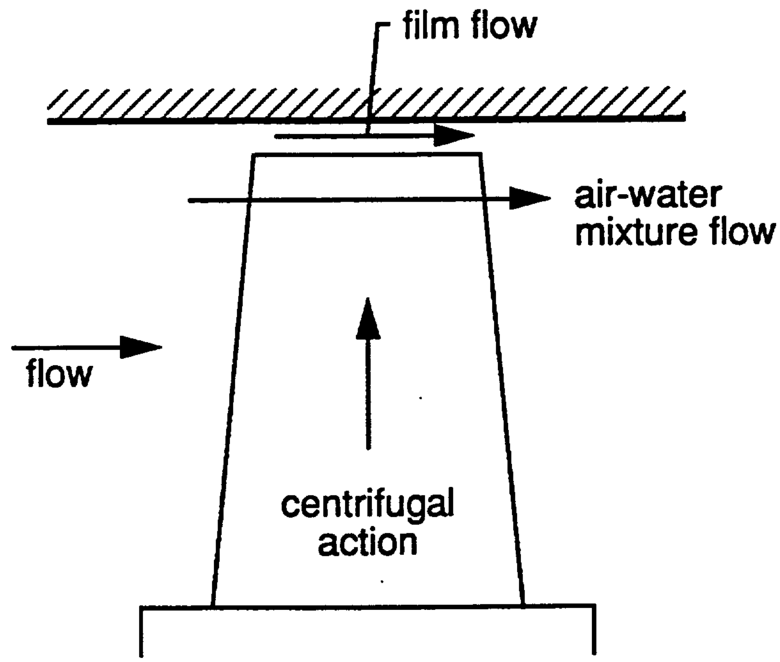

Figure II.1. Film formation and motion.

APPENDIX III

HEAT AND MASS TRANSFER PROCESSES

Heat and mass transfer between the gaseous phase (air and water vapor) and the liquid phase (water, especially in droplet form) is an important process occurring in a fan-compressor unit during water ingestion. The temperature of air increases along a compressor as work is added in the stages of the unit while that of water increases only by orders of degrees. This difference combined with increase in pressure of the mixture drives heat and mass transfer processes. The basic method of estimating interphase heat and mass transfer in the WINCOF-I code remains the same as in the WINCOF code (Reference 1). However there are two additional features introduced in the WINCOF-I code as follows.

(i) Changes due to the large numbers of droplets in a unit volume, that affects transfer processes; and

(ii) duration of heat and mass transfer processes noting the difference in residence time of air and droplets in the compressor.

There is obviously considerable empiricism in accounting for both of those since no data or adequately unambiguous methods of analysis are available in either case. However, a parametric study of those effects can be revealing, for example a study to establish conditions under which most of the liquid water may (or may not) become converted into vapor form at the exit plane of a multistage compressor.

III.1 Transfer Parameter

A transfer parameter is introduced as the ratio of actual (heat or mass) transfer occurring in a conglomeration of droplets to the ideal value of (heat or mass) transfer that can occur between a gas and a single droplet in it. In the current case of air-water droplet mixture flow in a compressor, the principal impediment to transfer is the presence of a number of droplets in any relevant volume.

A droplet can be expected to be surrounded by some water vapor, and in a sudden vaporization of the droplet, there can arise a volume of vapor at the ambient pressure equal to that of water in a droplet. The heating and vaporization processes in a process spread over a finite period of time are complex, especially because of the flow environment prevalent in an axial-flow compressor.

In the WINCOF-I code, a simple parameter has been introduced to correct heat and mass transfer rates for a single droplet to obtain values for a conglomeration of droplets. It has been named the heat and mass transfer factor. The basis for evolving the factor consists in the following assumptions.

(a) Droplets of diameter, (10 microns), in an air-water mixture with 2 per cent water by weight (approximately 10 diameters apart in vapor form under ambient conditions) may behave as single droplets, with no interference between droplets insofar as heat and mass transfer processes are concerned. But, similar droplets when they are 2 diameters apart in vapor form preclude heat and mass transfer completely.

(b) The factor varies linearly between a value of zero when heat and mass transfer is entirely eliminated and a value of unity when droplets are 10 or more vapor-diameters apart.

III.2. Residence Time of Droplets in a Stage

It has been assumed, as stated in Section 2 of the current report, that droplets of ingested water may be distinguished as (a) small, moving with velocity of air and (b) large, for which a velocity can be assigned independently of that of air, at entry to the fan-compressor unit and also at entry to any stage. However, this may only be done empirically as a parameter that can be varied in a specific calculation

III.3 Calculation Procedure

Given the composition of air-water mixture and the mean volumetric diameter of droplets at a specific location in the compressor one can calculate the number density of droplets per unit volume. Based on the local values of pressure and temperature, the vapor-diameter for a droplet can be found and thereby, the distance between the droplets in vapor form under local conditions. The heat and mass transfer factor then may be defined as follows.

$$\xi = \frac{N_{dia} - 2.0}{10 - 2.0} \qquad \text{(III.1)}$$

Here N_{dia} represents the number of vapor diameters that the droplets are apart locally.

The relative velocity factor accounting for the difference between air and droplet velocity, ζ is assigned various values as desired. In determining residence time of water in a stage, the ratio of stage width to mean axial flow velocity is multiplied by ζ, which can have any positive value less than unity.

Now, heat and mass transfer calculations may be performed at the exit plane of each blade row or stage of a fan-compressor unit. It is therefore possible to account for ζ and ξ factors at all such calculation stations as desired.

APPENDIX IV

MODIFICATIONS INTRODUCED IN WINCOF-I CODE RELATIVE TO WINCOF CODE

IV.1. Variable Names

XPHI	inlet flow coefficient
ICHORD	number of chord-wise steps in centrifugal calculation
JEND	number of sweeps through code
NWATER	flag for dry/water cases
ICASE	inlet water distribution case, usually uniform, with = water fraction
NS	number of stages
NSF	number of fan stages
NSLPC	number of low pressure compressor stages
NSHPC	number of high pressure compressor stages
RRHUB(I)	hub radius at Ith stage rotor
RCA(I,J)	chord length of Ith stage rotor
RBLADE(I)	number of blades for Ith stage rotor
STAGRA(I,J)	stagger angle for Ith stage rotor
SRHUB(I)	hub radius at Ith stage stator inlet
SCA(I,J)	chord length of Ith stage stator
SBLADE(I)	number of blades for Ith stage stator
STAGSA(I,J)	stager angle for Ith stage stator

SIGMRA(I,J)	solidity of Ith stage rotor
SIGMSA(I,J)	solidity of Ith stage stator
BETSSA(I,J)	stator outlet absolute flow angle at design pt. for Ith stage
FNF	fraction of design corrected rotor speed for a particular speed
XDIN	initial water content (mass fraction) of small droplets
ICENT	index for centrifugal calculation of small droplets
XDDIN	initial water content (mass fraction) of large droplets
IICENT	index for centrifugal calculation of large droplets
ICENTV	index for centrifugal calculation of water vapor
TOG	total temperature of gas phase at compressor inlet
TOW	temperature of droplet at compressor inlet
PO	total pressure at compressor inlet
DIN	initial diameter of small droplets
DDIN	initial diameter of large droplets
FND	rotor corrected speed at design pt.
TO1D	compressor inlet temperature at design pt.
PO1D	compressor inlet pressure at design pt.
FNDLPC	rotor corrected speed of LPC at design pt.
FNDHPC	rotor corrected speed of HPC at design pt.
XCH4	initial methane content (mass fraction)
RHUMID	initial relative humidity
FMWA	molecular weight of air

PREB	percent of water droplets that rebound after impingement on blade surface
DLIMT	maximum diameter for small droplets
GPR(I)	gap between Ith stage rotor
GAPS(I)	gap between rotor blade and stator blade for Ith stage
RRTIP(I)	blade tip radius at Ith stage rotor inlet
SRTIP(I)	blade tip radius at Ith stage stator outlet
IRAD	index for radius at which calculation is carried out
RT(I)	rotor inlet radius at which tip performance calculation is carried out
RM(I)	rotor inlet radius at which mean line performance calculation is carried out
RH(I)	rotor inlet radius at which hub performance calculation is carried out
RFC(I)	rotor inlet radius, streamline 3
ST(I)	stator inlet radius at which tip performance calculation is carried out
SM(I)	stator inlet radius at which mean line performance calculation is carried out
SH(I)	stator inlet radius at which hub performance calculation is carried out
SFC(I)	stator inlet radius, streamline 3
BLOCK(I)	blockage factor for the Ith stage rotor
BLOCKS(I)	blockage factor for Ith stage stator
IDESIN	index for output

IDESPT	index for design point output
JCENT	index for centrifugal calculation
BT1MRA(I,J)	blade metal angle at Ith stage rotor inlet
BT2MRA(I,J)	blade metal angle at Ith stage rotor outlet
BT1MSA(I,J)	blade metal angle at Ith stage stator inlet
BT2MSA(I,J)	blade metal angle at Ith stage stator outlet
DSMASS	streamtube design mass flow for fan
BYPASS	bypass ratio at design point
PR12DA(I,J)	total pressure ratio for the Ith stage rotor at design pt.
PR13DA(I,J)	total pressure ratio for the Ith stage at design pt.
ETARDA(I,J)	adiabatic efficiency for Ith stage
XSAREA(I,J)	stream tube area for Ith stage rotor inlet
XSAREAS(I,J)	stream tube area for Ith stage stator inlet
VAIRWA	initial guess at the film-water interface speed
CLEAR(I)	clearance of rotor
ZDIS(I)	length of stage
PREDES	pressure on standard day
TEMDES	temperature on standard day
AK1(I)	constant modifier of deviation angle calculation
AK2(I)	constant modifier of equivalent diffusion ratio calculation
AK3(I)	constant modifier of wake momentum thickness calculation
DVZ1(K,J)	gas axial velocity at rotor inlet at design pt.
DVZ2(I,J)	gas axial velocity at rotor outlet at design pt.
DVZ3(I,J)	gas axial velocity at stator outlet at design pt.

IV.1.1. Heat transfer routine

The new variables used in the heat transfer routine are as follows:

(i) Input Variables:

TG1	temperature of gaseous phase at stage inlet
TG3	temperature of gaseous phase at stage outlet
TW1	temperature of droplet at stage inlet
TW3	temperature of droplet at stage outlet
DAVEN2	droplet nominal diameter at stage inlet
DAVEN	droplet nominal diameter at stage outlet
DELZI	length of stage
VZ	axial velocity
TTIME	time of residence of average droplet
WMASS1	mass flow of water
VMASS1	mass flow of vapor
AMASS	mass flow rate of dry air
CHMASS	mass flow rate of methane
CPG	specific heat constant pressure to gaseous phase
CPW	specific heat of water
RE	Reynolds number based on relative velocity between droplet and gaseous phase

ii. Output Variables:

DELTGH	temperature drop in gaseous phase due to heat transfer between water droplet and gaseous phase
DELTWH	temperature rise in droplet due to heat transfer between water droplet and gaseous phase

IV.1.2. Mass transfer routine

The new variables used in the mass transfer routine are as follows:

(i) Input Variables:

XW	mass fraction of water to air
XNP	number of droplets in the span
VTOT	volume of span of stage
DDAVE	average droplet size in span

(ii) Output Variables:

FACMT	mass transfer factor

IV.2. Subroutines WICRON,WICDL and WICCEN

1. Description:

Subroutine WICRGN is called at end of rotor aerodynamic performance calculations to perform the centrifugal action calculations for all (10) streamtubes. The subroutines WICDML and WICCEN are called for individual streamtubes, and water is added and subtracted from each streamtube corresponding to addition (from a streamtube at lower radius) and depletion (to a streamtube of higher radius).

RT	radius of blade at tip
RRHUB	radius of blade at hub
FMMASS	mass of water in casing coming from previous stage

3. Output Variable:

WATRGN	mass of water in streamtubes

4. Usage:

CALL WICRGN (WATRGN, NREGON, ISTAGE, RT, RRHUB, FMMASS)

IV.3. Subroutine WICFLM

1. Description

Subroutine WICFLM is called after WICRGN and calculates a mean velocity of casing water film given the incoming mass of centrifuged water.

2. Input Variables:

VZ	axial velocity
FMMASS	mass of water in casing entering stage
XWT	percentage of water in streamtube
CLEAR	casing clearance
RCASE	radial distance of casing
NRADS	flag for redistributed water
REDMAS	amount of redistributed water
RHOM	density of water
RT	radius of blade at tip
WTMASS	mass of water in streamtube
HTOTL	thickness of casing film
WATRGN	mass of water in individual streamtube
RRHUB	radius of blade at hub
NREGON	number of streamlines
MMASS	mass of gas in streamtube

UMLAST	mean velocity of film coming from last stage
CSTAREA	casing area
FILMM	momentum of casing water
NS	number of stages
DELZZ	length of stage

3. Output Variables:

UIF	film-gas interface velocity

4. Usage:

CALL WICFLM (VZ, FMMASS XWT, CLEAR, RCASE, NRADS, REDMAS, RHOM, RT, WTMASS, HTOTL, WATRGN, RRHUB, NREGON, MMASS, UMLAST,CSTAREA, FILMM, UIF, NS, DELZZ)

IV.4 Subroutine Wichet

1. Description

Subroutine WICHET is called to determine heat transfer between air and water at blade row or stage after the aerodynamic performance calculation has been completed.

2. Input Variables

These are given in Section IV.1.1.

3. Output Variables

These are given in Section IV.1.1.

4. USAGE

Call WICHET (TG1, TG3, TW1, TW3, DAVEN2, DAVEN, DELZI, VZ, TTIME, WMASSI, VMASS1, AMASS, CHMASS, CPG, CPW, DELTGH, DELTWH, RE).

IV.5. Subroutine WICMTM

1. Description

Subroutine WICMTM is called to determine mass transfer between water and air at blade row or stage after performing the heat transfer calculations.

2. Input Variables

These are given in Section IV.1.2.

3. Output Variables

These are given in Section IV.1.2.

4. Usage

Call WICMTM (XW, XNP, VTOT, FACMT).

APPENDIX V

ILLUSTRATIVE CASE

In order to illustrate the application of the WINCOF-I code for determining the performance of a multi-stage compressor, a generic two-stage compressor has been chosen.

The details of the WINCOF-I code can be found in Ref. 1 and Appendix IV of the current report.

The three cases chosen for performance estimation are as follows.

1. Dry case: Basic operation of the compressor with air flow at entry.
2. Wet case 1: Operation of the compressor with ingestion of 4.0 per cent of large droplets, and output at the end of the first "sweep" through the two stages.
3. Wet case 2: Operation of the compressor as in Wet case 1, and output at the end of the first 10 "sweeps" through the two stages.

The input and the output in each of the three cases are presented in the following.

Input Data - Dry Case

```
0.450
01
01
01
00
02000200
06.9507.64
2.5202.453
2.1702.436
1.9092.383
36.0026.00
49.2051.40
37.2038.10
18.1018.50
07.3508.1008.73
2.1421.8441.617
1.8801.6651.484
1.5631.4511.326
36.0040.0046.00
37.0037.8037.90
28.7030.9031.80
20.8023.9025.40
1.0000.715
1.1060.891
1.5411.260
0.8570.8340.853
0.9580.9290.940
1.1981.1251.099
32.0333.2032.39
23.9125.8126.12
12.5414.4616.02
1.00
0.00010.00010
0602.000597.001944.00
0020.00600.0
08879.00602.001944.0008879.008879.0
0.0000000.00000
028.97018.00016.00
050.000300.0
0.577000.72800
0.790000.86000
14.46914.237
14.36614.11613.913
2
14.4714.24
11.2811.30
6.9477.639
14.4714.24
14.3714.12
11.2111.36
07.3508.10
14.3714.12
0.9850.950
0.9450.9550.965
112
51.0056.15
42.7045.60
37.9031.85
47.4046.65
31.7030.60
-1.7005.150
54.2254.0055.65
40.4043.9546.25
37.0041.7545.00
```

```
26.2226.8025.05
17.0017.8517.35
04.6006.0505.80
011.300000000.0000000
1.2881.232
1.2541.233
1.2771.201
1.2771.222
1.2481.227
1.2621.184
0.8860.943
0.9120.962
0.9110.927
00.375824900.3220294
00.338605600.2975193
00.349854100.2657488
00.365026700.313852200.2768841
00.309584900.283225100.2416014
00.278055900.245356500.2246608
080.00
0.00100.0010
04.50304.534
2
02116.200518.7
2.30001.4600
0.09000.0900
1.00001.5000
588.5576.6558.3
653.9634.6625.3
613.4725.9684.6
526.5511.4502.8
632.0606.5591.6
722.3729.5680.0
560.5543.5
623.2610.3
718.2676.2
0.37590.3219
0.36920.3241
0.32900.2545
1.47401.44871.42461.40181.38011.35951.33981.32121.30341.28651.27031.2549
1.24031.22631.21301.20031.18821.17671.16561.15521.14511.13561.12651.1179
1.10971.10181.09441.08731.08061.07421.06811.06241.05701.05191.04711.0425
1.03821.03421.03051.02701.02371.02071.01791.01531.01291.01081.00891.0071
1.00561.00431.00311.00211.00141.00081.00031.00011.00001.00011.00031.0007
1.00131.00201.00291.00391.00511.00641.00791.00951.01131.01321.0153
1.48431.45861.43411.41091.38881.36781.34791.31071.27701.24641.21861.1932
1.17021.14921.13021.11291.09721.08311.07031.05891.04861.03951.03151.0245
1.01851.01341.00921.00581.00321.00141.00041.00001.00031.00141.00301.0054
1.00831.01191.0160
done
9.99999
#eor
#eof
```

Output - Dry Case

JSWEEP = 1

```
  MEAN
  FRACTION OF DESIGN SPEED = 1.00000
 >>>>>>>>>> LOOP NUMBER 2 <<<<<<<<<<
  IGV AREA= 0.2416014000000
 NHG NUMBER OF STREAMLINES =   10.22089
1      ***************************** INPUT DATA ************************************
     HEAT TRANSFER AFTER ROTOR AND STATOR VERSION
0 NUMBER OF STAGES=  2 (FAN 0, LPC 2, HPC 0)
  PERFORMANCE AT MEAN
0 VAPOR IS CENTRIFUGED
0 LARGE DROPLETS IN ROTOR FREE STREAM ARE NOT CENTRIFUGED


  STAGE          1      2      3
  RRHUB(I)     6.95   7.64
  RC(I)       2.170  2.436
  RBLADE(I)   36.00  26.00
  STAGER(I)   37.20  38.10
  STAGES(I)   28.70  30.90  31.80
  SRHUB(I)     7.35   8.10   8.73
  SC(I)       1.880  1.665  1.484
  SBLADE(I)   36.00  40.00  46.00
  SIGUMR(I)   1.106  0.891
  SIGUMS(I)   0.958  0.929  0.940
  BET2SS(I)   23.91  25.81  26.12
  GAPR(I)     0.577  0.728
  GAPS(I)     0.790  0.860
  RRTIP(I)    14.47  14.24
  SRTIP(I)    14.37  14.12  13.91
  RT(I)       14.47  14.24
  RM(I)       11.28  11.30
  RH(I)        6.95   7.64
  ST(I)       14.37  14.12
  SM(I)       11.21  11.36
  SH(I)        7.35   8.10
  BLOCK(I)    0.985  0.950
  BLOCKS(I)   0.945  0.955  0.965
  BET1MR(I)   42.70  45.60
  BET2MR(I)   31.70  30.60
  BET1MS(I)   40.40  43.95  46.25
  BET2MS(I)   17.00  17.85  17.35
  PR12D(I)    1.254  1.233
  PR13D(I)    1.248  1.227
  ETARD(I)    0.912  0.962
  DVZ1(I)   653.9  634.6  625.3
  DVZ2(I)   632.0  606.5  591.6
  DVZ3(I)   623.2  610.3
  AK1(I)   2.300  1.460
  AK2(I)   0.090  0.090
  AK3(I)   1.000  1.500
1      ***************************** INPUT DATA ******************************
0 FNF(FRACTION OF DESIGN CORRECTED SPEED)=1.000
0 XDIN(INITIAL WATER CONTENT OF SMALL DROPLET)=0.000
  XDDIN(INITIAL WATER CONTENT OF LARGE DROPLET)=0.000
  RHUMID(INITIAL RELATIVE HUMIDITY)=  0.00 PER CENT
  XCH4(INITIAL METHANE CONTENT)=0.000
0 TOG(COMPRESSOR INLET TOTAL TEMPRATURE OF GAS)= 602.00
  TOW(COMPRESSOR INLET TEMPERATURE OF DROPLRET)= 597.00
  P0(COMPRESSOR INLET TOTAL PRESSURE)=1944.00
0 DIN(INITIAL DROPLET DIAMETER OF SMALL DROPLET)=  20.0
  DDIN(INITIAL DROPLET DIAMETER OF LARGE DROPLET)= 600.0
0 FND(DESIGN ROTATIONAL SPEED)= 8879.0
```

```
0 DSMASS(DESIGN MASS FLOW RATE)=   11.3000
0 BYPASS RATIO =      0.0000
0 COMPRESSOR INLET TOTAL TEMPERATURE(GAS PHASE) 602.00 R
0 COMPRESSOR INLET TOTAL PRESSURE=1944.00 LB/FT**2
0 PREB(PERCENT OF WATER THAT REBOUND AFTER IMPINGEMENT)= 50.0 PERCENT
0 ROTOR SPEED= 9565.4 RPM
0 CORRECTED ROTOR SPEED=  8879.0 RPM(  100.0PER CENT OF DESIGN CORRECTED SPEED)
0 MOLECULAR WEIGHT OF AIR= 28.9700
0 MAXIMUM DIAMETER OF SMALL DROPLETS=   300.0 MICRONS
0 ROTOR CORRECTED SPEED AT DESIGN POINT=  8879.0
  ROTOR CORRECTED SPEED OF LPC AT DESIGN POINT=  8879.0
  ROTOR CORRECTED SPEED OF HPC AT THE DESIGN POINT=  8879.0
  DESIGN FLOW COEFFICIENT AT INLET =0.7762894645834

1*************** DESIGN POINT INFORMATION ************ ***
0 ***** COMPRESSOR INLET *****
0 TOTAL TEMPERATURE AT COMPRESSOR INLET= 602.00000
  TOTAL PRESSURE AT COMPRESSOR INLET=   1944.00
  STATIC TEMPERATURE AT COMPRESSOR INLET= 557.29566
  STATIC PRESSURE AT COMPRESSOR INLET=   1483.22
  STATIC DENSITY AT COMPRESSOR INLET=   0.04988
0 ACOUSTIC SPEED AT COMPRESSOR INLET=1156.87477
  AXIAL VELOCITY AT COMPRESSOR INLET= 625.30000
  MACH NUMBER AT COMPRESSOR INLET=  -0.63408
  STREAMTUBE AREA AT COMPRESSOR INLET=   0.24160
  FLOW COEFFICIENT AT COMPRESSOR INLET=   0.77629
1*************** DESIGN POINT INFORMATION ************ ***
0 ***** STAGE= 1 *****
0                 TOTAL        TOTAL        STATIC       STATIC       STATIC
                  TEMP        PRESSURE       TEMP       PRESSURE      DENSITY
0 ROTOR INLET     602.000      1944.000      554.852     1460.540        0.049
  ROTOR OUTLET    646.018      2437.776      582.467     1694.070        0.055
0                 AXIAL       ABSOLUTE     RELATIVE     TAN COMP     TAN COMP
                VELOCITY      VELOCITY     VELOCITY    OF ABS VEL   OF REL VEL
0 ROTOR INLET   653.90000    728.27594    901.76441    320.62538    620.96203
  ROTOR OUTLET  632.00000    875.68251    762.34215    606.13188    329.61235
0                ROTOR       ABS MACH      REL MACH    REL TOTAL    REL TOTAL
                 SPEED        NUMBER        NUMBER       TEMP        PRESSURE
0 ROTOR INLET     941.587        0.653        0.781      622.410     2185.064
  ROTOR OUTLET    935.744        0.741        0.645      630.648     5747.723
0               ABS FLOW      REL FLOW    STREAMTUBE                  FLOW
                 ANGLE         ANGLE         AREA        RADIUS     COEFFICIENT
0 ROTOR INLET    26.12000     43.52001      0.33861     11.28000      0.54140
  ROTOR OUTLET   43.80310     25.61793      0.30958     11.21000      0.52327
0 STAGE TOTAL PRESSURE RATIO AT DESIGN POINT=    1.24800
  STAGE ADIABATIC EFFICIENCY AT DESIGN POINT=    0.89109
  ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT=    1.25400
  ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT=    0.91200
  ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT=    1.07312
1*************** DESIGN POINT INFORMATION ************ ***
0 ***** STAGE= 2 *****
0                 TOTAL        TOTAL        STATIC       STATIC       STATIC
                  TEMP        PRESSURE       TEMP       PRESSURE      DENSITY
0 ROTOR INLET     646.018      2426.112      606.280     1941.056        0.060
  ROTOR OUTLET    687.268      2991.396      632.514     2232.765        0.066
0                 AXIAL       ABSOLUTE     RELATIVE     TAN COMP     TAN COMP
                VELOCITY      VELOCITY     VELOCITY    OF ABS VEL   OF REL VEL
0 ROTOR INLET   634.60000    694.17156    916.97320    281.34853    661.90836
  ROTOR OUTLET  606.50000    813.80738    725.84181    542.62344    405.64189
0                ROTOR       ABS MACH      REL MACH    REL TOTAL    REL TOTAL
                 SPEED        NUMBER        NUMBER       TEMP        PRESSURE
0 ROTOR INLET     943.257        0.574        0.760      675.988     2845.160
  ROTOR OUTLET    948.265        0.661        0.589      676.086     6382.675
0               ABS FLOW      REL FLOW    STREAMTUBE                  FLOW
                 ANGLE         ANGLE         AREA        RADIUS     COEFFICIENT
0 ROTOR INLET    23.91000     46.20664      0.29752     11.30000      0.53399
```

```
 ROTOR OUTLET  41.81836     33.97680      0.28323     11.36000        0.51034
0 STAGE TOTAL PRESSURE RATIO AT DESIGN POINT=   1.22700
 STAGE ADIABATIC EFFICIENCY AT DESIGN POINT=   0.93777
 ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT=   1.23300
 ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT=   0.96200
 ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT=   1.06385
1*************** DESIGN POINT INFORMATION ************ ***
0********** OVERALL PERFORMANCE AT DESIGN POINT ****   ******
0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
0 COMPRESSOR INLET TOTAL PRESSURE=   1944.00
0 CORRECTED MASS FLOW RATE= 135.446
0 OVERALL TOTAL PRESSURE RATIO=  1.5313
0 OVERALL TOTAL TEMPERATURE RATIO=1.1416
0 OVERALL ADIABATIC EFFICIENCY=0.9102
0 OVERALL TEMPERATURE RISE=  85.268
0              1     2     3     4     5     6     7     8     9    10    11    12
 BET1SR(I)  43.52 46.21
 BET2SR(I)  25.62 33.98
 AINCSR(I)    0.82   0.61
 ADEVSR(I)   -6.08   3.38
 BET1SS(I)  43.80 41.82
 BET2SS(I)  23.91 25.81 26.12
 AINCSS(I)    3.40 -2.13
 ADEVSS(I)    6.91   7.96
 TD(I)        602.  646.
 OMEGR(I)   0.063 0.026
 OMEGS(I)   0.016 0.019
 SITADR(I)   .0399 .0174
 SITADS(I)   .0120 .0136
 DEQR(I)     1.601 1.587
 DEQS(I)     1.660 1.523

 PHI DESIGN  = 0.7762895

 INLET PHI =0.4500000
1  FAI=0.4500000
 XDDIN = 0.0000000000000
 NHG MAIN WS(1) TG(1) P(1) RHUMID =    0.00000 602.000001944.00000   0.00001
 NHG MAIN XV(1) XWT(1) XCH4 =    0.00000   0.00000   0.00000
0 VZ AT IGV INLET =  543.50378 MACH NUMBER =    0.46153
   I      XWT       WATRGN
 1 0.000000000000 0.000000000000
 2 0.000000000000 0.000000000000
 3 0.000000000000 0.000000000000
 4 0.000000000000 0.000000000000
 5 0.000000000000 0.000000000000
 6 0.000000000000 0.000000000000
 7 0.000000000000 0.000000000000
 8 0.000000000000 0.000000000000
 9 0.000000000000 0.000000000000
 10 0.000000000000 0.000000000000
  XV(1) = 1.1865857492804E-0009
  WATRGT = 0.000000000000
0     ISTAGE=0  (IGV)
0          0.45000        543.50378          1.00000
  CLEAR(1) = 0.018800000000000
 NHG MAIN START CALCULATIONS FOR STAGE  1
  D1 DWAKEM,W2= 0.000000000000 514.38689162770
  D2 DWAKEM,RDELV1= 0.000000000000 10.00000000000
  D3 DWAKEM,RDELV2= 0.000000000000 0.000000000000
 B N,DDAVE(N-2)(N)=3 0.000000000000 0.000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =   0.00000   0.00000   0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000   0.00000   0.00000   0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3   =   0.00000   0.00000
  FILMAS(1) = 0.000000000000
  UI = 0.000000000000
```

```
  HHC = 0.0000000000000
  HTOTL = 0.0000000000000
1 *******************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 1 )   *************
0     STAGE TOTAL PRESSURE RATIO=      1.35248
      STAGE TOTAL TEMPERATURE RATIO=      1.10864
      STAGE ADIABATIC EFFICIENCY=     0.82642
0     STAGE FLOW COEFFICIENT=0.305
      AXIAL VELOCITY= 368.37
      ROTOR SPEED=1207.79

0                             *ROTOR INLET* *ROTOR OUTLET* *STATOR OUTLET*
  TOTAL PRESSURE               1944.0000     2636.5495     2629.2242
  STATIC PRESSURE              1805.3335     2192.1522     2450.7589
  TOTAL TEMPERATURE(GAS)        602.0000      667.4007      667.4007
  STATIC TEMPERATURE(GAS)       589.4268      633.1831      654.1579
  STATIC DENSITY(GAS)             0.0574        0.0649        0.0702
  STATIC DENSITY(MIXTURE)         0.0574        0.0649        0.0702
0 AXIAL VELOCITY                368.3678      336.4388      339.1701
  ABSOLUTE VELOCITY             389.0255      641.8765      399.3158
  RELATIVE VELOCITY             895.7528      514.3869
  BLADE SPEED                   941.5874      935.7442      943.2569
  TANG. COMP. OF ABS. VEL.      125.0838      546.6391
  TANG. COMP. OF REL. VEL.      816.5036      389.1051
  ACOUSTIC SPEED               1189.7575     1253.3951     1253.3859
  ABSOLUTE MACH NUMBER            0.3270        0.5205        0.3186
  RELATIVE MACH NUMBER            0.7529        0.4171
0 FLOW COEFFICIENT                0.3050        0.2786        0.2854
  FLOW AREA                       0.3386        0.3280        0.3007
0 ABSOLUTE FLOW ANGLE            18.7555       58.3890       31.8559
  RELATIVE FLOW ANGLE            65.7174       49.1517
  INCIDENCE                      23.0174       17.9890
  DEVIATION                                    17.4517       14.8559
  DIFFUSION RATIO                               3.6654        2.6688
  MOMENTUM THICKNESS                            0.1314        0.0192
  OMEGA (GAS)                                    0.17567       0.01648
  OMEGA (TOTAL)                                  0.17567       0.01648
  D1 DWAKEM,V3= 0.0000000000000 399.31578652366
  D2 DWAKEM,SDELV1= 0.0000000000000 10.000000000000
  D3 DWAKEM,SDELV2= 0.0000000000000 0.0000000000000
 B N,DDAVE(N-2)(N)=4 0.0000000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000   0.00000   0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000   0.00000   0.00000   0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =   0.00000   0.00000
1 *******************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  1 )   ***********
0     STAGE TOTAL PRESSURE RATIO=      1.35248
      STAGE TOTAL TEMPERATURE RATIO=      1.10864
      STAGE ADIABATIC EFFICIENCY=     0.82642
  STAGE   1 TOTAL ETA      0.82642DEL T   65.40066
0PSI= 0.541560 PSI1= 0.447556 LOSS= 0.094004
0           **STAGE INLET**    **STAGE OUTLET**     **STAGE OUTLET**
                                (BEFORE INTER-       (AFTER INTER-
                                STAGE ADJUST-        STAGE ADJUST-
                                MENT)                MENT)
      XV=         0.00000          0.00000             0.00000
      XW=         0.00000          0.00000             0.00000
      XWW=         0.00000          0.00000             0.00000
      XF =         0.00000          0.00000             0.00000
      XWT=         0.00000          0.00000             0.00000
      XAIR=         1.00000          1.00000             1.00000
      XMETAN=         0.00000          0.00000             0.00000
      XGAS         1.00000          1.00000             1.00000
      WMASS=         0.00000          0.00000             0.00000
      WWMASS=         0.00000          0.00000             0.00000
      FMMASS=         0.00000          0.00000             0.00000
      WTMASS=         0.00000          0.00000             0.00000
      AMASS=         7.16060          7.16060             7.16060
```

```
    CHMASS=        0.00000                  0.00000                  0.00000
    VMASS=        0.00000                  0.00000                  0.00000
    GMASS=        7.16060                  7.16060                  7.16060
    TMASS=        7.16060                  7.16060                  7.16060
    WS=       0.00000                  0.00000                  0.00000
    RHOA=        0.06054                  0.06333                  0.07015
    RHOM=        0.05453                  0.06332                  0.07013
    RHOG=        0.05741                  0.06332                  0.07013
    TG=     602.00000              667.40066              667.40066
    TW=     597.00000              597.00000              597.00000
    TWW=     597.00000                  0.00000              597.00000
NHG: TRAGAS, TRAWAT =   1.10864   1.00000
    P=     1944.00000           2636.54951             2629.22421
    TB=     667.26838                0.00000              682.17635
    TDEW=      272.00755             274.47523              274.47523
 WRITING TO EXTERNAL PLOT FILES
 CLEAR(2) = 0.01650000000000
NHG MAIN START CALCULATIONS FOR STAGE  2
 D1 DWAKEM,W2= 0.0000000000000 581.75628581708
 D2 DWAKEM,RDELV1= 0.0000000000000 10.000000000000
 D3 DWAKEM,RDELV2= 0.0000000000000 0.0000000000000
B N,DDAVE(N-2)(N)=5 0.0000000000000 0.0000000000000
NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
NHG DS DL DLGE DSLL AMLGE AMSLL=    0.00000    0.00000    0.00000    0.00000    0.00000
NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =    0.00000    0.00000
 FILMAS(2) = 0.0000000000000
 UI = 0.0000000000000
 HHC = 0.0000000000000
 HTOTL = 0.0000000000000
1 ******************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 2 )   *************
0      STAGE TOTAL PRESSURE RATIO=      1.18858
       STAGE TOTAL TEMPERATURE RATIO=      1.06192
       STAGE ADIABATIC EFFICIENCY=     0.81180
0      STAGE FLOW COEFFICIENT=0.289
       AXIAL VELOCITY= 343.18
       ROTOR SPEED=1188.42

0                          *ROTOR INLET* *ROTOR OUTLET* *STATOR OUTLET*
  TOTAL PRESSURE              2629.2242     3143.2899      3125.0534
  STATIC PRESSURE             2446.6287     2724.6550      2926.7483
  TOTAL TEMPERATURE(GAS)       667.4007      708.7291       708.7291
  STATIC TEMPERATURE(GAS)      653.8834      680.5190       695.6472
  STATIC DENSITY(GAS)            0.0701        0.0750         0.0789
  STATIC DENSITY(MIXTURE)        0.0701        0.0750         0.0789
0 AXIAL VELOCITY               343.1789      338.8467       322.4618
  ABSOLUTE VELOCITY            404.0355      583.7812       397.5421
  RELATIVE VELOCITY            806.6541      581.7563
  BLADE SPEED                  943.2569      948.2653         0.0000
  TANG. COMP. OF ABS. VEL.     213.2438      475.3771
  TANG. COMP. OF REL. VEL.     730.0131      472.8882
  ACOUSTIC SPEED              1252.2959     1291.6200      1291.6693
  ABSOLUTE MACH NUMBER           0.3226        0.4570         0.3078
  RELATIVE MACH NUMBER           0.6441        0.4554
0 FLOW COEFFICIENT               0.2888        0.2851         0.2713
  FLOW AREA                      0.2975        0.2816         0.2816
0 ABSOLUTE FLOW ANGLE           31.8559       54.5189        35.7933
  RELATIVE FLOW ANGLE           64.8218       54.3766
  INCIDENCE                     19.2218       10.5689
  DEVIATION                                   23.7766        17.9433
  DIFFUSION RATIO                              3.9221         3.4434
  MOMENTUM THICKNESS                           0.0816         0.0371
  OMEGA (GAS)                                   0.13314        0.04356
  OMEGA (TOTAL)                                 0.13314        0.04356
  D1 DWAKEM,V3= 0.0000000000000 397.54214855740
  D2 DWAKEM,SDELV1= 0.0000000000000 10.000000000000
  D3 DWAKEM,SDELV2= 0.0000000000000 0.0000000000000
```

```
 B N,DDAVE(N-2)(N)=6 0.0000000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000   0.00000    0.00000    0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.00000    0.00000
1 ********************    INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  2 )   ***********
0     STAGE TOTAL PRESSURE RATIO=      1.18858
      STAGE TOTAL TEMPERATURE RATIO=      1.06192
      STAGE ADIABATIC EFFICIENCY=      0.81180
  STAGE  2 TOTAL ETA      0.81376DEL T   41.32848
0PSI= 0.886120 PSI1= 0.721090 LOSS= 0.165029
0            **STAGE INLET**    **STAGE OUTLET**    **STAGE OUTLET**
                                  (BEFORE INTER-      (AFTER INTER-
                                   STAGE ADJUST-       STAGE ADJUST-
                                   MENT)               MENT)
      XV=         0.00000             0.00000             0.00000
      XW=         0.00000             0.00000             0.00000
      XWW=         0.00000             0.00000             0.00000
      XF =         0.00000             0.00000             0.00000
      XWT=         0.00000             0.00000             0.00000
      XAIR=         1.00000             1.00000             1.00000
      XMETAN=         0.00000             0.00000             0.00000
      XGAS         1.00000             1.00000             1.00000
      WMASS=         0.00000             0.00000             0.00000
      WWMASS=         0.00000             0.00000             0.00000
      FMMASS=         0.00000             0.00000             0.00000
      WTMASS=         0.00000             0.00000             0.00000
      AMASS=         7.16060             7.16060             7.16060
      CHMASS=         0.00000             0.00000             0.00000
      VMASS=         0.00000             0.00000             0.00000
      GMASS=         7.16060             7.16060             7.16060
      TMASS=         7.16060             7.16060             7.16060
      WS=         0.00000             0.00000             0.00000
      RHOA=         0.07385             0.07516             0.07892
      RHOM=         0.05453             0.07515             0.07890
      RHOG=         0.07013             0.07515             0.07890
      TG=       667.40066           708.72914           708.72914
      TW=       597.00000           597.00000           597.00000
      TWW=       597.00000             0.00000           597.00000
 NHG: TRAGAS, TRAWAT =    1.06192    1.00000
      P=     2629.22421          3143.28986          3125.05337
      TB=       682.17635             0.00000           692.03622
      TDEW=       274.47523           268.01367           268.01367
  WRITING TO EXTERNAL PLOT FILES
1********** OVERALL PERFORMANCE *********
0 INITIAL FLOW COEFFICIENT=0.450
0 CORRECTED SPEED= 8879.0      1.000 FRACTION OF DESIGN CORRECTED SPEED
0 INITIAL WATER CONTENT(SMALL DROPLET)=0.000
  INITIAL WATER CONTENT(LARGE DROPLET)=0.000
  INITIAL WATER CONTENT(TOTAL)=0.000
  INITIAL RELATIVE HUMIDITY=  0.0 PER CENT
  INITIAL METHANE CONTENT=0.000
0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
0 COMPRESSOR INLET TOTAL PRESSURE= 1944.00
0 CORRECTED MASS FLOW RATE OF MIXTURE= 120.29
0 CORRECTED MASS FLOW RATE OF GAS PHASE  120.29
0 OVERALL TOTAL PRESSURE RATIO= 1.6075
0 OVERALL TOTAL TEMPERATURE RATIO=1.1773
0 OVERALL ADIABATIC EFFICIENCY=0.8152
0********** PERFORMANCE OF FAN,LPC,HPC **********
0       GAS PHASE  STAGNATION  STAGNATION   ADIABATIC
0       CORRECTED  PRESSURE    TEMPERATURE  EFFICIENCY
0       MASS FLOW    RATIO        RATIO
0 FAN      0.0000     0.0000      0.0000       0.0000
0 LPC      0.0000     0.0000      0.0000       0.0000
0 HPC      0.0000     0.0000      0.0000       0.0000
0PSI= 0.917751 PSI1= 0.748161 LOSS= 0.169590
```

```
    0  0.000000  708.7   3125.1  597.0  0.815  0.0000
  I= 68
    1  0.000000  708.7   3125.1  597.0  0.815  0.0000
  NUMBER OF LOOPS = 1
  TOTAL MASS = 1.0000000000000E-0008
0PSI= 0.917751 PSI1= 0.748161 LOSS= 0.169590
  I= 68
  GEMACH = 0.2731038592486
```

Input Data - Wet Case 1

```
0.450
01
01
02
04
02000200
06.9507.64
2.5202.453
2.1702.436
1.9092.383
36.0026.00
49.2051.40
37.2038.10
18.1018.50
07.3508.1008.73
2.1421.8441.617
1.8801.6651.484
1.5631.4511.326
36.0040.0046.00
37.0037.8037.90
28.7030.9031.80
20.8023.9025.40
1.0000.715
1.1060.891
1.5411.260
0.8570.8340.853
0.9580.9290.940
1.1981.1251.099
32.0333.2032.39
23.9125.8126.12
12.5414.4616.02
1.00
0.00011.00010
0602.000597.001944.00
0020.00600.0
08879.00602.001944.0008879.008879.0
0.0000000.00000
028.97018.00016.00
050.000300.0
0.577000.72800
0.790000.86000
14.46914.237
14.36614.11613.913
2
14.4714.24
11.2811.30
6.9477.639
14.4714.24
14.3714.12
11.2111.36
07.3508.10
14.3714.12
0.9850.950
0.9450.9550.965
112
51.0056.15
42.7045.60
37.9031.85
47.4046.65
31.7030.60
-1.7005.150
54.2254.0055.65
40.4043.9546.25
37.0041.7545.00
```

```
26.2226.8025.05
17.0017.8517.35
04.6006.0505.80
011.300000000.0000000
1.2881.232
1.2541.233
1.2771.201
1.2771.222
1.2481.227
1.2621.184
0.8860.943
0.9120.962
0.9110.927
00.375824900.3220294
00.338605600.2975193
00.349854100.2657488
00.365026700.313852200.2768841
00.309584900.283225100.2416014
00.278055900.245356500.2246608
080.00
0.00100.0010
04.50304.534
2
02116.200518.7
2.30001.4600
0.09000.0900
1.00001.5000
588.5576.6558.3
653.9634.6625.3
613.4725.9684.6
526.5511.4502.8
632.0606.5591.6
722.3729.5680.0
560.5543.5
623.2610.3
718.2676.2
0.37590.3219
0.36920.3241
0.32900.2545
1.47401.44871.42461.40181.38011.35951.33981.32121.30341.28651.27031.2549
1.24031.22631.21301.20031.18821.17671.16561.15521.14511.13561.12651.1179
1.10971.10181.09441.08731.08061.07421.06811.06241.05701.05191.04711.0425
1.03821.03421.03051.02701.02371.02071.01791.01531.01291.01081.00891.0071
1.00561.00431.00311.00211.00141.00081.00031.00011.00001.00011.00031.0007
1.00131.00201.00291.00391.00511.00641.00791.00951.01131.01321.0153
1.48431.45861.43411.41091.38881.36781.34791.31071.27701.24641.21861.1932
1.17021.14921.13021.11291.09721.08311.07031.05891.04861.03951.03151.0245
1.01851.01341.00921.00581.00321.00141.00041.00001.00031.00141.00301.0054
1.00831.01191.0160
done
9.99999
#eor
#eof
```

Output - Wet Case 1

JSWEEP = 1

```
  MEAN
  FRACTION OF DESIGN SPEED = 1.00000
 >>>>>>>>>> LOOP NUMBER 2 <<<<<<<<<<
  IGV AREA= 0.2416014000000
 NHG NUMBER OF STREAMLINES =    10.22089
1      ***************************** INPUT DATA ************************************
     HEAT TRANSFER AFTER ROTOR AND STATOR VERSION
0 NUMBER OF STAGES=  2 (FAN 0, LPC 2, HPC 0)
  PERFORMANCE AT MEAN
0 VAPOR IS CENTRIFUGED
0 LARGE DROPLETS IN ROTOR FREE STREAM ARE NOT CENTRIFUGED


  STAGE          1      2      3
  RRHUB(I)     6.95   7.64
  RC(I)       2.170  2.436
  RBLADE(I)   36.00  26.00
  STAGER(I)   37.20  38.10
  STAGES(I)   28.70  30.90  31.80
  SRHUB(I)     7.35   8.10   8.73
  SC(I)       1.880  1.665  1.484
  SBLADE(I)   36.00  40.00  46.00
  SIGUMR(I)   1.106  0.891
  SIGUMS(I)   0.958  0.929  0.940
  BET2SS(I)   23.91  25.81  26.12
  GAPR(I)     0.577  0.728
  GAPS(I)     0.790  0.860
  RRTIP(I)    14.47  14.24
  SRTIP(I)    14.37  14.12  13.91
  RT(I)       14.47  14.24
  RM(I)       11.28  11.30
  RH(I)        6.95   7.64
  ST(I)       14.37  14.12
  SM(I)       11.21  11.36
  SH(I)        7.35   8.10
  BLOCK(I)    0.985  0.950
  BLOCKS(I)   0.945  0.955  0.965
  BET1MR(I)   42.70  45.60
  BET2MR(I)   31.70  30.60
  BET1MS(I)   40.40  43.95  46.25
  BET2MS(I)   17.00  17.85  17.35
  PR12D(I)    1.254  1.233
  PR13D(I)    1.248  1.227
  ETARD(I)    0.912  0.962
  DVZ1(I)    653.9  634.6  625.3
  DVZ2(I)    632.0  606.5  591.6
  DVZ3(I)    623.2  610.3
  AK1(I)    2.300  1.460
  AK2(I)    0.090  0.090
  AK3(I)    1.000  1.500
1      ***************************** INPUT DATA *****************************
0 FNF(FRACTION OF DESIGN CORRECTED SPEED)=1.000
0 XDIN(INITIAL WATER CONTENT OF SMALL DROPLET)=0.000
  XDDIN(INITIAL WATER CONTENT OF LARGE DROPLET)=1.000
  RHUMID(INITIAL RELATIVE HUMIDITY)=  0.00 PER CENT
  XCH4(INITIAL METHANE CONTENT)=0.000
0 TOG(COMPRESSOR INLET TOTAL TEMPRATURE OF GAS)= 602.00
  TOW(COMPRESSOR INLET TEMPERATURE OF DROPLRET)= 597.00
  PO(COMPRESSOR INLET TOTAL PRESSURE)=1944.00
0 DIN(INITIAL DROPLET DIAMETER OF SMALL DROPLET)=  20.0
  DDIN(INITIAL DROPLET DIAMETER OF LARGE DROPLET)= 600.0
0 FND(DESIGN ROTATIONAL SPEED)= 8879.0
```

0 DSMASS(DESIGN MASS FLOW RATE)= 11.3000
0 BYPASS RATIO = 0.0000
0 COMPRESSOR INLET TOTAL TEMPERATURE(GAS PHASE) 602.00 R
0 COMPRESSOR INLET TOTAL PRESSURE=1944.00 LB/FT**2
0 PREB(PERCENT OF WATER THAT REBOUND AFTER IMPINGEMENT)= 50.0 PERCENT
0 ROTOR SPEED= 9565.4 RPM
0 CORRECTED ROTOR SPEED= 8879.0 RPM(100.0PER CENT OF DESIGN CORRECTED SPEED)
0 MOLECULAR WEIGHT OF AIR= 28.9700
0 MAXIMUM DIAMETER OF SMALL DROPLETS= 300.0 MICRONS
0 ROTOR CORRECTED SPEED AT DESIGN POINT= 8879.0
ROTOR CORRECTED SPEED OF LPC AT DESIGN POINT= 8879.0
ROTOR CORRECTED SPEED OF HPC AT THE DESIGN POINT= 8879.0
DESIGN FLOW COEFFICIENT AT INLET =0.7762894645834

1*************** DESIGN POINT INFORMATION ************ ***
0 ***** COMPRESSOR INLET *****
0 TOTAL TEMPERATURE AT COMPRESSOR INLET= 602.00000
TOTAL PRESSURE AT COMPRESSOR INLET= 1944.00
STATIC TEMPERATURE AT COMPRESSOR INLET= 557.29566
STATIC PRESSURE AT COMPRESSOR INLET= 1483.22
STATIC DENSITY AT COMPRESSOR INLET= 0.04988
0 ACOUSTIC SPEED AT COMPRESSOR INLET=1156.87477
AXIAL VELOCITY AT COMPRESSOR INLET= 625.30000
MACH NUMBER AT COMPRESSOR INLET= -0.63408
STREAMTUBE AREA AT COMPRESSOR INLET= 0.24160
FLOW COEFFICIENT AT COMPRESSOR INLET= 0.77629

1*************** DESIGN POINT INFORMATION ************ ***
0 ***** STAGE= 1 *****

0	TOTAL TEMP	TOTAL PRESSURE	STATIC TEMP	STATIC PRESSURE	STATIC DENSITY
0 ROTOR INLET	602.000	1944.000	554.852	1460.540	0.049
ROTOR OUTLET	646.018	2437.776	582.467	1694.070	0.055
0	AXIAL VELOCITY	ABSOLUTE VELOCITY	RELATIVE VELOCITY	TAN COMP OF ABS VEL	TAN COMP OF REL VEL
0 ROTOR INLET	653.90000	728.27594	901.76441	320.62538	620.96203
ROTOR OUTLET	632.00000	875.68251	762.34215	606.13188	329.61235
0	ROTOR SPEED	ABS MACH NUMBER	REL MACH NUMBER	REL TOTAL TEMP	REL TOTAL PRESSURE
0 ROTOR INLET	941.587	0.653	0.781	622.410	2185.064
ROTOR OUTLET	935.744	0.741	0.645	630.648	5747.723
0	ABS FLOW ANGLE	REL FLOW ANGLE	STREAMTUBE AREA	RADIUS	FLOW COEFFICIENT
0 ROTOR INLET	26.12000	43.52001	0.33861	11.28000	0.54140
ROTOR OUTLET	43.80310	25.61793	0.30958	11.21000	0.52327

0 STAGE TOTAL PRESSURE RATIO AT DESIGN POINT= 1.24800
STAGE ADIABATIC EFFICIENCY AT DESIGN POINT= 0.89109
ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT= 1.25400
ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT= 0.91200
ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT= 1.07312

1*************** DESIGN POINT INFORMATION ************ ***
0 ***** STAGE= 2 *****

0	TOTAL TEMP	TOTAL PRESSURE	STATIC TEMP	STATIC PRESSURE	STATIC DENSITY
0 ROTOR INLET	646.018	2426.112	606.280	1941.056	0.060
ROTOR OUTLET	687.268	2991.396	632.514	2232.765	0.066
0	AXIAL VELOCITY	ABSOLUTE VELOCITY	RELATIVE VELOCITY	TAN COMP OF ABS VEL	TAN COMP OF REL VEL
0 ROTOR INLET	634.60000	694.17156	916.97320	281.34853	661.90836
ROTOR OUTLET	606.50000	813.80738	725.84181	542.62344	405.64189
0	ROTOR SPEED	ABS MACH NUMBER	REL MACH NUMBER	REL TOTAL TEMP	REL TOTAL PRESSURE
0 ROTOR INLET	943.257	0.574	0.760	675.988	2845.160
ROTOR OUTLET	948.265	0.661	0.589	676.086	6382.675
0	ABS FLOW ANGLE	REL FLOW ANGLE	STREAMTUBE AREA	RADIUS	FLOW COEFFICIENT
0 ROTOR INLET	23.91000	46.20664	0.29752	11.30000	0.53399

```
  ROTOR OUTLET  41.81836     33.97680      0.28323     11.36000       0.51034
0 STAGE TOTAL PRESSURE RATIO AT DESIGN POINT=   1.22700
  STAGE ADIABATIC EFFICIENCY AT DESIGN POINT=   0.93777
  ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT=   1.23300
  ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT=   0.96200
  ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT=   1.06385
1*************** DESIGN POINT INFORMATION ************ ***
0********** OVERALL PERFORMANCE AT DESIGN POINT ****    ******
0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
0 COMPRESSOR INLET TOTAL PRESSURE=   1944.00
0 CORRECTED MASS FLOW RATE= 135.446
0 OVERALL TOTAL PRESSURE RATIO=  1.5313
0 OVERALL TOTAL TEMPERATURE RATIO=1.1416
0 OVERALL ADIABATIC EFFICIENCY=0.9102
0 OVERALL TEMPERATURE RISE=  85.268
0              1     2     3     4     5     6     7     8     9    10    11    12
  BET1SR(I)  43.52 46.21
  BET2SR(I)  25.62 33.98
  AINCSR(I)    0.82   0.61
  ADEVSR(I)   -6.08   3.38
  BET1SS(I)  43.80 41.82
  BET2SS(I)  23.91 25.81 26.12
  AINCSS(I)    3.40 -2.13
  ADEVSS(I)    6.91   7.96
  TD(I)       602.  646.
  OMEGR(I)   0.063 0.026
  OMEGS(I)   0.016 0.019
  SITADR(I)   .0399 .0174
  SITADS(I)   .0120 .0136
  DEQR(I)     1.601 1.587
  DEQS(I)     1.660 1.523

 PHI DESIGN  = 0.7762895

 INLET PHI =0.4500000
1  FAI=0.4500000
  XDDIN = 0.0000000000000
 NHG MAIN WS(1) TG(1) P(1) RHUMID =    0.00000 602.000001944.00000   0.00001
 NHG MAIN XV(1) XWT(1) XCH4 =    0.00000   0.00000   0.00000
0 VZ AT IGV INLET =  543.50378 MACH NUMBER =     0.46153
   I       XWT        WATRGN
 1 0.000000000000 0.000000000000
 2 0.000000000000 0.000000000000
 3 0.000000000000 0.000000000000
 4 0.000000000000 0.000000000000
 5 0.000000000000 0.000000000000
 6 0.000000000000 0.000000000000
 7 0.000000000000 0.000000000000
 8 0.000000000000 0.000000000000
 9 0.000000000000 0.000000000000
 10 0.000000000000 0.000000000000
  XV(1) = 1.1865857492804E-0009
  WATRGT = 0.000000000000
0     ISTAGE=0  (IGV)
0         0.45000        543.50378          1.00000
  CLEAR(1) = 0.01880000000000
 NHG MAIN START CALCULATIONS FOR STAGE  1
  D1 DWAKEM,W2= 0.000000000000 514.38689162770
  D2 DWAKEM,RDELV1= 0.000000000000 10.00000000000
  D3 DWAKEM,RDELV2= 0.000000000000 0.000000000000
 B N,DDAVE(N-2)(N)=3 0.000000000000 0.000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =     0.00000    0.00000    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=    0.00000   0.00000   0.00000    0.00000    0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =   0.00000   0.00000
  FILMAS(1) = 0.000000000000
  UI = 0.000000000000
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 HHC = 0.0000000000000
 HTOTL = 0.0000000000000
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 1 )   *************
0     STAGE TOTAL PRESSURE RATIO=      1.35248
      STAGE TOTAL TEMPERATURE RATIO=      1.10864
      STAGE ADIABATIC EFFICIENCY=      0.82642
0     STAGE FLOW COEFFICIENT=0.305
      AXIAL VELOCITY= 368.37
      ROTOR SPEED=1207.79

0                           *ROTOR INLET* *ROTOR OUTLET* *STATOR OUTLET*
 TOTAL PRESSURE               1944.0000      2636.5495      2629.2242
 STATIC PRESSURE              1805.3335      2192.1522      2450.7589
 TOTAL TEMPERATURE(GAS)        602.0000       667.4007       667.4007
 STATIC TEMPERATURE(GAS)       589.4268       633.1831       654.1579
 STATIC DENSITY(GAS)             0.0574         0.0649         0.0702
 STATIC DENSITY(MIXTURE)         0.0574         0.0649         0.0702
0 AXIAL VELOCITY               368.3678       336.4388       339.1701
 ABSOLUTE VELOCITY             389.0255       641.8765       399.3158
 RELATIVE VELOCITY             895.7528       514.3869
 BLADE SPEED                   941.5874       935.7442       943.2569
 TANG. COMP. OF ABS. VEL.      125.0838       546.6391
 TANG. COMP. OF REL. VEL.      816.5036       389.1051
 ACOUSTIC SPEED               1189.7575      1253.3951      1253.3859
 ABSOLUTE MACH NUMBER            0.3270         0.5205         0.3186
 RELATIVE MACH NUMBER            0.7529         0.4171
0 FLOW COEFFICIENT               0.3050         0.2786         0.2854
 FLOW AREA                       0.3386         0.3280         0.3007
0 ABSOLUTE FLOW ANGLE           18.7555        58.3890        31.8559
 RELATIVE FLOW ANGLE            65.7174        49.1517
 INCIDENCE                      23.0174        17.9890
 DEVIATION                                     17.4517        14.8559
 DIFFUSION RATIO                                3.6654         2.6688
 MOMENTUM THICKNESS                             0.1314         0.0192
 OMEGA (GAS)                                    0.17567        0.01648
 OMEGA (TOTAL)                                  0.17567        0.01648
 D1 DWAKEM,V3= 0.0000000000000 399.31578652366
 D2 DWAKEM,SDELV1= 0.0000000000000 10.000000000000
 D3 DWAKEM,SDELV2= 0.0000000000000 0.0000000000000
 B N,DDAVE(N-2)(N)=4 0.0000000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000   0.00000    0.00000    0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =   0.00000    0.00000
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  1 )   ***********
0     STAGE TOTAL PRESSURE RATIO=      1.35248
      STAGE TOTAL TEMPERATURE RATIO=      1.10864
      STAGE ADIABATIC EFFICIENCY=      0.82642
 STAGE  1 TOTAL ETA      0.82642DEL T   65.40066
0PSI= 0.541560 PSI1= 0.447556 LOSS= 0.094004
0           **STAGE INLET**    **STAGE OUTLET**     **STAGE OUTLET**
                                (BEFORE INTER-       (AFTER INTER-
                                 STAGE ADJUST-        STAGE ADJUST-
                                 MENT)                MENT)
     XV=          0.00000          0.00000              0.00000
     XW=          0.00000          0.00000              0.00000
     XWW=          0.00000          0.00000              0.00000
     XF =          0.00000          0.00000              0.00000
     XWT=          0.00000          0.00000              0.00000
     XAIR=          1.00000          1.00000              1.00000
     XMETAN=          0.00000          0.00000              0.00000
     XGAS          1.00000          1.00000              1.00000
     WMASS=          0.00000          0.00000              0.00000
     WWMASS=          0.00000          0.00000              0.00000
     FMMASS=          0.00000          0.00000              0.00000
     WTMASS=          0.00000          0.00000              0.00000
     AMASS=          7.16060          7.16060              7.16060
```

```
     CHMASS=        0.00000                 0.00000                 0.00000
     VMASS=        0.00000                 0.00000                 0.00000
     GMASS=        7.16060                 7.16060                 7.16060
     TMASS=        7.16060                 7.16060                 7.16060
     WS=        0.00000                 0.00000                 0.00000
     RHOA=        0.06054                 0.06333                 0.07015
     RHOM=        0.05453                 0.06332                 0.07013
     RHOG=        0.05741                 0.06332                 0.07013
     TG=     602.00000             667.40066             667.40066
     TW=     597.00000             597.00000             597.00000
     TWW=     597.00000                0.00000             597.00000
 NHG: TRAGAS, TRAWAT =   1.10864   1.00000
     P=    1944.00000           2636.54951            2629.22421
     TB=     667.26838              0.00000             682.17635
     TDEW=       272.00755             274.47523             274.47523
  WRITING TO EXTERNAL PLOT FILES
  CLEAR(2) = 0.01650000000000
 NHG MAIN START CALCULATIONS FOR STAGE  2
  D1 DWAKEM,W2= 0.0000000000000 581.75628581708
  D2 DWAKEM,RDELV1= 0.0000000000000 10.000000000000
  D3 DWAKEM,RDELV2= 0.0000000000000 0.0000000000000
 B N,DDAVE(N-2)(N)=5 0.0000000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000   0.00000   0.00000   0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =    0.00000    0.00000
  FILMAS(2) = 0.0000000000000
  UI = 0.0000000000000
  HHC = 0.0000000000000
  HTOTL = 0.0000000000000
1 *******************    INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 2 )   *************
0      STAGE TOTAL PRESSURE RATIO=       1.18858
       STAGE TOTAL TEMPERATURE RATIO=       1.06192
       STAGE ADIABATIC EFFICIENCY=       0.81180
0      STAGE FLOW COEFFICIENT=0.289
       AXIAL VELOCITY= 343.18
       ROTOR SPEED=1188.42

0                            *ROTOR INLET* *ROTOR OUTLET* *STATOR OUTLET*
  TOTAL PRESSURE               2629.2242      3143.2899      3125.0534
  STATIC PRESSURE              2446.6287      2724.6550      2926.7483
  TOTAL TEMPERATURE(GAS)        667.4007       708.7291       708.7291
  STATIC TEMPERATURE(GAS)       653.8834       680.5190       695.6472
  STATIC DENSITY(GAS)             0.0701         0.0750         0.0789
  STATIC DENSITY(MIXTURE)         0.0701         0.0750         0.0789
0 AXIAL VELOCITY                343.1789       338.8467       322.4618
  ABSOLUTE VELOCITY             404.0355       583.7812       397.5421
  RELATIVE VELOCITY             806.6541       581.7563
  BLADE SPEED                   943.2569       948.2653         0.0000
  TANG. COMP. OF ABS. VEL.      213.2438       475.3771
  TANG. COMP. OF REL. VEL.      730.0131       472.8882
  ACOUSTIC SPEED               1252.2959      1291.6200      1291.6693
  ABSOLUTE MACH NUMBER            0.3226         0.4570         0.3078
  RELATIVE MACH NUMBER            0.6441         0.4554
0 FLOW COEFFICIENT                0.2888         0.2851         0.2713
  FLOW AREA                       0.2975         0.2816         0.2816
0 ABSOLUTE FLOW ANGLE            31.8559        54.5189        35.7933
  RELATIVE FLOW ANGLE            64.8218        54.3766
  INCIDENCE                      19.2218        10.5689
  DEVIATION                                     23.7766        17.9433
  DIFFUSION RATIO                                3.9221         3.4434
  MOMENTUM THICKNESS                             0.0816         0.0371
  OMEGA (GAS)                                    0.13314        0.04356
  OMEGA (TOTAL)                                  0.13314        0.04356
  D1 DWAKEM,V3= 0.0000000000000 397.54214855740
  D2 DWAKEM,SDELV1= 0.0000000000000 10.000000000000
  D3 DWAKEM,SDELV2= 0.0000000000000 0.0000000000000
```

```
 B N,DDAVE(N-2)(N)=6 0.0000000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =   0.00000   0.00000   0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000   0.00000   0.00000   0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =   0.00000   0.00000
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  2 )   ***********
0     STAGE TOTAL PRESSURE RATIO=      1.18858
      STAGE TOTAL TEMPERATURE RATIO=      1.06192
      STAGE ADIABATIC EFFICIENCY=      0.81180
  STAGE  2 TOTAL ETA     0.81376DEL T   41.32848
0PSI= 0.886120 PSI1= 0.721090 LOSS= 0.165029
0            **STAGE INLET**    **STAGE OUTLET**    **STAGE OUTLET**
                                  (BEFORE INTER-      (AFTER INTER-
                                   STAGE ADJUST-       STAGE ADJUST-
                                   MENT)               MENT)
      XV=          0.00000           0.00000           0.00000
      XW=          0.00000           0.00000           0.00000
      XWW=          0.00000           0.00000           0.00000
      XF =          0.00000           0.00000           0.00000
      XWT=          0.00000           0.00000           0.00000
      XAIR=          1.00000           1.00000           1.00000
      XMETAN=          0.00000           0.00000           0.00000
      XGAS          1.00000           1.00000           1.00000
      WMASS=          0.00000           0.00000           0.00000
      WWMASS=          0.00000           0.00000           0.00000
      FMMASS=          0.00000           0.00000           0.00000
      WTMASS=          0.00000           0.00000           0.00000
      AMASS=          7.16060           7.16060           7.16060
      CHMASS=          0.00000           0.00000           0.00000
      VMASS=          0.00000           0.00000           0.00000
      GMASS=          7.16060           7.16060           7.16060
      TMASS=          7.16060           7.16060           7.16060
      WS=          0.00000           0.00000           0.00000
      RHOA=          0.07385           0.07516           0.07892
      RHOM=          0.05453           0.07515           0.07890
      RHOG=          0.07013           0.07515           0.07890
      TG=        667.40066         708.72914         708.72914
      TW=        597.00000         597.00000         597.00000
      TWW=        597.00000           0.00000         597.00000
  NHG: TRAGAS, TRAWAT =   1.06192   1.00000
      P=      2629.22421        3143.28986        3125.05337
      TB=        682.17635           0.00000         692.03622
      TDEW=        274.47523         268.01367         268.01367
  WRITING TO EXTERNAL PLOT FILES
 1********** OVERALL PERFORMANCE *********
 0 INITIAL FLOW COEFFICIENT=0.450
 0 CORRECTED SPEED= 8879.0      1.000 FRACTION OF DESIGN CORRECTED SPEED
 0 INITIAL WATER CONTENT(SMALL DROPLET)=0.000
   INITIAL WATER CONTENT(LARGE DROPLET)=0.000
   INITIAL WATER CONTENT(TOTAL)=0.000
   INITIAL RELATIVE HUMIDITY=  0.0 PER CENT
   INITIAL METHANE CONTENT=0.000
 0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
 0 COMPRESSOR INLET TOTAL PRESSURE= 1944.00
 0 CORRECTED MASS FLOW RATE OF MIXTURE= 120.29
 0 CORRECTED MASS FLOW RATE OF GAS PHASE  120.29
 0 OVERALL TOTAL PRESSURE RATIO= 1.6075
 0 OVERALL TOTAL TEMPERATURE RATIO=1.1773
 0 OVERALL ADIABATIC EFFICIENCY=0.8152
 0********** PERFORMANCE OF FAN,LPC,HPC **********
 0        GAS PHASE  STAGNATION  STAGNATION   ADIABATIC
 0        CORRECTED  PRESSURE    TEMPERATURE  EFFICIENCY
 0        MASS FLOW    RATIO       RATIO
 0 FAN      0.0000      0.0000      0.0000      0.0000
 0 LPC      0.0000      0.0000      0.0000      0.0000
 0 HPC      0.0000      0.0000      0.0000      0.0000
 0PSI= 0.917751 PSI1= 0.748161 LOSS= 0.169590
```

```
   0  0.000000  708.7   3125.1  597.0  0.815  0.0000
 I= 68

 PHI DESIGN  = 0.7762895

1  FAI=0.4500000
  XDDIN = 0.04000000000000
 NHG MAIN WS(1) TG(1) P(1) RHUMID =   0.01187 602.000001944.00000 100.00000
 NHG MAIN XV(1) XWT(1) XCH4 =   0.01126   0.04000   0.00000
0 VZ AT IGV INLET =  543.50378 MACH NUMBER =    0.46995
   I       XWT       WATRGN
 1 0.04000000000000 0.3016412676757
 2 0.04000000000000 0.3016412676757
 3 0.04000000000000 0.3016412676757
 4 0.04000000000000 0.3016412676757
 5 0.04000000000000 0.3016412676757
 6 0.04000000000000 0.3016412676757
 7 0.04000000000000 0.3016412676757
 8 0.04000000000000 0.3016412676757
 9 0.04000000000000 0.3016412676757
 10 0.04000000000000 0.3016412676757
  XV(1) = 0.01125764163510
  WATRGT = 3.0164126767578
  D0 DWAKEM,W2= 600.00000000000 543.50378458031
0     ISTAGE=0  (IGV)
0          0.45000         543.50378          0.94874
  CLEAR(1) = 0.01880000000000
 NHG MAIN START CALCULATIONS FOR STAGE  1
  D1 DWAKEM,W2= 0.0000000000000 513.95749648846
  D2 DWAKEM,RDELV1= 600.00000000000 18.867096152077
  D3 DWAKEM,RDELV2= 436.40800073893 0.0000000000000
 B N,DDAVE(N-2)(N)=3 600.00000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =   0.00000   0.14756   0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 473.99116   0.00000   0.14756
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =   0.00000   0.14756
  FILMAS(1) = 0.3114420393203
  UI = 319.86671351019
  HHC = 0.001830860297993
  HTOTL = 3.4420173602285E-0005
 N,DDAVE(N-1)(N)=3 600.00000000000 473.99116130186
 N,DDAVE(N-1)(N)=3 600.00000000000 473.99116130186
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 1 )   *************
0      STAGE TOTAL PRESSURE RATIO=     1.34569
       STAGE TOTAL TEMPERATURE RATIO=     1.10846
       STAGE ADIABATIC EFFICIENCY=     0.81082
0      STAGE FLOW COEFFICIENT=0.304
       AXIAL VELOCITY= 367.58
       ROTOR SPEED=1207.79
```

0	*ROTOR INLET*	*ROTOR OUTLET*	*STATOR OUTLET*
TOTAL PRESSURE	1944.0000	2624.4055	2616.0249
STATIC PRESSURE	1801.3200	2162.9053	2431.1640
TOTAL TEMPERATURE(GAS)	602.0000	667.2949	667.2949
STATIC TEMPERATURE(GAS)	589.0906	632.9487	654.1192
STATIC DENSITY(GAS)	0.0569	0.0636	0.0692
STATIC DENSITY(MIXTURE)	0.0593	0.0662	0.0720
0 AXIAL VELOCITY	367.5771	339.5677	340.5856
ABSOLUTE VELOCITY	388.1904	646.3270	400.9942
RELATIVE VELOCITY	895.6727	513.9575	
BLADE SPEED	941.5874	935.7442	943.2569
TANG. COMP. OF ABS. VEL.	124.8153	549.9385	
TANG. COMP. OF REL. VEL.	816.7721	385.8057	
ACOUSTIC SPEED	1168.8862	1211.6172	1230.8882
ABSOLUTE MACH NUMBER	0.3321	0.5334	0.3258
RELATIVE MACH NUMBER	0.7663	0.4242	
0 FLOW COEFFICIENT	0.3043	0.2811	0.2866

```
  FLOW AREA .                         0.3386          0.3280          0.3007
0 ABSOLUTE FLOW ANGLE                18.7555         58.3061         31.8587
  RELATIVE FLOW ANGLE                65.7705         48.6473
  INCIDENCE                           23.0705         17.9061
  DEVIATION                                           16.9473         14.8587
  DIFFUSION RATIO                                      3.6741          2.6690
  MOMENTUM THICKNESS                                  0.1392          0.0195
  OMEGA (GAS)                                          0.17986         0.01679
  OMEGA (TOTAL)                                         0.18603         0.02515
  D1 DWAKEM,V3= 600.00000000000 400.99420772009
  D2 DWAKEM,SDELV1= 600.00000000000 18.867096152074
  D3 DWAKEM,SDELV2= 399.87962081246 0.0000000000000
 B N,DDAVE(N-2)(N)=4 600.00000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.08549    0.12973    0.06207
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 464.52000    4.47702    0.01783
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =    0.08549    0.12973
 N,DDAVE(N-1)(N)=4 473.99116130186 464.51999818913
 N,DDAVE(N-1)(N)=4 473.99116130186 464.51999818913
 XNP,TG(3),P(3)=32007536709.313 667.21481348588 2616.0249275938
1 *******************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  1 )   ***********
0      STAGE TOTAL PRESSURE RATIO=       1.34569
       STAGE TOTAL TEMPERATURE RATIO=       1.10833
       STAGE ADIABATIC EFFICIENCY=      0.81182
  STAGE  1 TOTAL ETA       0.81182DEL T    65.21481
0PSI= 0.545538 PSI1= 0.442878 LOSS= 0.102660
0            **STAGE INLET**    **STAGE OUTLET**    **STAGE OUTLET**
                                 (BEFORE INTER-      (AFTER INTER-
                                  STAGE ADJUST-       STAGE ADJUST-
                                  MENT)               MENT)
      XV=          0.01126          0.01126             0.01128
      XW=          0.00000          0.00000             0.00000
      XWW=          0.04000          0.04000             0.03998
      XF =          0.00140          0.00140             0.00413
      XWT=          0.04000          0.04000             0.03998
      XAIR=          0.94874          0.94874             0.94874
      XMETAN=          0.00000          0.00000             0.00000
      XGAS          0.96000          0.96000             0.96002
      WMASS=          0.00000          0.00000             0.00000
      WWMASS=          0.29512          0.29512             0.29498
      FMMASS=          0.00000          0.00000             0.31144
      WTMASS=          0.29512          0.29512             0.29498
      AMASS=          6.99988          6.99988             6.99988
      CHMASS=          0.00000          0.00000             0.00000
      VMASS=          0.08306          0.08306             0.08320
      GMASS=          7.08293          7.08293             7.08307
      TMASS=          7.37806          7.37806             7.37806
      WS=          0.01187          0.01187             0.01189
      RHOA=          0.06054          0.06256             0.06553
      RHOM=          0.05619          0.06469             0.07203
      RHOG=          0.05691          0.06211             0.06915
      TG=        602.00000        667.29487           667.21481
      TW=        597.00000        597.00000           597.00000
      TWW=        597.00000        597.00000           597.44952
  NHG: TRAGAS, TRAWAT =    1.10833   1.00075
      P=      1944.00000        2624.40546          2616.02493
      TB=        667.26838          0.00000           681.92240
      TDEW=        518.09930        526.98696           526.94014
   WRITING TO EXTERNAL PLOT FILES
   CLEAR(2) = 0.01650000000000
  NHG MAIN START CALCULATIONS FOR STAGE  2
   D1 DWAKEM,W2= 0.0000000000000 581.54035901182
   D2 DWAKEM,RDELV1= 600.00000000000 18.739086560407
   D3 DWAKEM,RDELV2= 363.78484232851 0.0000000000000
  B N,DDAVE(N-2)(N)=5 473.99116130186 0.0000000000000
  NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.14749    0.00000
  NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 411.14024    0.00000    0.14749
```

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NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.00000    0.14749
 FILMAS(2) = 0.6208438817958
 UI = 286.4680371688
 HHC = 0.004811309023339
 HTOTL = 7.9386598885093E-0005
N,DDAVE(N-1)(N)=5 464.51999818913 411.14023858397
N,DDAVE(N-1)(N)=5 464.51999818913 411.14023858397
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 2 )   *************
0      STAGE TOTAL PRESSURE RATIO=      1.18312
       STAGE TOTAL TEMPERATURE RATIO=      1.06183
       STAGE ADIABATIC EFFICIENCY=      0.78832
0      STAGE FLOW COEFFICIENT=0.290
       AXIAL VELOCITY= 344.27
       ROTOR SPEED=1188.42
```

0	*ROTOR INLET*	*ROTOR OUTLET*	*STATOR OUTLET*
TOTAL PRESSURE	2616.0249	3118.1280	3095.0801
STATIC PRESSURE	2427.0784	2683.6525	2889.3275
TOTAL TEMPERATURE(GAS)	667.2148	708.4709	708.4709
STATIC TEMPERATURE(GAS)	653.1883	680.1123	695.3672
STATIC DENSITY(GAS)	0.0692	0.0734	0.0773
STATIC DENSITY(MIXTURE)	0.0720	0.0765	0.0805
0 AXIAL VELOCITY	344.2742	342.5236	325.2771
ABSOLUTE VELOCITY	405.3371	588.2975	400.4374
RELATIVE VELOCITY	806.4845	581.5404	
BLADE SPEED	943.2569	948.2653	0.0000
TANG. COMP. OF ABS. VEL.	213.9473	478.3007	
TANG. COMP. OF REL. VEL.	729.3096	469.9647	
ACOUSTIC SPEED	1230.0358	1255.1304	1268.4592
ABSOLUTE MACH NUMBER	0.3295	0.4687	0.3157
RELATIVE MACH NUMBER	0.6557	0.4633	
0 FLOW COEFFICIENT	0.2897	0.2882	0.2737
FLOW AREA	0.2975	0.2816	0.2816
0 ABSOLUTE FLOW ANGLE	31.8587	54.3926	35.6783
RELATIVE FLOW ANGLE	64.7301	53.9144	
INCIDENCE	19.1301	10.4426	
DEVIATION		23.3144	17.8283
DIFFUSION RATIO		3.9115	3.4311
MOMENTUM THICKNESS		0.0850	0.0370
OMEGA (GAS)		0.13510	0.04353
OMEGA (TOTAL)		0.14237	0.05711

```
 D1 DWAKEM,V3= 600.00000000000 400.43739382676
 D2 DWAKEM,SDELV1= 600.00000000000 18.739086560403
 D3 DWAKEM,SDELV2= 341.41060899562 0.0000000000000
B N,DDAVE(N-2)(N)=6 464.51999818913 0.0000000000000
NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.09935    0.13015    0.04814
NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 419.44960    3.46783    0.01734
NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.09935    0.13015
N,DAVE(N-1)(N)=6 0.0000000000000 3.4678316406546
N,DDAVE(N-1)(N)=6 411.14023858397 419.44960239536
N,DAVE(N-1)(N)=6 0.0000000000000 3.4678316406546
N,DDAVE(N-1)(N)=6 411.14023858397 419.44960239536
N,DAVE(N-1)(N)=6 0.0000000000000 3.4678316406546
N,DDAVE(N-1)(N)=6 411.14023858397 419.44960239536
XNP,TG(3),P(3)=32007536709.313 708.33570034424 3095.0801326574
XNP,TG(3),P(3)=31992431033.269 708.33570034424 3095.0801326574
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  2 )   ***********
0      STAGE TOTAL PRESSURE RATIO=      1.18312
       STAGE TOTAL TEMPERATURE RATIO=      1.06163
       STAGE ADIABATIC EFFICIENCY=      0.79091
  STAGE   2 TOTAL ETA      0.79645DEL T    41.12089
0PSI= 0.891954 PSI1= 0.710396 LOSS= 0.181558
0             **STAGE INLET**    **STAGE OUTLET**     **STAGE OUTLET**
                                   (BEFORE INTER-       (AFTER INTER-
                                   STAGE ADJUST-        STAGE ADJUST-
                                   MENT)                MENT)
```

```
    XV=         0.01128                 0.01128                 0.01133
    XW=         0.00000                 0.00000                 0.00000
    XWW=         0.03998                 0.03998                 0.03993
    XF =         0.00413                 0.00413                 0.00823
    XWT=         0.03998                 0.03998                 0.03993
    XAIR=         0.94874                 0.94874                 0.94874
    XMETAN=         0.00000                 0.00000                 0.00000
    XGAS         0.96002                 0.96002                 0.96007
    WMASS=          0.00000                 0.00000                 0.00000
    WWMASS=          0.29498                 0.29498                 0.29458
    FMMASS=          0.31144                 0.31144                 0.62084
    WTMASS=          0.29498                 0.29498                 0.29458
    AMASS=          6.99988                 6.99988                 6.99988
    CHMASS=          0.00000                 0.00000                 0.00000
    VMASS=          0.08320                 0.08320                 0.08360
    GMASS=          7.08307                 7.08307                 7.08348
    TMASS=          7.37806                 7.37806                 7.37806
    WS=         0.01189                 0.01189                 0.01194
    RHOA=          0.07350                 0.07422                 0.07377
    RHOM=          0.05619                 0.07675                 0.08067
    RHOG=          0.06915                 0.07368                 0.07745
    TG=       667.21481              708.47090              708.33570
    TW=       597.00000              597.00000              597.00000
    TWW=       597.44952              597.44952              598.21106
 NHG: TRAGAS, TRAWAT =   1.06163   1.00127
    P=     2616.02493            3118.12802            3095.08013
    TB=       681.92240              0.00000              691.50661
    TDEW=       526.94014              525.79479              525.71037
  WRITING TO EXTERNAL PLOT FILES
1********** OVERALL PERFORMANCE *********
0 INITIAL FLOW COEFFICIENT=0.450
0 CORRECTED SPEED= 8879.0     1.000 FRACTION OF DESIGN CORRECTED SPEED
0 INITIAL WATER CONTENT(SMALL DROPLET)=0.000
  INITIAL WATER CONTENT(LARGE DROPLET)=0.040
  INITIAL WATER CONTENT(TOTAL)=0.040
  INITIAL RELATIVE HUMIDITY=100.0 PER CENT
  INITIAL METHANE CONTENT=0.000
0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
0 COMPRESSOR INLET TOTAL PRESSURE= 1944.00
0 CORRECTED MASS FLOW RATE OF MIXTURE= 123.94
0 CORRECTED MASS FLOW RATE OF GAS PHASE  118.99
0 OVERALL TOTAL PRESSURE RATIO= 1.5921
0 OVERALL TOTAL TEMPERATURE RATIO=1.1766
0 OVERALL ADIABATIC EFFICIENCY=0.7979
0********** PERFORMANCE OF FAN,LPC,HPC **********
0       GAS PHASE  STAGNATION  STAGNATION   ADIABATIC
0       CORRECTED  PRESSURE    TEMPERATURE  EFFICIENCY
0       MASS FLOW    RATIO       RATIO
0 FAN      0.0000      0.0000      0.0000       0.0000
0 LPC      0.0000      0.0000      0.0000       0.0000
0 HPC      0.0000      0.0000      0.0000       0.0000
0PSI= 0.914367 PSI1= 0.729576 LOSS= 0.184791
  I= 68
    1  0.001948  708.3   3095.1  598.2  0.798  0.0048
  NUMBER OF LOOPS = 1
  TOTAL MASS = 0.3781818163733
0PSI= 0.914367 PSI1= 0.729576 LOSS= 0.184791
  I= 68
  GEMACH = 0.2731038592486
```

Input Data - Wet Case 2

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0.450
01
10
02
04
02000200
06.9507.64
2.5202.453
2.1702.436
1.9092.383
36.0026.00
49.2051.40
37.2038.10
18.1018.50
07.3508.1008.73
2.1421.8441.617
1.8801.6651.484
1.5631.4511.326
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28.7030.9031.80
20.8023.9025.40
1.0000.715
1.1060.891
1.5411.260
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0.9580.9290.940
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32.0333.2032.39
23.9125.8126.12
12.5414.4616.02
1.00
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0020.00600.0
08879.00602.001944.0008879.008879.0
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028.97018.00016.00
050.000300.0
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0.790000.86000
14.46914.237
14.36614.11613.913
2
14.4714.24
11.2811.30
6.9477.639
14.4714.24
14.3714.12
11.2111.36
07.3508.10
14.3714.12
0.9850.950
0.9450.9550.965
112
51.0056.15
42.7045.60
37.9031.85
47.4046.65
31.7030.60
-1.7005.150
54.2254.0055.65
40.4043.9546.25
37.0041.7545.00
```

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26.2226.8025.05
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011.300000000.0000000
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1.2541.233
1.2771.201
1.2771.222
1.2481.227
1.2621.184
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0.9110.927
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00.338605600.2975193
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00.365026700.313852200.2768841
00.309584900.283225100.2416014
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080.00
0.00100.0010
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2
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2.30001.4600
0.09000.0900
1.00001.5000
588.5576.6558.3
653.9634.6625.3
613.4725.9684.6
526.5511.4502.8
632.0606.5591.6
722.3729.5680.0
560.5543.5
623.2610.3
718.2676.2
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0.36920.3241
0.32900.2545
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1.24031.22631.21301.20031.18821.17671.16561.15521.14511.13561.12651.1179
1.10971.10181.09441.08731.08061.07421.06811.06241.05701.05191.04711.0425
1.03821.03421.03051.02701.02371.02071.01791.01531.01291.01081.00891.0071
1.00561.00431.00311.00211.00141.00081.00031.00011.00001.00011.00031.0007
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1.17021.14921.13021.11291.09721.08311.07031.05891.04861.03951.03151.0245
1.01851.01341.00921.00581.00321.00141.00041.00001.00031.00141.00301.0054
1.00831.01191.0160
done
9.99999
#eor
#eof
```

Ouput - Wet Case 2

JSWEEP = 10

```
  MEAN
  FRACTION OF DESIGN SPEED = 1.00000
 >>>>>>>>>> LOOP NUMBER 2 <<<<<<<<<<
  IGV AREA= 0.2416014000000
 NHG NUMBER OF STREAMLINES =    10.22089
1     **************************** INPUT DATA *************************************
     HEAT TRANSFER AFTER ROTOR AND STATOR VERSION
0 NUMBER OF STAGES=  2 (FAN 0, LPC 2, HPC 0)
  PERFORMANCE AT MEAN
0 VAPOR IS CENTRIFUGED
0 LARGE DROPLETS IN ROTOR FREE STREAM ARE NOT CENTRIFUGED


  STAGE         1     2     3
  RRHUB(I)    6.95  7.64
  RC(I)      2.170 2.436
  RBLADE(I)  36.00 26.00
  STAGER(I)  37.20 38.10
  STAGES(I)  28.70 30.90 31.80
  SRHUB(I)    7.35  8.10  8.73
  SC(I)      1.880 1.665 1.484
  SBLADE(I)  36.00 40.00 46.00
  SIGUMR(I)  1.106 0.891
  SIGUMS(I)  0.958 0.929 0.940
  BET2SS(I)  23.91 25.81 26.12
  GAPR(I)    0.577 0.728
  GAPS(I)    0.790 0.860
  RRTIP(I)   14.47 14.24
  SRTIP(I)   14.37 14.12 13.91
  RT(I)      14.47 14.24
  RM(I)      11.28 11.30
  RH(I)       6.95  7.64
  ST(I)      14.37 14.12
  SM(I)      11.21 11.36
  SH(I)       7.35  8.10
  BLOCK(I)   0.985 0.950
  BLOCKS(I)  0.945 0.955 0.965
  BET1MR(I)  42.70 45.60
  BET2MR(I)  31.70 30.60
  BET1MS(I)  40.40 43.95 46.25
  BET2MS(I)  17.00 17.85 17.35
  PR12D(I)   1.254 1.233
  PR13D(I)   1.248 1.227
  ETARD(I)   0.912 0.962
  DVZ1(I)   653.9 634.6 625.3
  DVZ2(I)   632.0 606.5 591.6
  DVZ3(I)   623.2 610.3
  AK1(I)   2.300 1.460
  AK2(I)   0.090 0.090
  AK3(I)   1.000 1.500
1     ***************************** INPUT DATA *****************************
0 FNF(FRACTION OF DESIGN CORRECTED SPEED)=1.000
0 XDIN(INITIAL WATER CONTENT OF SMALL DROPLET)=0.000
  XDDIN(INITIAL WATER CONTENT OF LARGE DROPLET)=1.000
  RHUMID(INITIAL RELATIVE HUMIDITY)=  0.00 PER CENT
  XCH4(INITIAL METHANE CONTENT)=0.000
0 TOG(COMPRESSOR INLET TOTAL TEMPRATURE OF GAS)= 602.00
  TOW(COMPRESSOR INLET TEMPERATURE OF DROPLRET)= 597.00
  PO(COMPRESSOR INLET TOTAL PRESSURE)=1944.00
0 DIN(INITIAL DROPLET DIAMETER OF SMALL DROPLET)=  20.0
  DDIN(INITIAL DROPLET DIAMETER OF LARGE DROPLET)= 600.0
0 FND(DESIGN ROTATIONAL SPEED)= 8879.0
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0 DSMASS(DESIGN MASS FLOW RATE)=   11.3000
0 BYPASS RATIO =      0.0000
0 COMPRESSOR INLET TOTAL TEMPERATURE(GAS PHASE) 602.00 R
0 COMPRESSOR INLET TOTAL PRESSURE=1944.00 LB/FT**2
0 PREB(PERCENT OF WATER THAT REBOUND AFTER IMPINGEMENT)= 50.0 PERCENT
0 ROTOR SPEED= 9565.4 RPM
0 CORRECTED ROTOR SPEED=  8879.0 RPM(  100.0PER CENT OF DESIGN CORRECTED SPEED)
0 MOLECULAR WEIGHT OF AIR= 28.9700
0 MAXIMUM DIAMETER OF SMALL DROPLETS=   300.0 MICRONS
0 ROTOR CORRECTED SPEED AT DESIGN POINT=  8879.0
  ROTOR CORRECTED SPEED OF LPC AT DESIGN POINT=  8879.0
  ROTOR CORRECTED SPEED OF HPC AT THE DESIGN POINT=  8879.0
  DESIGN FLOW COEFFICIENT AT INLET =0.7762894644891

1*************** DESIGN POINT INFORMATION ************ ***
0 ***** COMPRESSOR INLET *****
0 TOTAL TEMPERATURE AT COMPRESSOR INLET= 602.00000
  TOTAL PRESSURE AT COMPRESSOR INLET=   1944.00
  STATIC TEMPERATURE AT COMPRESSOR INLET= 557.29566
  STATIC PRESSURE AT COMPRESSOR INLET=   1483.22
  STATIC DENSITY AT COMPRESSOR INLET=   0.04988
0 ACOUSTIC SPEED AT COMPRESSOR INLET=1156.87477
  AXIAL VELOCITY AT COMPRESSOR INLET= 625.30000
  MACH NUMBER AT COMPRESSOR INLET=  -0.63408
  STREAMTUBE AREA AT COMPRESSOR INLET=   0.24160
  FLOW COEFFICIENT AT COMPRESSOR INLET=   0.77629
1*************** DESIGN POINT INFORMATION ************ ***
0 ***** STAGE= 1 *****
0                TOTAL        TOTAL       STATIC       STATIC       STATIC
                 TEMP        PRESSURE      TEMP       PRESSURE      DENSITY
0 ROTOR INLET    602.000     1944.000     554.852     1460.540        0.049
  ROTOR OUTLET   646.018     2437.776     582.467     1694.070        0.055
0                AXIAL       ABSOLUTE     RELATIVE    TAN COMP     TAN COMP
               VELOCITY      VELOCITY     VELOCITY   OF ABS VEL   OF REL VEL
0 ROTOR INLET  653.90000    728.27594    901.76441    320.62538    620.96203
  ROTOR OUTLET 632.00000    875.68251    762.34215    606.13188    329.61235
0               ROTOR       ABS MACH     REL MACH     REL TOTAL    REL TOTAL
                SPEED        NUMBER       NUMBER        TEMP       PRESSURE
0 ROTOR INLET    941.587        0.653        0.781      622.410     2185.064
  ROTOR OUTLET   935.744        0.741        0.645      630.648     5747.723
0              ABS FLOW      REL FLOW    STREAMTUBE                  FLOW
                ANGLE         ANGLE        AREA        RADIUS     COEFFICIENT
0 ROTOR INLET   26.12000     43.52001      0.33861     11.28000      0.54140
  ROTOR OUTLET  43.80310     25.61793      0.30958     11.21000      0.52327
0 STAGE TOTAL PRESSURE RATIO AT DESIGN POINT=    1.24800
  STAGE ADIABATIC EFFICIENCY AT DESIGN POINT=    0.89109
  ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT=    1.25400
  ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT=    0.91200
  ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT=    1.07312
1*************** DESIGN POINT INFORMATION ************ ***
0 ***** STAGE= 2 *****
0                TOTAL        TOTAL       STATIC       STATIC       STATIC
                 TEMP        PRESSURE      TEMP       PRESSURE      DENSITY
0 ROTOR INLET    646.018     2426.112     606.280     1941.056        0.060
  ROTOR OUTLET   687.268     2991.396     632.514     2232.765        0.066
0                AXIAL       ABSOLUTE     RELATIVE    TAN COMP     TAN COMP
               VELOCITY      VELOCITY     VELOCITY   OF ABS VEL   OF REL VEL
0 ROTOR INLET  634.60000    694.17156    916.97320    281.34853    661.90836
  ROTOR OUTLET 606.50000    813.80738    725.84181    542.62344    405.64189
0               ROTOR       ABS MACH     REL MACH     REL TOTAL    REL TOTAL
                SPEED        NUMBER       NUMBER        TEMP       PRESSURE
0 ROTOR INLET    943.257        0.574        0.760      675.988     2845.160
  ROTOR OUTLET   948.265        0.661        0.589      676.086     6382.675
0              ABS FLOW      REL FLOW    STREAMTUBE                  FLOW
                ANGLE         ANGLE        AREA        RADIUS     COEFFICIENT
0 ROTOR INLET   23.91000     46.20664      0.29752     11.30000      0.53399
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  ROTOR OUTLET  41.81836     33.97680      0.28323     11.36000       0.51034
0 STAGE TOTAL PRESSURE RATIO AT DESIGN POINT=   1.22700
  STAGE ADIABATIC EFFICIENCY AT DESIGN POINT=   0.93777
  ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT=   1.23300
  ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT=   0.96200
  ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT=   1.06385
1************** DESIGN POINT INFORMATION ************ ***
0********** OVERALL PERFORMANCE AT DESIGN POINT ****    ******
0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
0 COMPRESSOR INLET TOTAL PRESSURE=   1944.00
0 CORRECTED MASS FLOW RATE= 135.446
0 OVERALL TOTAL PRESSURE RATIO=  1.5313
0 OVERALL TOTAL TEMPERATURE RATIO=1.1416
0 OVERALL ADIABATIC EFFICIENCY=0.9102
0 OVERALL TEMPERATURE RISE=  85.268
0              1     2     3     4     5     6     7     8     9    10    11    12
  BET1SR(I)  43.52 46.21
  BET2SR(I)  25.62 33.98
  AINCSR(I)    0.82   0.61
  ADEVSR(I)   -6.08   3.38
  BET1SS(I)  43.80 41.82
  BET2SS(I)  23.91 25.81 26.12
  AINCSS(I)    3.40 -2.13
  ADEVSS(I)    6.91   7.96
  TD(I)        602.  646.
  OMEGR(I)   0.063 0.026
  OMEGS(I)   0.016 0.019
  SITADR(I)    .0399 .0174
  SITADS(I)    .0120 .0136
  DEQR(I)      1.601 1.587
  DEQS(I)      1.660 1.523
1  FAI=0.4500000
  XDDIN = 0.0000000000000
 NHG MAIN WS(1) TG(1) P(1) RHUMID =    0.00000 602.000001944.00000   0.00001
 NHG MAIN XV(1) XWT(1) XCH4 =    0.00000   0.00000   0.00000
0 VZ AT IGV INLET =  543.50378 MACH NUMBER =     0.46153
   I       XWT         WATRGN
  1 0.000000000000 0.000000000000
  2 0.000000000000 0.000000000000
  3 0.000000000000 0.000000000000
  4 0.000000000000 0.000000000000
  5 0.000000000000 0.000000000000
  6 0.000000000000 0.000000000000
  7 0.000000000000 0.000000000000
  8 0.000000000000 0.000000000000
  9 0.000000000000 0.000000000000
  10 0.000000000000 0.000000000000
  XV(1) = 1.1865857492804E-0009
  WATRGT = 0.0000000000000
0     ISTAGE=0  (IGV)
0          0.45000          543.50378          1.00000
  CLEAR(1) = 0.01880000000000
 NHG MAIN START CALCULATIONS FOR STAGE  1
  D1 DWAKEM,W2= 0.000000000000 514.38689162816
  D2 DWAKEM,RDELV1= 0.000000000000 10.000000000000
  D3 DWAKEM,RDELV2= 0.000000000000 0.000000000000
 B N,DDAVE(N-2)(N)=3 0.000000000000 473.99116130186
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=    0.00000 473.99116   0.00000    0.00000    0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.00000    0.00000
  FILMAS(1) = 2.8017523868103
  UI = 180.80262815912
  HHC = 0.03580445235613
  HTOTL = 6.7312370429536E-0004
1 *******************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 1 )   *************
0     STAGE TOTAL PRESSURE RATIO=      1.35248
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```
      STAGE TOTAL TEMPERATURE RATIO=      1.10864
      STAGE ADIABATIC EFFICIENCY=      0.82642
 0    STAGE FLOW COEFFICIENT=0.305
      AXIAL VELOCITY= 368.37
      ROTOR SPEED=1207.79

 0                           *ROTOR INLET* *ROTOR OUTLET* *STATOR OUTLET*
   TOTAL PRESSURE              1944.0000      2636.5495      2629.2242
   STATIC PRESSURE             1805.3335      2192.1522      2450.7589
   TOTAL TEMPERATURE(GAS)       602.0000       667.4007       667.4007
   STATIC TEMPERATURE(GAS)      589.4268       633.1831       654.1579
   STATIC DENSITY(GAS)            0.0574         0.0649         0.0702
   STATIC DENSITY(MIXTURE)        0.0574         0.0649         0.0702
 0 AXIAL VELOCITY               368.3678       336.4388       339.1701
   ABSOLUTE VELOCITY            389.0255       641.8765       399.3158
   RELATIVE VELOCITY            895.7528       514.3869
   BLADE SPEED                  941.5874       935.7442       943.2569
   TANG. COMP. OF ABS. VEL.     125.0838       546.6391
   TANG. COMP. OF REL. VEL.     816.5036       389.1051
   ACOUSTIC SPEED              1189.7575      1253.3951      1253.3859
   ABSOLUTE MACH NUMBER           0.3270         0.5205         0.3186
   RELATIVE MACH NUMBER           0.7529         0.4171
 0 FLOW COEFFICIENT               0.3050         0.2786         0.2854
   FLOW AREA                      0.3386         0.3280         0.3007
 0 ABSOLUTE FLOW ANGLE           18.7555        58.3890        31.8559
   RELATIVE FLOW ANGLE           65.7174        49.1517
   INCIDENCE                      23.0174        17.9890
   DEVIATION                                    17.4517        14.8559
   DIFFUSION RATIO                               3.6654         2.6688
   MOMENTUM THICKNESS                            0.1314         0.0192
   OMEGA (GAS)                                    0.17567        0.01648
   OMEGA (TOTAL)                                   0.17567        0.01648
   D1 DWAKEM,V3= 0.0000000000000 399.31578652344
   D2 DWAKEM,SDELV1= 0.0000000000000 10.000000000000
   D3 DWAKEM,SDELV2= 0.0000000000000 0.0000000000000
  B N,DDAVE(N-2)(N)=4 0.0000000000000 464.51999818913
  NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
  NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000 464.52000    0.00000    0.00000    0.00000
  NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =    0.00000    0.00000
 1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  1 )   ***********
 0      STAGE TOTAL PRESSURE RATIO=      1.35248
        STAGE TOTAL TEMPERATURE RATIO=      1.10864
        STAGE ADIABATIC EFFICIENCY=      0.82642
   STAGE   1 TOTAL ETA      0.82642DEL T   65.40066
 0PSI= 0.541560 PSI1= 0.447556 LOSS= 0.094004
 0             **STAGE INLET**     **STAGE OUTLET**      **STAGE OUTLET**
                                    (BEFORE INTER-        (AFTER INTER-
                                     STAGE ADJUST-         STAGE ADJUST-
                                     MENT)                 MENT)
        XV=          0.00000          0.00000              0.00000
        XW=          0.00000          0.00000              0.00000
        XWW=          0.00000          0.00000              0.00000
        XF =          0.00000          0.00000              0.03828
        XWT=          0.00000          0.00000              0.00000
        XAIR=          1.00000          1.00000              1.00000
        XMETAN=          0.00000          0.00000              0.00000
        XGAS          1.00000          1.00000              1.00000
        WMASS=          0.00000          0.00000              0.00000
        WWMASS=          0.00000          0.00000              0.00000
        FMMASS=          2.80175          2.80175              2.80175
        WTMASS=          0.00000          0.00000              0.00000
        AMASS=          7.16060          7.16060              7.16060
        CHMASS=          0.00000          0.00000              0.00000
        VMASS=          0.00000          0.00000              0.00000
        GMASS=          7.16060          7.16060              7.16060
        TMASS=          7.16060          7.16060              7.16060
```

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     WS=        0.00000              0.00000              0.00000
     RHOA=         0.06054              0.06333              0.07015
     RHOM=         0.05453              0.06332              0.07013
     RHOG=         0.05741              0.06332              0.07013
     TG=      602.00000           667.40066            667.40066
     TW=      597.00000           597.00000            597.00000
     TWW=       597.00000              0.00000            597.00000
 NHG: TRAGAS, TRAWAT =   1.10864   1.00000
     P=     1944.00000          2636.54951           2629.22421
     TB=      667.26838              0.00000            682.17635
     TDEW=       272.00755            274.47523            274.47523
  WRITING TO EXTERNAL PLOT FILES
  CLEAR(2) = 0.01650000000000
 NHG MAIN START CALCULATIONS FOR STAGE  2
  D1 DWAKEM,W2= 0.0000000000000 581.75628581723
  D2 DWAKEM,RDELV1= 0.0000000000000 10.000000000000
  D3 DWAKEM,RDELV2= 0.0000000000000 0.0000000000000
 B N,DDAVE(N-2)(N)=5 0.0000000000000 411.14023858397
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000 411.14024    0.00000    0.00000    0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.00000    0.00000
  FILMAS(2) = 2.8017523868103
  UI = 180.80262815912
  HHC = 0.05352129167392
  HTOTL = 8.8310131261979E-0004
1 ********************    INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 2 )   *************
0      STAGE TOTAL PRESSURE RATIO=       1.18858
       STAGE TOTAL TEMPERATURE RATIO=       1.06192
       STAGE ADIABATIC EFFICIENCY=       0.81180
0      STAGE FLOW COEFFICIENT=0.289
       AXIAL VELOCITY= 343.18
       ROTOR SPEED=1188.42

0                               *ROTOR INLET* *ROTOR OUTLET* *STATOR OUTLET*
  TOTAL PRESSURE                 2629.2242      3143.2899      3125.0534
  STATIC PRESSURE                2446.6287      2724.6550      2926.7483
  TOTAL TEMPERATURE(GAS)          667.4007       708.7291       708.7291
  STATIC TEMPERATURE(GAS)        653.8834       680.5190       695.6472
  STATIC DENSITY(GAS)               0.0701         0.0750         0.0789
  STATIC DENSITY(MIXTURE)           0.0701         0.0750         0.0789
0 AXIAL VELOCITY                  343.1789       338.8467       322.4618
  ABSOLUTE VELOCITY               404.0355       583.7812       397.5421
  RELATIVE VELOCITY               806.6541       581.7563
  BLADE SPEED                     943.2569       948.2653         0.0000
  TANG. COMP. OF ABS. VEL.        213.2438       475.3771
  TANG. COMP. OF REL. VEL.        730.0131       472.8882
  ACOUSTIC SPEED                 1252.2959      1291.6200      1291.6693
  ABSOLUTE MACH NUMBER              0.3226         0.4570         0.3078
  RELATIVE MACH NUMBER              0.6441         0.4554
0 FLOW COEFFICIENT                  0.2888         0.2851         0.2713
  FLOW AREA                         0.2975         0.2816         0.2816
0 ABSOLUTE FLOW ANGLE              31.8559        54.5189        35.7933
  RELATIVE FLOW ANGLE              64.8218        54.3766
  INCIDENCE                         19.2218        10.5689
  DEVIATION                                       23.7766        17.9433
  DIFFUSION RATIO                                  3.9221         3.4434
  MOMENTUM THICKNESS                              0.0816         0.0371
  OMEGA (GAS)                                       0.13314        0.04356
  OMEGA (TOTAL)                                      0.13314        0.04356
  D1 DWAKEM,V3= 0.0000000000000 397.54214855734
  D2 DWAKEM,SDELV1= 0.0000000000000 10.000000000000
  D3 DWAKEM,SDELV2= 0.0000000000000 0.0000000000000
 B N,DDAVE(N-2)(N)=6 0.0000000000000 419.44960239536
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.00000    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000 419.44960    0.00000    0.00000    0.00000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.00000    0.00000
```

```
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  2 )   ***********
0      STAGE TOTAL PRESSURE RATIO=       1.18858
       STAGE TOTAL TEMPERATURE RATIO=       1.06192
       STAGE ADIABATIC EFFICIENCY=      0.81180
  STAGE  2 TOTAL ETA      0.81376DEL T    41.32848
0PSI= 0.886120 PSI1= 0.721090 LOSS= 0.165029
0            **STAGE INLET**    **STAGE OUTLET**    **STAGE OUTLET**
                                 (BEFORE INTER-      (AFTER INTER-
                                  STAGE ADJUST-       STAGE ADJUST-
                                  MENT)               MENT)
      XV=         0.00000          0.00000             0.00000
      XW=         0.00000          0.00000             0.00000
      XWW=         0.00000          0.00000             0.00000
      XF =         0.03828          0.03828             0.03828
      XWT=         0.00000          0.00000             0.00000
      XAIR=         1.00000          1.00000             1.00000
      XMETAN=         0.00000          0.00000             0.00000
      XGAS         1.00000          1.00000             1.00000
      WMASS=          0.00000          0.00000             0.00000
      WWMASS=          0.00000          0.00000             0.00000
      FMMASS=          2.80175          2.80175             2.80175
      WTMASS=          0.00000          0.00000             0.00000
      AMASS=          7.16060          7.16060             7.16060
      CHMASS=          0.00000          0.00000             0.00000
      VMASS=          0.00000          0.00000             0.00000
      GMASS=          7.16060          7.16060             7.16060
      TMASS=          7.16060          7.16060             7.16060
      WS=         0.00000          0.00000             0.00000
      RHOA=          0.07385          0.07516             0.07892
      RHOM=          0.05453          0.07515             0.07890
      RHOG=          0.07013          0.07515             0.07890
      TG=       667.40066        708.72914           708.72914
      TW=       597.00000        597.00000           597.00000
      TWW=       597.00000          0.00000           597.00000
 NHG: TRAGAS, TRAWAT =   1.06192   1.00000
      P=     2629.22421       3143.28986          3125.05337
      TB=       682.17635          0.00000           692.03622
      TDEW=       274.47523        268.01367           268.01367
  WRITING TO EXTERNAL PLOT FILES
1********** OVERALL PERFORMANCE *********
0 INITIAL FLOW COEFFICIENT=0.450
0 CORRECTED SPEED= 8879.0     1.000 FRACTION OF DESIGN CORRECTED SPEED
0 INITIAL WATER CONTENT(SMALL DROPLET)=0.000
  INITIAL WATER CONTENT(LARGE DROPLET)=0.000
  INITIAL WATER CONTENT(TOTAL)=0.000
  INITIAL RELATIVE HUMIDITY=  0.0 PER CENT
  INITIAL METHANE CONTENT=0.000
0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
0 COMPRESSOR INLET TOTAL PRESSURE= 1944.00
0 CORRECTED MASS FLOW RATE OF MIXTURE= 120.29
0 CORRECTED MASS FLOW RATE OF GAS PHASE  120.29
0 OVERALL TOTAL PRESSURE RATIO= 1.6075
0 OVERALL TOTAL TEMPERATURE RATIO=1.1773
0 OVERALL ADIABATIC EFFICIENCY=0.8152
0********** PERFORMANCE OF FAN,LPC,HPC **********
0       GAS PHASE  STAGNATION  STAGNATION   ADIABATIC
0       CORRECTED  PRESSURE    TEMPERATURE  EFFICIENCY
0       MASS FLOW    RATIO        RATIO
0 FAN      0.0000     0.0000      0.0000       0.0000
0 LPC      0.0000     0.0000      0.0000       0.0000
0 HPC      0.0000     0.0000      0.0000       0.0000
0PSI= 0.917751 PSI1= 0.748161 LOSS= 0.169590
  I= 68
1  FAI=0.4500000
  XDDIN = 0.04000000000000
 NHG MAIN WS(1) TG(1) P(1) RHUMID =    0.01187 602.000001944.00000 100.00000
```

```
 NHG MAIN XV(1) XWT(1) XCH4 =    0.01126   0.04000   0.00000
0 VZ AT IGV INLET =  543.50378 MACH NUMBER =    0.46995
   I      XWT       WATRGN
 1 0.04000000000000 0.3016412676757
 2 0.04000000000000 0.3016412676757
 3 0.04000000000000 0.3016412676757
 4 0.04000000000000 0.3016412676757
 5 0.04000000000000 0.3016412676757
 6 0.04000000000000 0.3016412676757
 7 0.04000000000000 0.3016412676757
 8 0.04000000000000 0.3016412676757
 9 0.04000000000000 0.3016412676757
 10 0.04000000000000 0.3016412676757
  XV(1) = 0.01125764163510
  WATRGT = 3.0164126767578
  D0 DWAKEM,W2= 600.0000000000 543.50378458031
0     ISTAGE=0  (IGV)
0          0.45000         543.50378         0.94874
  CLEAR(1) = 0.01880000000000
 NHG MAIN START CALCULATIONS FOR STAGE  1
  D1 DWAKEM,W2= 0.0000000000000 513.95749648891
  D2 DWAKEM,RDELV1= 600.0000000000 18.867096152029
  D3 DWAKEM,RDELV2= 436.40800073631 0.0000000000000
 B N,DDAVE(N-2)(N)=3 600.0000000000 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000   0.14756   0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 473.99116   0.00000   0.14756
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =   0.00000   0.14756   (
  FILMAS(1) = 3.1127784005606
  UI = 137.33246072363
  HHC = 0.04420138993732
  HTOTL = 8.3098613082176E-0004
 N,DDAVE(N-1)(N)=3 600.0000000000 473.99116129979
 N,DDAVE(N-1)(N)=3 600.0000000000 473.99116129979
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 1 )   *************
0      STAGE TOTAL PRESSURE RATIO=      1.34569
       STAGE TOTAL TEMPERATURE RATIO=      1.10846
       STAGE ADIABATIC EFFICIENCY=      0.81082
0      STAGE FLOW COEFFICIENT=0.304
       AXIAL VELOCITY= 367.58
       ROTOR SPEED=1207.79
```

0	*ROTOR INLET*	*ROTOR OUTLET*	*STATOR OUTLET*
TOTAL PRESSURE	1944.0000	2624.4055	2616.0249
STATIC PRESSURE	1801.3200	2162.9053	2431.1640
TOTAL TEMPERATURE(GAS)	602.0000	667.2949	667.2949
STATIC TEMPERATURE(GAS)	589.0906	632.9487	654.1192
STATIC DENSITY(GAS)	0.0569	0.0636	0.0692
STATIC DENSITY(MIXTURE)	0.0593	0.0662	0.0720
0 AXIAL VELOCITY	367.5771	339.5677	340.5856
ABSOLUTE VELOCITY	388.1904	646.3270	400.9942
RELATIVE VELOCITY	895.6727	513.9575	
BLADE SPEED	941.5874	935.7442	943.2569
TANG. COMP. OF ABS. VEL.	124.8153	549.9385	
TANG. COMP. OF REL. VEL.	816.7721	385.8057	
ACOUSTIC SPEED	1168.8862	1211.6172	1230.8882
ABSOLUTE MACH NUMBER	0.3321	0.5334	0.3258
RELATIVE MACH NUMBER	0.7663	0.4242	
0 FLOW COEFFICIENT	0.3043	0.2811	0.2866
FLOW AREA	0.3386	0.3280	0.3007
0 ABSOLUTE FLOW ANGLE	18.7555	58.3061	31.8587
RELATIVE FLOW ANGLE	65.7705	48.6473	
INCIDENCE	23.0705	17.9061	
DEVIATION		16.9473	14.8587
DIFFUSION RATIO		3.6741	2.6690
MOMENTUM THICKNESS		0.1392	0.0195
OMEGA (GAS)		0.17986	0.01679

```
 OMEGA (TOTAL)                                              0.18603          0.02515
 D1 DWAKEM,V3= 600.0000000000 400.99420771989
 D2 DWAKEM,SDELV1= 600.0000000000 18.867096152027
 D3 DWAKEM,SDELV2= 399.87962081002 0.0000000000000
B N,DDAVE(N-2)(N)=4 600.0000000000 0.0000000000000
NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.08549    0.12973    0.06207
NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 464.52000   4.47702    0.01783
NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.08549    0.12973    (
N,DDAVE(N-1)(N)=4 473.99116129979 464.51999818754
N,DDAVE(N-1)(N)=4 473.99116129979 464.51999818754
XNP,TG(3),P(3)=32007536709.313 667.21481348613 2616.0249275946
1 ******************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  1 )   ***********
0      STAGE TOTAL PRESSURE RATIO=      1.34569
       STAGE TOTAL TEMPERATURE RATIO=      1.10833
       STAGE ADIABATIC EFFICIENCY=      0.81180
  STAGE  1 TOTAL ETA      0.81180DEL T   65.21481
0PSI= 0.545629 PSI1= 0.442940 LOSS= 0.102689
0            **STAGE INLET**    **STAGE OUTLET**    **STAGE OUTLET**
                                  (BEFORE INTER-      (AFTER INTER-
                                   STAGE ADJUST-       STAGE ADJUST-
                                   MENT)               MENT)
      XV=          0.01126          0.01126             0.01146
      XW=          0.00000          0.00000             0.00000
      XWW=          0.04000          0.04000             0.03979
      XF =          0.00140          0.00140             0.04128
      XWT=          0.04000          0.04000             0.03979
      XAIR=          0.94874          0.94874             0.94874
      XMETAN=          0.00000          0.00000             0.00000
      XGAS          0.96000          0.96000             0.96021
      WMASS=          0.00000          0.00000             0.00000
      WWMASS=          0.29512          0.29512             0.29360
      FMMASS=          2.80175          2.80175             3.11278
      WTMASS=          0.29512          0.29512             0.29360
      AMASS=          6.99988          6.99988             6.99988
      CHMASS=          0.00000          0.00000             0.00000
      VMASS=          0.08306          0.08306             0.08458
      GMASS=          7.08293          7.08293             7.08445
      TMASS=          7.37806          7.37806             7.37806
      WS=          0.01187          0.01187             0.01208
      RHOA=          0.06054          0.06256             0.06552
      RHOM=          0.05619          0.06469             0.07200
      RHOG=          0.05691          0.06211             0.06914
      TG=        602.00000        667.29487           667.21481
      TW=        597.00000        597.00000           597.00000
      TWW=        597.00000        597.00000           597.44952
 NHG: TRAGAS, TRAWAT =    1.10833    1.00075
      P=      1944.00000       2624.40546          2616.02493
      TB=        667.26838          0.00000           681.92240
      TDEW=        518.09930        526.98696           527.42653
  WRITING TO EXTERNAL PLOT FILES
  CLEAR(2) = 0.01650000000000
 NHG MAIN START CALCULATIONS FOR STAGE  2
  D1 DWAKEM,W2= 0.0000000000000 581.57288050930
  D2 DWAKEM,RDELV1= 600.0000000000 18.736622631016
  D3 DWAKEM,RDELV2= 363.92477277446 0.0000000000000
 B N,DDAVE(N-2)(N)=5 473.99116129979 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =    0.00000    0.14680    0.00000
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 411.26398   0.00000    0.14680
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3     =    0.00000    0.14680    (
  FILMAS(2) = 3.4204451329624
  UI = 169.65473048130
  HHC = 0.04545078593931
  HTOTL = 7.4993796799873E-0004
 N,DDAVE(N-1)(N)=5 464.51999818754 411.26397697453
 N,DDAVE(N-1)(N)=5 464.51999818754 411.26397697453
1 ******************   INITIAL FLOW COEFFICIENT= 0.450 (STAGE= 2 )   ************
```

```
0     STAGE TOTAL PRESSURE RATIO=      1.18315
      STAGE TOTAL TEMPERATURE RATIO=     1.06181
      STAGE ADIABATIC EFFICIENCY=      0.78865
0     STAGE FLOW COEFFICIENT=0.290
      AXIAL VELOCITY= 344.39
      ROTOR SPEED=1188.42

0                             *ROTOR INLET* *ROTOR OUTLET* *STATOR OUTLET*
  TOTAL PRESSURE                2616.0249      3118.1626      3095.1560
  STATIC PRESSURE               2427.0139      2683.6917      2889.3858
  TOTAL TEMPERATURE(GAS)         667.2148       708.4574       708.4574
  STATIC TEMPERATURE(GAS)        653.1841       680.0961       695.3513
  STATIC DENSITY(GAS)              0.0691         0.0734         0.0773
  STATIC DENSITY(MIXTURE)          0.0720         0.0765         0.0805
0 AXIAL VELOCITY                 344.3882       342.6169       325.3643
  ABSOLUTE VELOCITY              405.4713       588.3744       400.5076
  RELATIVE VELOCITY              806.4691       581.5729
  BLADE SPEED                    943.2569       948.2653         0.0000
  TANG. COMP. OF ABS. VEL.       214.0181       478.3284
  TANG. COMP. OF REL. VEL.       729.2388       469.9369
  ACOUSTIC SPEED                1230.2106      1255.2980      1268.6291
  ABSOLUTE MACH NUMBER             0.3296         0.4687         0.3157
  RELATIVE MACH NUMBER             0.6556         0.4633
0 FLOW COEFFICIENT                 0.2898         0.2883         0.2738
  FLOW AREA                        0.2975         0.2816         0.2816
0 ABSOLUTE FLOW ANGLE             31.8587        54.3867        35.6709
  RELATIVE FLOW ANGLE             64.7206        53.9053
  INCIDENCE                       19.1206        10.4367
  DEVIATION                                      23.3053        17.8209
  DIFFUSION RATIO                                 3.9100         3.4303
  MOMENTUM THICKNESS                              0.0849         0.0370
  OMEGA (GAS)                                     0.13491        0.04351
  OMEGA (TOTAL)                                   0.14214        0.05701
  D1 DWAKEM,V3= 600.00000000000 400.50763293193
  D2 DWAKEM,SDELV1= 600.00000000000 18.736622631013
  D3 DWAKEM,SDELV2= 341.52501255762 0.0000000000000
 B N,DDAVE(N-2)(N)=6 464.51999818754 0.0000000000000
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DL,DS,D1,D2,D3 =   0.09890   0.12954   0.04790
 NHG DS DL DLGE DSLL AMLGE AMSLL=   0.00000   0.00000 419.54008   3.46657   0.01727
 NHG WICSIZ WMASSS WMASSL AMING1 2 3 DSLL,DLGE,D1,D2,D3    =   0.09890   0.12954
 N,DAVE(N-1)(N)=6 0.0000000000000 3.4665741052753
 N,DDAVE(N-1)(N)=6 411.26397697453 419.54007507640
 N,DAVE(N-1)(N)=6 0.0000000000000 3.4665741052753
 N,DDAVE(N-1)(N)=6 411.26397697453 419.54007507640
 N,DAVE(N-1)(N)=6 0.0000000000000 3.4665741052753
 N,DDAVE(N-1)(N)=6 411.26397697453 419.54007507640
 XNP,TG(3),P(3)=32007536709.313 708.32307639771 3095.1559980129
 XNP,TG(3),P(3)=31842809389.321 708.32307639771 3095.1559980129
1 ********************   INITIAL FLOW COEFFICIENT= 0.450 (ISTAGE=  2 )   ***********
0     STAGE TOTAL PRESSURE RATIO=      1.18315
      STAGE TOTAL TEMPERATURE RATIO=      1.06161
      STAGE ADIABATIC EFFICIENCY=      0.79117
  STAGE   2 TOTAL ETA      0.79648DEL T   41.10826
0PSI= 0.892426 PSI1= 0.710803 LOSS= 0.181623
0           **STAGE INLET**    **STAGE OUTLET**     **STAGE OUTLET**
                                (BEFORE INTER-        (AFTER INTER-
                                 STAGE ADJUST-         STAGE ADJUST-
                                 MENT)                 MENT)
      XV=          0.01146          0.01146              0.01206
      XW=          0.00000          0.00000              0.00000
      XWW=          0.03979          0.03979              0.03920
      XF =          0.04128          0.04128              0.04536
      XWT=          0.03979          0.03979              0.03920
      XAIR=          0.94874          0.94874              0.94874
      XMETAN=          0.00000          0.00000              0.00000
      XGAS          0.96021          0.96021              0.96080
```

```
     WMASS=        0.00000              0.00000              0.00000
     WWMASS=        0.29360              0.29360              0.28921
     FMMASS=        3.11278              3.11278              3.42045
     WTMASS=        0.29360              0.29360              0.28921
     AMASS=        6.99988              6.99988              6.99988
     CHMASS=        0.00000              0.00000              0.00000
     VMASS=        0.08458              0.08458              0.08897
     GMASS=        7.08445              7.08445              7.08885
     TMASS=        7.37806              7.37806              7.37806
     WS=      0.01208              0.01208              0.01271
     RHOA=        0.07350              0.07423              0.07374
     RHOM=        0.05619              0.07673              0.08057
     RHOG=        0.06914              0.07368              0.07742
     TG=     667.21481           708.45743           708.32308
     TW=     597.00000           597.00000           597.00000
     TWW=      597.44952           597.44952           598.21027
 NHG: TRAGAS, TRAWAT =   1.06161   1.00127
     P=    2616.02493          3118.16261          3095.15600
     TB=     681.92240              0.00000           691.50795
     TDEW=      527.42653           526.30787           527.65598
  WRITING TO EXTERNAL PLOT FILES
1********** OVERALL PERFORMANCE *********
0 INITIAL FLOW COEFFICIENT=0.450
0 CORRECTED SPEED= 8879.0      1.000 FRACTION OF DESIGN CORRECTED SPEED
0 INITIAL WATER CONTENT(SMALL DROPLET)=0.000
  INITIAL WATER CONTENT(LARGE DROPLET)=0.040
  INITIAL WATER CONTENT(TOTAL)=0.040
  INITIAL RELATIVE HUMIDITY=100.0 PER CENT
  INITIAL METHANE CONTENT=0.000
0 COMPRESSOR INLET TOTAL TEMPERATURE=  602.00
0 COMPRESSOR INLET TOTAL PRESSURE= 1944.00
0 CORRECTED MASS FLOW RATE OF MIXTURE= 123.94
0 CORRECTED MASS FLOW RATE OF GAS PHASE  118.99
0 OVERALL TOTAL PRESSURE RATIO= 1.5922
0 OVERALL TOTAL TEMPERATURE RATIO=1.1766
0 OVERALL ADIABATIC EFFICIENCY=0.7980
0********** PERFORMANCE OF FAN,LPC,HPC **********
0       GAS PHASE  STAGNATION  STAGNATION   ADIABATIC
0       CORRECTED  PRESSURE    TEMPERATURE  EFFICIENCY
0       MASS FLOW    RATIO       RATIO
0 FAN      0.0000      0.0000      0.0000      0.0000
0 LPC      0.0000      0.0000      0.0000      0.0000
0 HPC      0.0000      0.0000      0.0000      0.0000
0PSI= 0.914259 PSI1= 0.729541 LOSS= 0.184717
  I= 68
   10  0.019479  708.3   3095.2  598.2  0.798  0.0455
  NUMBER OF LOOPS = 10
  TOTAL MASS = 0.3781818163733
0PSI= 0.914259 PSI1= 0.729541 LOSS= 0.184717
  I= 68
  GEMACH = 0.2731038592486
```

APPENDIX VI

PERFORMANCE MAPS FOR ENGINE SIMULATION

The engine simulation code utilized (Reference 2) permits calculation of transient performance of a bypass engine for given ambient, flight (altitude and Mach number), and power demand conditions with a standard aviation fuel. The code is written in a form in which the working fluid (air) is taken through the engine from inlet to nozzle while fuel is added in the burner. Thus the performance of any of the engine components can be calculated by using a substitute method (or sub-routine in the code) when so desired in place of the original method or subroutine. However, it is obvious that, for simplicity of engine simulation code operation, it is best if the component performance is obtained in any substitute subroutine in the same manner as in the original.

In the current investigation, wherein the interest is in transient engine simulation under conditions of water ingestion, one of the primary components affected and on which investigations have been carried out specifically and in detail is the fan-compressor unit. The performance of that unit can be established utilizing the WINCOF-I code. In the following, a brief description is provided on the manner in which the output from the WINCOF-I code for the fan-compressor unit of the generic engine is processed such that it is compatible with the engine simulation code.

Traditionally, performance data for a compressor are presented in the form of standard compressor maps; these are curves showing variation of overall pressure ratio and adiabatic efficiency as a function of corrected mass flow, at a range of corrected operating speeds. For use in an engine simulation code, these curves would have to be stored in tabular data form, which would require very large amounts of memory. Also, when the engine is operating in conditions between available data points, interpolation would be required. However, since these curves are highly non-linear, any interpolation would very likely be in error. Therefore, in order to run an engine simulation code efficiently and accurately, a better method of storing compressor performance data is required.

One such method is based on the loss characteristics of a compressor (Reference 10). This method is used to generate a set of parametrized compressor performance maps.

The maps are presented in two ways: a compressor efficiency representation and a compressor flow representation. The compressor efficiency representation consists of three maps: (a) minimum work coefficient versus corrected rotational speed, (b) minimum loss versus speed, and (c) loss minus minimum loss versus work coefficient minus minimum-loss work coefficient squared, with the sign maintained. These quantities are defined as follows.

(a) work coefficient.

$$\psi = \frac{\Delta H}{U^2 / 2GJ} \tag{VI.1}$$

(b) pressure coefficient

$$\psi_1 = \frac{\Delta H_1}{U^2 / 2GJ} \tag{VI.2}$$

and

(c) loss

$$LOSS = \psi - \psi_1 \tag{VI.3}$$

In the three definitions, referring to figure VI.1, ΔH represents the work actually done on air during compression and ΔH_1 the amount of work that, ideally, would have resulted in the same pressure ratio across the compressor.

They are non-dimensionalized with respect to the kinetic energy of rotation at compressor wheel speed.

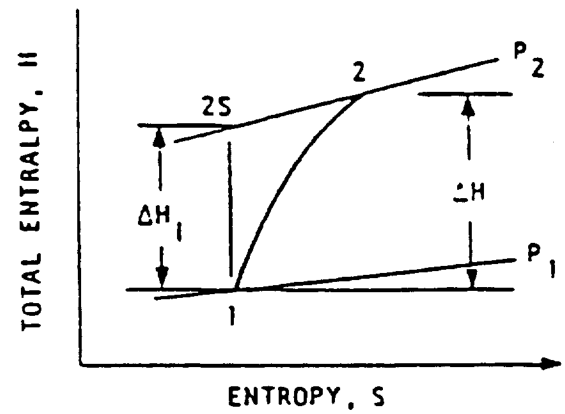
The compressor flow representation consists of: (d) minimum loss flow coefficient versus corrected rotational speed, and (e) pseudo-Mach number versus work coefficient minus minimum loss work coefficient. The latter may be explained as follows. When the flow in the compressor is near choking, or a maximum value, it is assumed that there is a Mach number of unity somewhere along the gas path. From this a critical flow area can be calculated. If this area can be assumed to be constant for operation at a given rotational speed, a pseudo-Mach number can be defined at each point along the speed line as follows.

$$\frac{\dot{m}_{corr}}{\dot{m}_{corr,max}} = \frac{M}{\left(1 + \left(\frac{\gamma-1}{2}\right) M^2\right)^{\frac{r+1}{2(\gamma-1)}}} \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \qquad \text{(VI.4)}$$

It may be pointed out that the ratio of mass fluxes is nothing but the ratio of flow coefficients.

Examples of the five maps (a) - (e) are given in figure VI.2.

Utilizing the five curves, one can generate two sets of curves: (1) loss minus minimum loss as a function of $(\psi - \psi_{ML}) \cdot |\psi - \psi_M|$ for various values of operating rotor speeds and (2) psendo-Mach number as a function of $(\psi - \psi_{ML})$. In both cases it is interesting that the result is linear with breaks corresponding to stalling and choking of compressor. This is the main feature that one needed to realize so that the maps may be inserted in a simple table look-up in the engine simulation code.



LET: C_{z_1} = AXIAL VELOCITY COMPONENT AT ROTOR INLET

v = WHEEL SPEED

DEFINE:

1. WORK COEFFICIENT, $\psi = \Delta H/(v^2/2g_oJ)$
2. PRESSURE COEFFICIENT, $\psi_I = \Delta H_I/(v^2/2g_oJ)$
3. FLOW COEFFICIENT, $\phi = C_{z_1}/v$
4. EFFICIENCY, EFF = ψ_I/ψ
5. LOSS, XLS = $(\Delta H - \Delta H_I)/(v^2/2g_oJ) = \psi - \psi_I$

Figure VI.1. Compressor stage performance parameters: definitions.

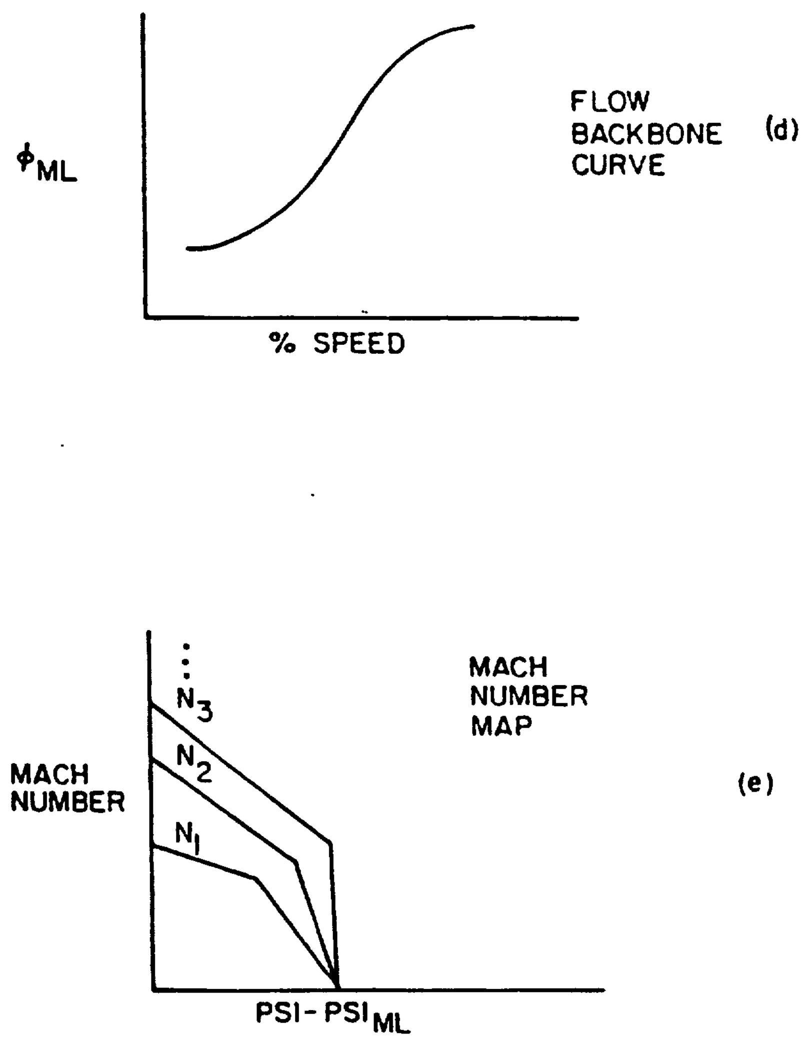


Figure VI.2. Compressor stage performance parameters: ϕ for minimum loss and pseudo-Mach number.

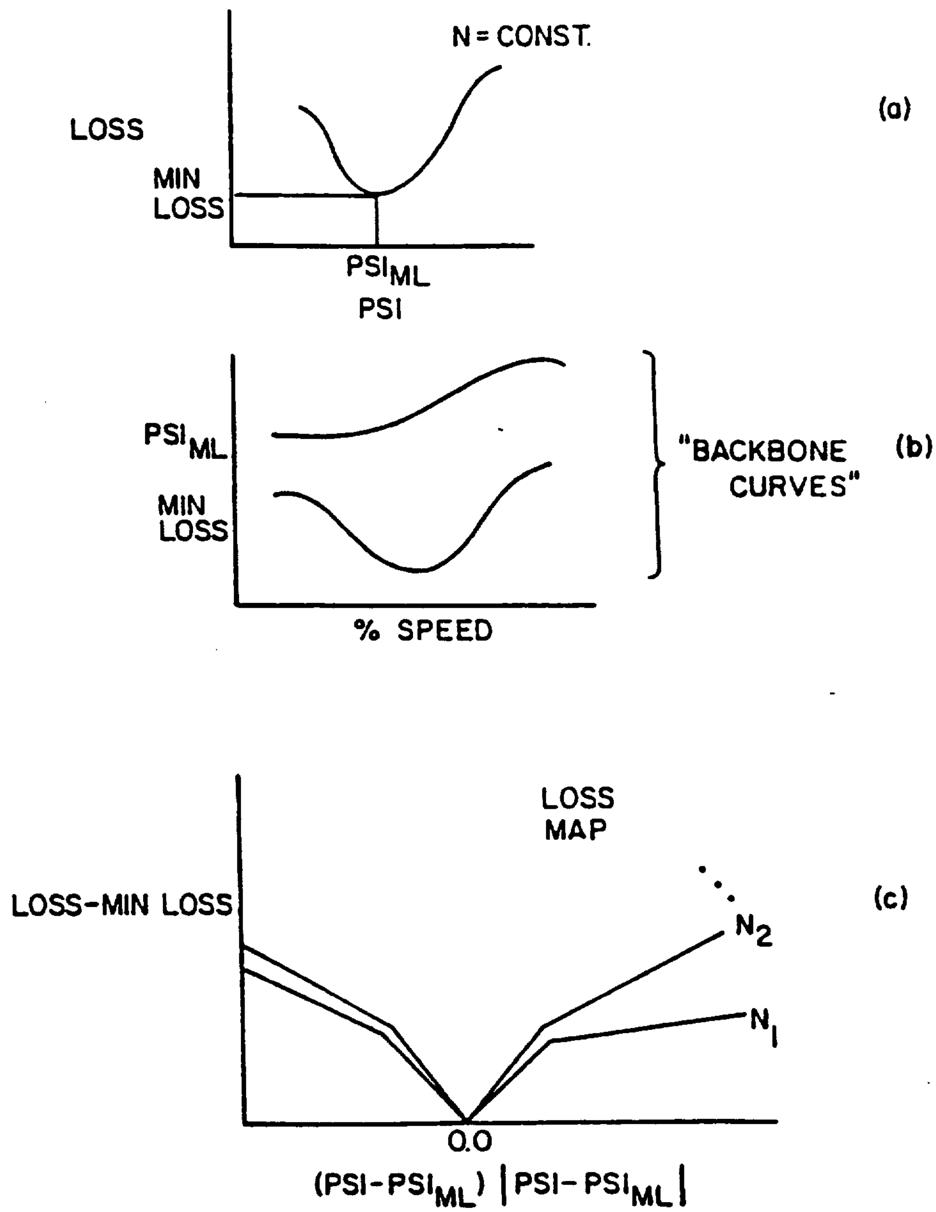


Figure VI.2. Compressor stage performance parameters: loss and (loss–minimum loss). (continued)

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13. ABSTRACT *(Maximum 200 words)*

The performance of an axial-flow fan-compressor unit is basically unsteady when there is ingestion of water along with the gas phase. The gas phase is a mixture of air and water vapor in the case of a bypass fan engine that provides thrust power to an aircraft. The liquid water may be in the form of droplets and film at entry to the fan. The unsteadiness is then associated with the relative motion between the gas phase and water, at entry and within the machine, while the water undergoes impact on material surfaces, centrifuging, heat and mass transfer processes, and reingestion in blade wakes, following peal off from blade surfaces. The unsteadiness may be caused by changes in atmospheric conditions, and at entry into and exit from rain storms while the aircraft is in flight. In a multi-stage machine, with an uneven distribution of blade tip clearance, the combined effect of various processes in the presence of steady or time-dependent ingestion is such as to make the performance of a fan and a compressor unit time-dependent from the start of ingestion up to a short time following termination of ingestion. The original WINCOF code was developed without accounting for the relative motion between gas and liquid phases in the ingested fluid. A modification of the WINCOF code has now been developed, named the WINCOF-I, which can provide the transient performance of a fan-compressor unit under a variety of input conditions.

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