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A COMPUTER PROGRAM FOR THE TRANSIENT THERMAL ANALYSIS OF AN IMPINGEMENT COOLED TURBINE BLADE

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A COMPUTER PROGRAM FOR THE TRANSIENT THERMAL ANALYSIS OF AN IMPINGEMENT COOLED TURBINE BLADE

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Abstract

A computer program to calculate transient and steady state temperatures, pressures, and coolant flows in a cooled turbine blade or vane with an impingement insert is described. Input to the program includes a description of the blade geometry, coolant supply conditions, outside thermal boundary conditions and wheel speed. Coolant-side heat transfer coefficients are calculated internally in the program, with the user specifying the mode of heat transfer at each internal flow station. Program output includes the temperature at each node, the coolant pressures and flow rates, and the inside heat transfer coefficients. A sample problem is discussed.

Nomenclature

b	equivalent impingement slot width
C1-C7	user supplied constants in general impingement correlation
D_j	impingement hole diameter
D_p	pin fin diameter
D1-D6	user supplied constants in general leading edge impingement correlation
h_c	coolant side heat transfer coefficient
h_g	hot gas side heat transfer coefficient
L_p	pin fin length
ℓ	surface half length over which leading edge impingement heat transfer is averaged
M	film cooling mass velocity ratio, coolant to free stream
m	exponent in equation (1)
Nu_D	Nusselt number based on channel hydraulic diameter
Nu_j	Nusselt number based on impingement jet diameter
Pr	Prandtl number
Re_D	Reynolds number based on channel hydraulic diameter
Re_j	Reynolds number based on hole diameter
Re_n	Reynolds number based on equivalent slot width
S_p	pin fin spacing
St	Stanton number
s	equivalent slot height for film cooling
U_c	coolant crossflow velocity
U_j	impingement jet velocity
X_n	impingement hole spanwise spacing
x	distance downstream of film cooling hole or slot
Z_n	impingement channel width
η'	film cooling effectiveness
μ_g	outside gas viscosity
μ_j	film cooling jet viscosity
ρ_c	crossflow gas density
ρ_j	impingement jet density
φ_1, φ_2	constants in equation (1)

Introduction

As core turbine engine operating conditions become more severe, it becomes more difficult to effectively cool blades and vanes. Advanced transient thermal calculational techniques are needed in order to design reliable turbine blades. There appears to be no generally available computer program that utilizes these advanced techniques in combining the required heat transfer and coolant flow distribution calculations. Thus, it was decided to create a computer program that would perform transient and steady state heat transfer and coolant flow analyses for a cooled blade, given the outside hot gas boundary conditions, the coolant inlet pressure or flow rate, the geometry of the blade shell, and the cooling configuration.

The resulting program, TACT1, can handle a turbine blade or vane which is equipped with a central coolant plenum insert, from which coolant air flows through holes to impinge on the inner surface of the blade shell. It is assumed that the spent impingement air then flows chordwise and is dumped through a split or drilled trailing edge and/or through film cooling holes. The blade is modeled by dividing it by chordwise planes into slices, with each slice broken up into chordwise calculational stations. Temperatures at each station are calculated for four points through the wall and one in the coolant

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channel. Included in this model is the capability to analyze a blade with a ceramic thermal barrier coating.

The TACT1 program is used at the NASA Lewis Research Center on an IBM TSS/360-67 computer. The source program consists of approximately 5400 lines of code and the program requires about 60 000 words of storage. Typical running times for the program are in the neighborhood of 1.4 seconds of CPU time per calculational station for a steady state run, and about 0.4 seconds of CPU time per station per time step for a transient run.

The TACT1 program is described in detail in Refs. 1 and 2. This paper presents an overview of the program and a sample problem to illustrate the use and capabilities of the program.

Method of Analysis

Blade Geometric Model

The key to creating a usable computer program is to have as simple a geometric model as possible for the system being analyzed. In this program, the emphasis is on a blade or vane with a central coolant plenum and chordwise flow of the coolant after impingement; therefore, it was decided that the primary calculational direction would also be chordwise. The blade is divided into layers which are bounded by chordwise cuts through the blade as shown in Fig. 1. Each slice is treated separately in the program, with radial heat conduction in the wall the only communication between layers.

Figure 2 shows the details of the geometric model for a single slice of a blade, showing the breakdown of the blade or vane into calculational stations and nodes. Each calculational station is broken down into five nodes, located at: (1) the outer surface, (2) the interface between coating and blade metal, (3) a point midway through the wall metal, (4) the wall inner surface, and (5) at a mid-coolant channel location.

For input to the program, the following basic elements of the geometry are needed for each station: (1) the thickness of the wall coating and the wall metal and coolant channel width, (2) the chordwise distance of each node from the adjacent lower numbered node, and (3) the radial span for this slice. In addition, depending on the mode of heat transfer specified, the user must supply diameter and spacing for impingement holes or the diameter and spacing for pin fins. The input is described in detail in Ref. 1.

Numerical Model

The numerical solution for the temperatures throughout the blade involves writing a transient energy balance equation for each node and forming a set of equations to be solved for the temperature distribution. Similarly, the coolant pressure distribution is determined by writing the transient momentum equation for flow between adjacent fluid nodes and solving the resulting set of equations for static pressures.

The nodal energy balances are linearized one-dimensional heat conduction equations at the outside node, the junction of cladding and metal node, and the inside wall surface node. At the midmetal node, a linearized three-dimensional heat conduction equation is used. In the coolant channel, energy and momentum equations for one-dimensional compressible flow including friction and heat transfer are written for the elemental channel length between two coolant nodes. The equations used are presented in Ref. 1.

Heat Transfer Correlations

Three different modes of coolant side heat transfer are built into the program. The user must indicate the mode to be used at each station. Built-in correlations are available for: (1) impingement, including separate correlations for the stagnation point in the concave leading edge and for stations where crossflow is present, (2) forced convection channel flow, and (3) forced convection over an equilateral triangular array of pin fins. In addition, the program has two general correlations that may be used in place of the specific impingement correlations by including the appropriate constants in the input.

For impingement cooling, the correlation due to Kercher and Tabakoff,[3] including the effects of crossflow, is used.

$$Nu_j = \varphi_1 \varphi_2 Re_j^m Pr^{0.33} \left(\frac{Z_n}{D_j}\right)^{0.091} \tag{1}$$

where φ_1 and m are functions of the ratio of jet spacing to jet diameter and φ_2 is a function of the ratio of coolant crossflow to jet flow. The values of the coefficients can be found in Ref. 1. The alternative general correlation is of the form:

$$St = C1\left(\frac{\rho_c U_c}{\rho_j U_j}\right)^{C2} \left(\frac{\rho_c U_c^2}{\rho_j U_j^2}\right)^{C3} \left(\frac{Z_n}{D_j}\right)^{C4} \left(\frac{X_n}{D_j}\right)^{C5} Re_j^{C6} Pr^{C7} \tag{2}$$

where the constants C1 through C7 are specified by the user in the input. A correlation specifically for impingement into a concave surface is used to calculate the coolant side heat transfer coefficient at the leading edge impingement stagnation point. The built-in correlation is due to Metzger, Yamashita, and Jenkins,[4] and has the form:

$$St = 0.355\, Re_n^{-0.27} \left(\frac{\ell}{b}\right)^{-0.52} \tag{3}$$

where the Reynolds number is based on the equivalent slot width, b, and ℓ is the surface half length over which the heat transfer is averaged. The alternate general correlation is of the form:

$$St = D1\, Re^{D2}\, Pr^{D3} \left(\frac{Z_n}{d_j}\right)^{D4} \left(\frac{X_n}{d_j}\right)^{D5} \left(\frac{\ell}{d_j}\right)^{D6} \tag{4}$$

where the constants D1 through D6 are specified by the user in the input.

The correlation used for turbulent forced convection channel flow is:

$$Nu_D = 0.023\, Re_D^{0.8}\, Pr^{0.333} \tag{5}$$

where the subscript D indicates that the channel hydraulic diameter is to be used as the reference length.

The correlation for forced convection in an equilateral triangular array of pin fins is taken from Faulkner,[5] and is:

$$Nu_D = 0.023 + \frac{4.143 \exp\left[-3.094 \frac{D_p}{S_p} - 0.89 \left(\frac{S_p}{L_p}\right)^{.5075}\right]}{Re_D^{0.2946}} Re^{0.8}\, Pr^{0.3} \tag{6}$$

The program contains the capability to handle local film cooling from a row of holes or a slot. However, due to a program requirement for continuous rearward flow in the coolant channel, the use of the film cooling option must be limited. If local film cooling is included, the user has the option of specifying the outside heat transfer coefficient for the film cooled case directly, or specifying an unblown heat transfer coefficient and letting the program calculate an effectiveness. An effectiveness is calculated from the correlation due to Stollery and El-Ehwany:[6]

$$\eta' = \left(\frac{x}{Ms}\right) Re_j \left(\frac{\mu_j}{\mu_g}\right)^{-0.25} + 4.1^{-0.8} \tag{7}$$

where s is an equivalent slot height, x is the distance from the row of holes, M is the mass velocity ratio, coolant to free stream, Re_j is the coolant jet Reynolds number, and μ_j and μ_g are the coolant and free stream viscosities.

The air properties needed in the various correlations are evaluated in the program at a local reference temperature. A table of air properties versus temperature at 20 atmospheres pressure, from Poferl and Svehla,[7] is included in TACT1.

Program Description

Figure 3 shows an overall flow chart for the TACT1 program. The method of solution can be shown by describing what is involved in doing a steady state calculation for a multi-slice blade. For transient runs, a steady state solution must be done first to provide the initial state for the transient. There are three basic nested calculational loops that must converge for a solution to be reached. These are labeled as A, B, and C in Fig. 3. The innermost loop, A, results in a stable set of temperatures at all nodes and pressures at the coolant channel nodes. The intermediate loop, B, results in a stable coolant flow split between suction and pressure sides of the blade, and the outermost loop, C, is an overall coolant mass balance between the coolant supply and the coolant discharge to the main stream.

The program starts with the coolant supply pressure and total coolant flow fixed. The impingement flow is initially assumed to split uniformly at the leading edge stagnation station, station 1. All coolant flows for the slice under consideration are calculated first, based on the latest pressure distribution. The temperatures at each node are then calculated by solving simultaneously the energy equations presented in Ref. 1, and the pressures at all coolant nodes are calculated by solving simultaneously the momentum equations presented in Ref. 1. This cycle of calculating coolant flows, all temperatures, and coolant channel pressures is repeated until the pressures converge. The flow split between suction and pressure side coolant channels is then checked by comparing the pressures at the entrance to the trailing edge region. If they do not match, the impingement flow split at the leading edge is adjusted and the inner loop calculations are repeated. Once the proper flow split is achieved, the program moves up the blade to the next slice and repeats the above sequence. After all N slices have converged, the total coolant flow used is compared to the inlet value. If there is an imbalance, either the inlet flow or supply pressure is adjusted, depending on which was specified in the input, and the calculations start over again. Once the overall coolant balance is satisfied, the steady state solution is complete and the transient calculations begin. During a transient, loop B is bypassed, as the coolant flow split is primarily a function of blade geometry.

Sample Problem

A conceptual design of an impingement cooled blade for an advanced high pressure turbine is used to demonstrate the program. Two cases were run, a rapid engine acceleration transient, and a similar engine deceleration. The transient calculations were carried out to 5 seconds, using 0.25 second time steps. Running times on the TSS/360-67 computer were about 3200 seconds of CPU time for each 5 second transient.

The blade considered has a span of 3.81 cm and is divided into three slices. Figure 4 is a mid-span cross section view of the blade showing the locations of the computational stations and impingement holes. Figure 5 shows the time variations assumed for the transient input variables and Fig. 6 is a plot of the hot gas side heat transfer coefficient distribution for these cases. The heat transfer coefficients were calculated from a cylinder leading edge correlation and the STAN5 boundary layer computer program of Ref. 8.

Figures 7 to 9 are representative output from the TACT1 computations. Figure 7 shows h_c, the coolant side heat transfer coefficient distribution calculated by the program for the high speed steady state starting condition. Note the very high heat transfer coefficients around the forward stagnation point due to pure impingement into a concave surface. Further down the blade the h_c values drop off as the effect of coolant crossflow is felt. The sharp dip in the curve for both suction and pressure sides occurs at the end of the impingement insert where there is a reduction in coolant velocity.

Figure 8 shows the high speed steady state temperature distribution around the blade for a slice at the blade hub region, a slice at the blade mid-span region, and a slice at the blade tip region. The temperatures plotted in Fig. 8 are mid-wall temperatures. Although the hub and tip regions have the same hot gas conditions and cooling configurations for this problem, the tip region runs cooler due to the coolant having a higher pressure in this region.

Figure 9 presents the transient behavior of some of the temperatures. The three curves are for the outside surface, mid-span hot spot, the outside surface, mid-span cold spot, and the overall bulk metal temperature. The symbols on the curves indicate the location on the blade of the hot and cold spots. Note that the locations of the mid-span hot spot and cold spot change during the transient.

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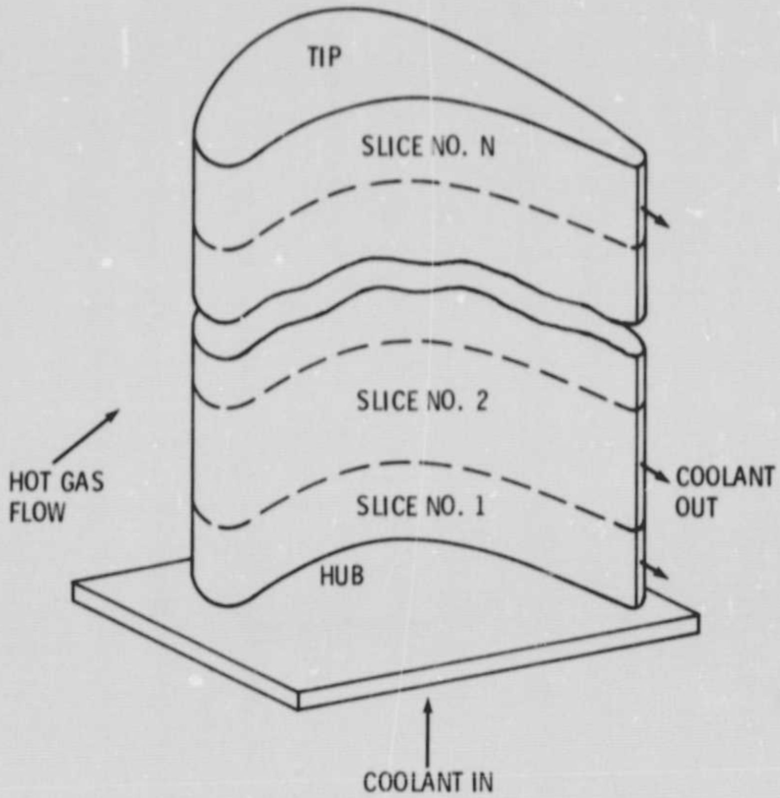

Figure 1. - Overall breakdown of the blade into slices.

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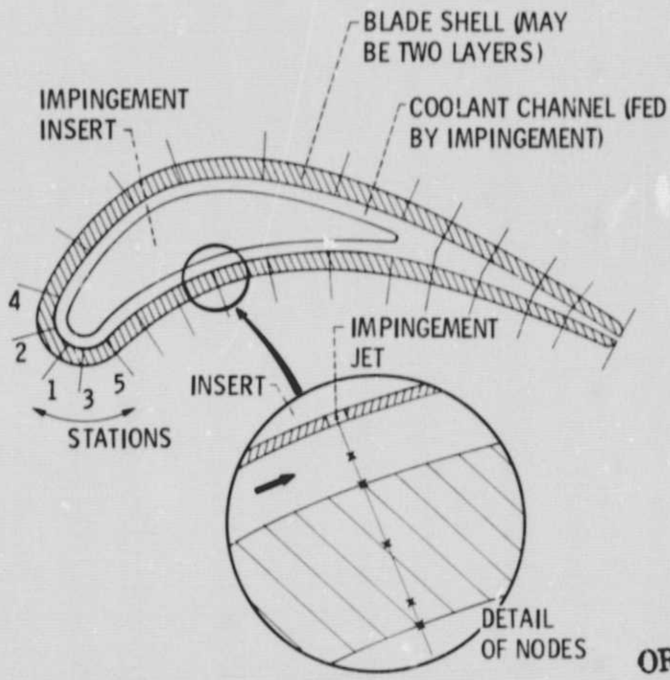

Figure 2. - Blade geometric model.

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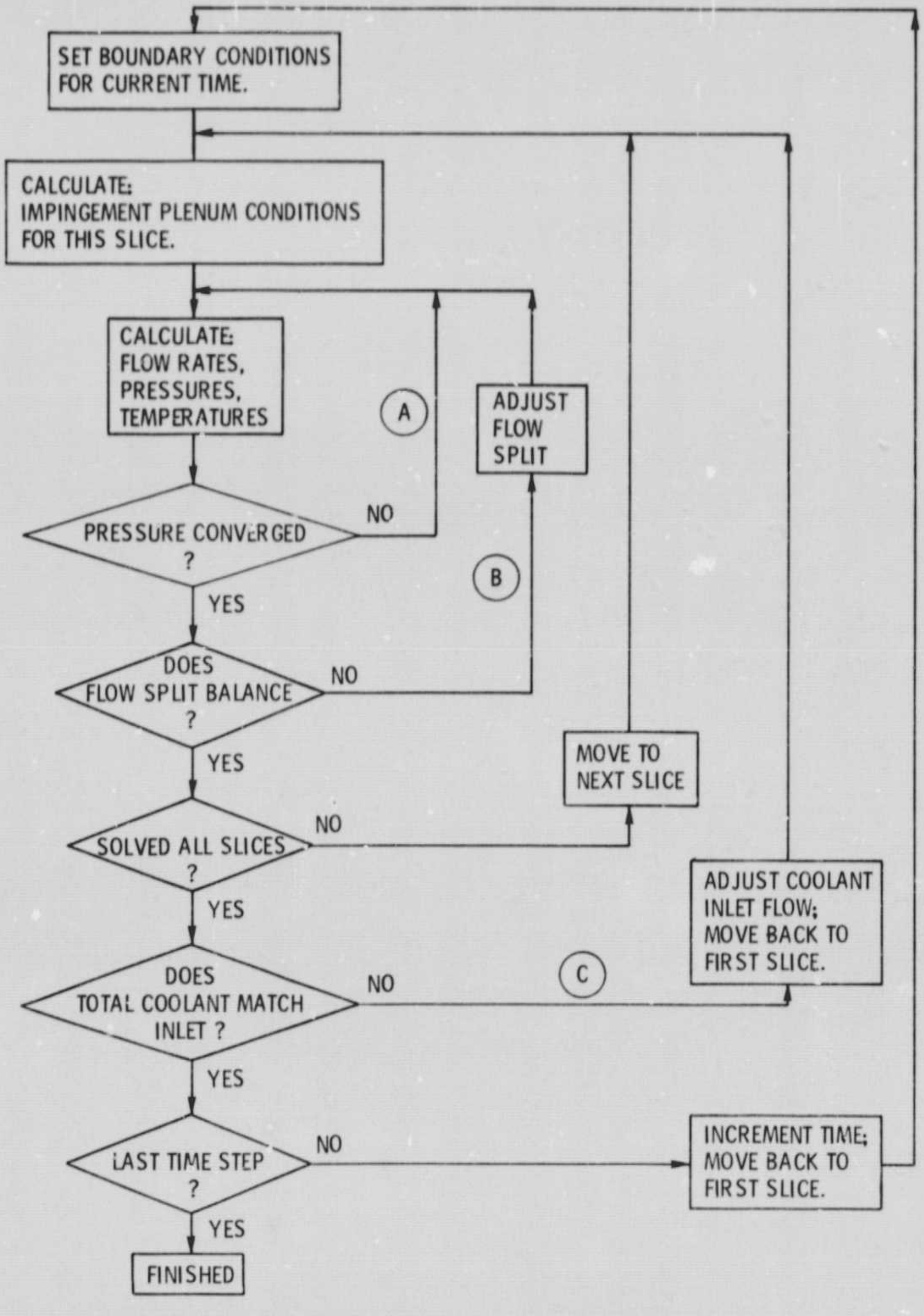

Figure 3. - Overall program flow chart.

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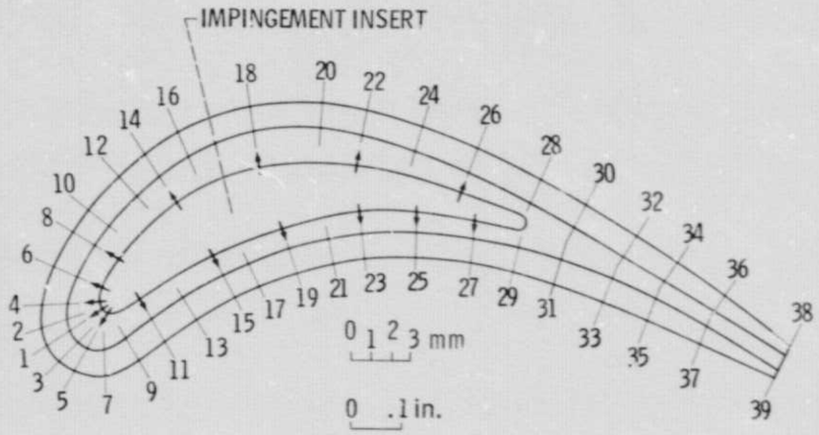

Figure 4. - Mid-span cross section of the blade for the sample problem.

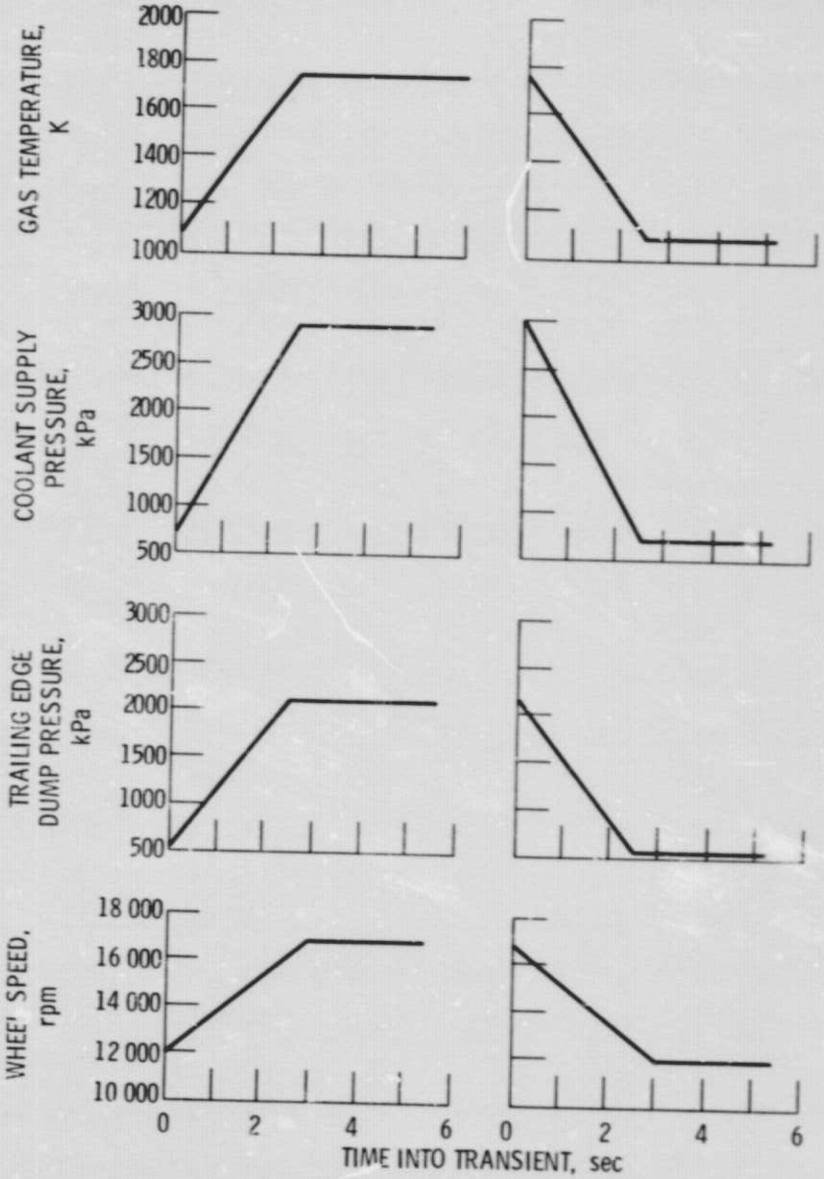

Figure 5. - Transient input for sample problem.

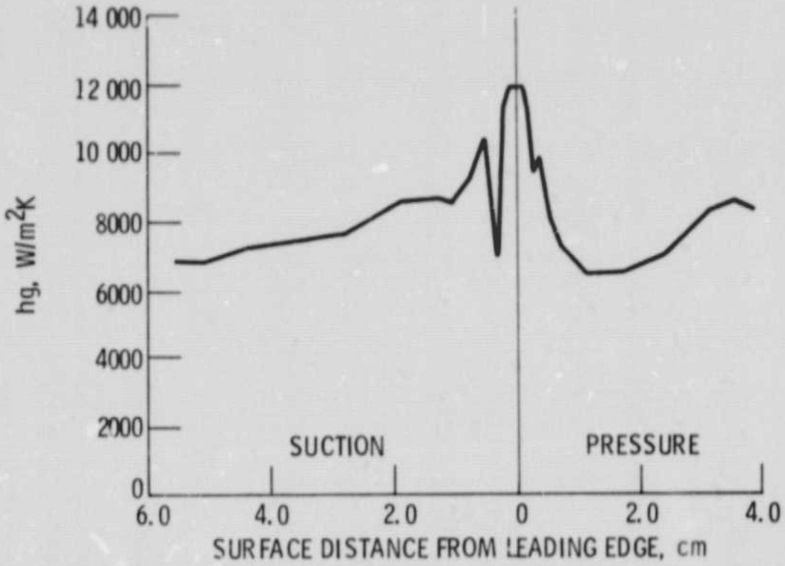

Figure 6. - Hot gas side heat transfer coefficient distribution.

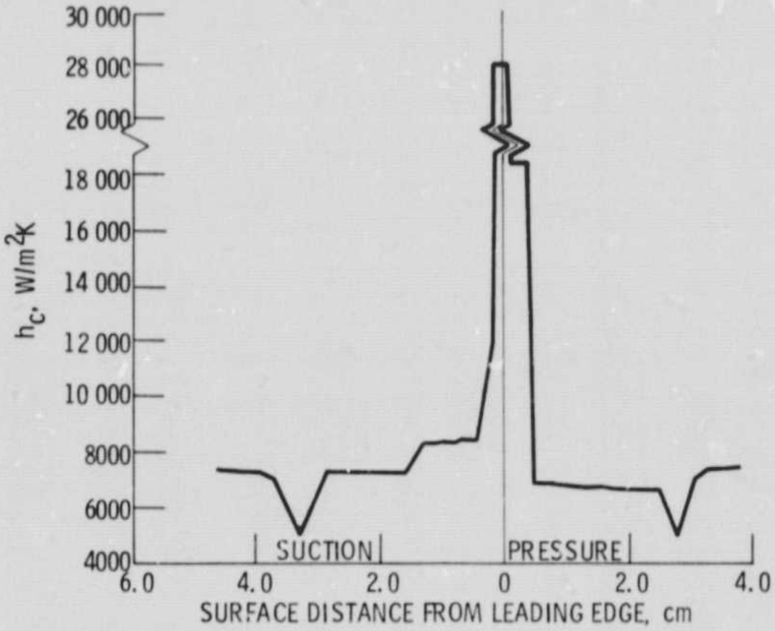

Figure 7. - Calculated mid-span coolant-side heat transfer coefficient distribution.

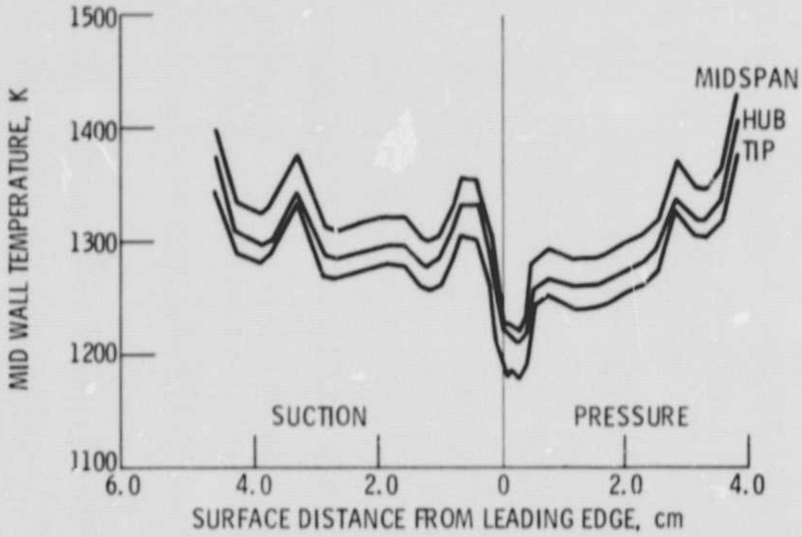

Figure 8. - Mid-wall steady state temperature distribution.

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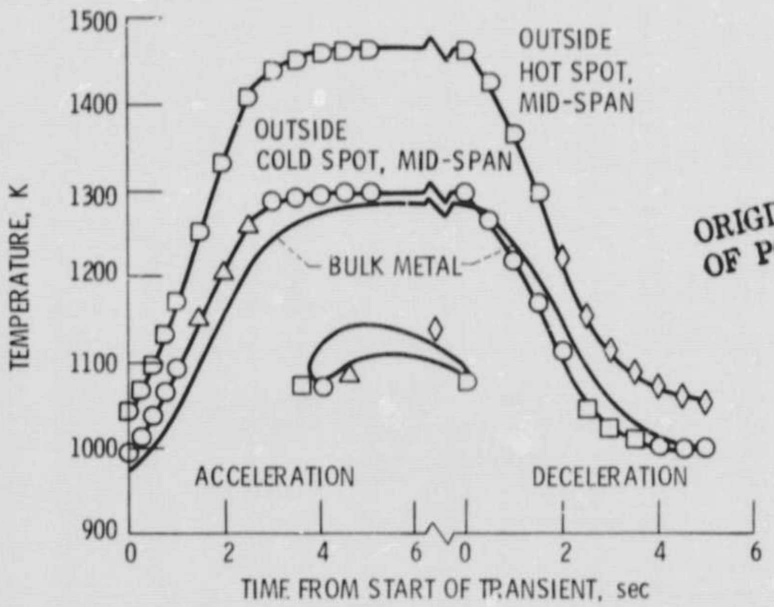

Figure 9. - Transient behavior of blade temperatures.

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