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FORTRAN PROGRAM FOR CALCULATING TOTAL-EFFICIENCY - SPECIFIC-SPEED CHARACTERISTICS OF CENTRIFUGAL COMPRESSORS

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16. Abstract

A computer program for predicting design point specific speed - efficiency characteristics of centrifugal compressors is presented with instructions for its use. The method permits rapid selection of compressor geometry that yields maximum total efficiency for a particular application. A numerical example is included to demonstrate the selection procedure.

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SUMMARY

A method of predicting design point specific speed - efficiency characteristics of centrifugal compressors is presented with the computer program developed for the analysis. The method is a one-dimensional mean streamline analysis conducted at fixed inlet stagnation conditions. Seven specific losses are calculated for each set of compressor geometric variables and inlet velocity diagram characteristics studied. The effect of these losses is then related to overall compressor performance and specific speed. By examining the program output the user can select values of inducer hub-tip diameter ratio, inducer tip-exit diameter ratio, impeller blade exit backsweep, impeller exit blade height-diameter ratio, and impeller exit absolute flow angle that will result in maximum total efficiency for the chosen application. A numerical example is included to demonstrate compressor geometry selection for maximum efficiency.

INTRODUCTION

Compressor efficiency has been shown to be a function of specific speed. Specific speed is a characteristic that relates compressor inlet volume flow rate, rotation speed, and ideal enthalpy rise. High efficiencies are generally associated with high specific speeds and low efficiencies with low specific speeds. Compressor design point geometries that produce maximum attainable efficiency are also functions of specific speed. Knowing the variation in optimum design point geometric variables with specific speed permits rapid selection of high efficiency configurations.

Balje (ref. 1) analytically correlated centrifugal compressor losses with specific speed and specific diameter. His major conclusions were that, for swirl-free centrifugal compressors, the optimum exit-inlet diameter ratio was primarily a function of specific diameter and that backswept impellers produced highest efficiency in the specific speed range of 0. 70 to 1. 02.

Another analytical method for predicting the variation in centrifugal compressor total efficiency with specific speed was described in reference 2. The velocity diagram characteristics and geometric variables that result in maximum total efficiency are presented as functions of specific speed for several impeller tip speeds. A FORTRAN program was developed for the study reported in reference 2 and is given here with instructions for its use.

For given inlet stagnation conditions, the user can generate efficiency, pressure ratio, specific speed, and relative loss distribution data corresponding to various combinations of impeller inlet velocity diagram characteristics and impeller overall geometries. By examining the output data a compressor geometry can be chosen which will yield maximum efficiency under the constraints imposed. The program can be used for working fluids other than air which approximate ideal gas behavior since the thermodynamic properties needed for the equations solved in the program are specified inputs.

ANALYSIS

The method of analysis is a one-dimensional mean streamline flow solution. Seven specific losses are calculated for each compressor configuration and specified inlet velocity diagram characteristics. These are inlet guide vane, blade loading, skin friction, disk friction, recirculation, vaneless diffuser, and vaned diffuser losses. Each of these individual losses is expressed as a decrement in compressor total efficiency.

The enthalpy loss across the inlet guide vanes is computed at the rms inlet diameter using the equation for boundary layer losses presented in reference 3.

The impeller losses due to blade loading and skin friction are calculated from the equations of reference 4.

Impeller recirculation loss is computed using a modified form of the equation presented in reference 4.

Disk friction loss is calculated by the method of reference 5.

Vaneless diffuser loss is determined by the numerical solution of the differential equations describing adiabatic flow in a radial passage derived in reference 6. These flow solutions were then used to solve the equation for total pressure presented in reference 4.

Vaned diffuser loss is calculated by determining pressure recovery attained in the vaned diffuser. Lines of maximum pressure recovery at a given area ratio were extrapolated from test data reported in reference 7. The pressure recovery coefficient corresponding to an assumed exit Mach number of 0.2 and throat conditions of Mach number and blockage was then determined by the iterative method described in reference 2.

INPUT INFORMATION

Input information may be classified into the following different categories: (1) compressor geometry, (2) thermodynamic properties of the working fluid, (3) velocity diagram characteristics, and (4) iteration limits. The compressor geometry inputs are (1) inducer tip diameter, (2) inducer hub-tip diameter ratio, and (3) impeller exit backsweep angles. The thermodynamic properties are (1) inlet stagnation temperature, (2) inlet stagnation pressure, (3) inlet stagnation dynamic viscosity, specific heat ratio, and gas constant of the working fluid, and (4) an estimated skin friction coefficient. The velocity diagram characteristics are (1) inducer tip speed, (2) inducer tip absolute critical velocity ratio, (3) impeller exit-inlet tip relative velocity ratio, (4) inducer tip speed, and (5) prewhirl tangential-inducer velocity ratio. The prewhirl used in this analysis is solid-body vortex. Hereafter, "prewhirl velocity ratio" will be used in its discussion with the understanding that it is solid-body vortex. For iterations on inducer tip absolute critical velocity ratio the inducer tip speed is adjusted to preserve inlet velocity triangle similarity with that determined by the first pair of input inducer tip speed and inducer tip absolute critical velocity ratio. That is, the absolute and relative flow angles are held constant for successive iterations (see fig. 1). The input iteration limits are the numbers of values of (1) inducer tip absolute critical velocity ratios, (2) prewhirl velocity ratios, (3) inducer tip-exit diameter ratios, (4) inducer hub-tip diameter ratios, and (5) impeller exit backsweep angles.

A numerical example is included to demonstrate use of the FORTRAN program. For the example case, a compressor with a total pressure ratio of 6 to 1 and a mass flow rate of approximately 0.9 kilogram per second was selected. Since high efficiency was of prime importance, a value of specific speed in the range of 0.9 to 1.0 was the preliminary target. This was determined by interpolation of the results reported in reference 2. The target range of specific speed was used to select an inducer tip diameter of 0.0861 meter and rotative speed of 75 000 rpm. An inducer hub-tip diameter ratio of

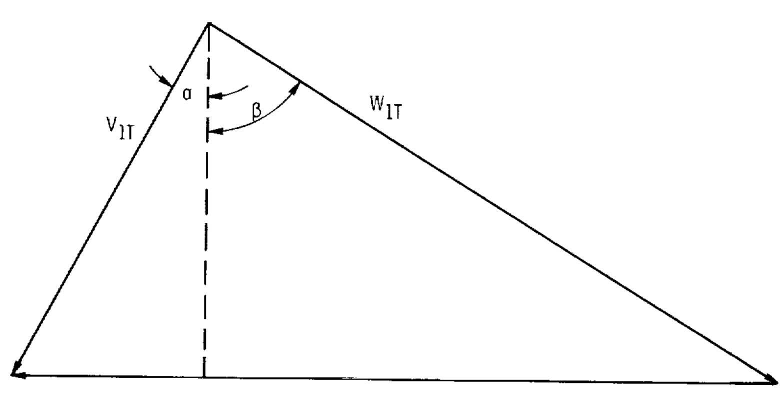

Figure 1. - Generalized inducer tip velocity triangle.

0.3 was chosen on the basis of mechanical considerations. This represented a practical limit because of the large blade thicknesses encountered at the inducer hub.

A one-dimensional continuity calculation (eqs. (B29) and (B31) to (B36)) indicated that an inlet Mach number of approximately 0.7 (V_{1T}/V_{cr} = 0.628) would result in good inducer velocity diagrams with ample margin in mass flow to allow for blockage due to blade thickness. Inducer tip-exit diameter ratios in the range 0.545 to 0.565 were considered for the pressure ratio of interest. Impeller exit backsweep angles of 0° to 45° were studied to determine which backsweep would produce greatest efficiency at the 6 to 1 pressure ratio. An inducer hub-tip diameter ratio of 0.35 was studied to determine whether aerodynamic improvements could be expected by increasing the selected ratio.

Input information which corresponds to the sample case is given in the following table:

Compressor geometry	
Inducer tip diameter, D_{1T}, m	0.0861
Inducer hub-tip diameter ratios, λ	0.3, 0.35
Inducer tip-exit diameter ratios, D_{1T}/D_2	0.54, 0.545, 0.55, 0.555, 0.56
Impeller exit backsweep angles, β_{2b}, deg from meridional	0, 5, 10, 15, 20, 25, 30, 35, 40, 45
Thermodynamic properties	
Inlet stagnation pressure, p_0', N/m^2	101 325.35
Inlet stagnation temperature, T_0', K	288.15
Inlet stagnation dynamic viscosity, μ_0', (N)(sec)/m^2	1.788×10^{-5}
Specific heat ratio, γ	1.4
Skin friction coefficient, C_f	0.004
Gas constant, R, J/(kg)(K)	287.04
Velocity diagram characteristics	
Inducer tip absolute critical velocity ratio, V_{1T}/V_{cr}	0.628
Prewhirl velocity ratio, $(V_u/u)_1$	0
Impeller exit-inlet tip relative velocity ratio, W_2/W_{1T}	0.7
Inducer tip speed, u_{1T}, m/sec	338.14
Iteration limits	
Number of values of inducer tip absolute critical velocity ratios	1
Number of values of inducer tip-exit diameter ratios	5
Number of values of inducer hub-tip diameter ratios	2
Number of values of impeller exit backsweep angles	10
Number of values of prewhirl velocity ratios	1

10	20	30	40	50	60	70
GAM	RGAS	POP	TOP	UIT	DIT	MU0
1.4	287.04	101325.35	288.0	338.14	0.0861	0.00001788
CF	W2OWIT					
0.004	0.7					
NVUT 4	NLAM 8	NDRAT 12	NVOVCR 16	NB2 20		
1	2	5	1	10		
DRAT ARRAY						
0.54	0.545	0.55	0.555	0.56		
LAM ARRAY						
0.3	0.35					
BETA2 ARRAY						
0.	5.	10.	15.	20.	25.	30.
35.	40.	45.				
VUT ARRAY						
0.						
VOVCR ARRAY						
0.628						

Figure 2. - Sample input sheet.

Additionally, if a working fluid other than air is used in the analysis, an empirical equation expressing the dynamic viscosity of a function of temperature must be substituted for those corresponding to equations (B59) and (B93).

A sample input sheet is shown in figure 2.

OUTPUT INFORMATION

Before the computation of compressor performance is started, a complete list of input is printed out. Then, for each iteration the following information is tabulated:

Compressor geometry

Inducer tip-exit diameter ratio, D_{1T}/D_2

Inducer hub-tip diameter ratio, λ

Impeller exit backsweep angle, β_{2b}, deg from meridional

Impeller exit blade height-diameter ratio, b_2/D_2

Velocity diagram characteristics

Inducer tip absolute critical velocity ratio, V_{1T}/V_{cr}

Prewhirl velocity ratio, $(V_u/u)_1$

Impeller exit absolute flow angle, α_2, deg from meridional

Compressor performance characteristics

Total efficiency, η

Individual decrements in efficiency, $\Delta\eta$

Total pressure ratio, PR

Specific speed, N_s

Head coefficient, ψ

Sample output for the example case is shown in the next section. A survey of the output data for the example indicated that maximum efficiency at the approximate pressure ratio of interest was attained at an inducer tip-exit diameter ratio of 0.555. Optimum impeller blade exit backsweep was 40° from meridional. Optimum impeller exit blade height-diameter ratio was 0.0306, and optimum inducer hub-tip diameter ratio was the initial selection of 0.3. This combination of geometric variables resulted in a compressor total pressure ratio of 6.07 and a total efficiency of 79.1 percent.

Head coefficient is an indication of the amount of deviation from maximum total efficiency at a given specific speed. By comparing the calculated value to a value interpolated from the figures of optimum head coefficient as a function of specific speed from reference 2, the relative penalty in off-optimum efficiency can be estimated.

SAMPLE OUTPUT

```
BEGIN EXECUTION.
  GAM           RGAS           POP           TOP           U1T           D1T          MUO
   1.4000       287.0400      101325.350     288.1500      338.1400      0.0861    0.00001780
  CF            W2OW1T          NVUT          NLAM          NDRAT         NVOVCR        NB2
   0.0040         0.7000          1             2             5             1           10
DRAT ARRAY
       0.5450     0.5500     0.5550     0.5600     0.5650
LAM ARRAY
       0.3000     0.3500
BETA2 ARRAY
       0.          5.0000    10.0000    15.0000    20.0000    25.0000    30.0000    35.0000
      40.0000     45.0000
VUT ARRAY
       0.
VOVCR ARRAY
       0.6280
```

INLET PREWHIRL (VU/U)1 0.   IMPELLER INLET TIP ABSOLUTE CRITICAL VELOCITY RATIO 0.6280   IMPELLER INLET-EXIT DIAMETER RATIO 0.5450

INLET HUB-TIP DIAMETER RATIO 0.3000

IMPELLER BACKSWEEP	IGV	EFFICIENCY DECREMENTS BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0220	0.0419	0.0304	0.0126	0.0677	0.1463	7.820	0.7854	0.0169	63.978	0.5722	0.6792
5.0000	0.	0.0222	0.0429	0.0317	0.0127	0.0589	0.1316	7.650	0.7938	0.0176	63.868	0.5642	0.7000
10.0000	0.	0.0225	0.0441	0.0330	0.0129	0.0509	0.1184	7.462	0.8038	0.0184	63.979	0.5548	0.7182
15.0000	0.	0.0228	0.0454	0.0343	0.0131	0.0436	0.1066	7.267	0.8148	0.0195	64.307	0.5448	0.7342
20.0000	0.	0.0232	0.0468	0.0355	0.0135	0.0371	0.0959	7.076	0.8264	0.0208	64.849	0.5346	0.7480
25.0000	0.	0.0236	0.0484	0.0366	0.0140	0.0314	0.0862	6.893	0.8383	0.0223	65.595	0.5246	0.7599
30.0000	0.	0.0240	0.0501	0.0377	0.0146	0.0263	0.0773	6.721	0.8500	0.0241	66.535	0.5149	0.7699
35.0000	0.	0.0245	0.0521	0.0386	0.0153	0.0219	0.0692	6.563	0.8615	0.0262	67.655	0.5058	0.7784
40.0000	0.	0.0251	0.0544	0.0394	0.0162	0.0180	0.0617	6.417	0.8727	0.0288	68.940	0.4972	0.7851
45.0000	0.	0.0257	0.0572	0.0401	0.0172	0.0147	0.0548	6.283	0.8836	0.0320	70.377	0.4891	0.7903

INLET HUB-TIP DIAMETER RATIO 0.3500

IMPELLER BACKSWEEP	IGV	EFFICIENCY DECREMENTS BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0218	0.0425	0.0314	0.0125	0.0652	0.1408	7.888	0.7684	0.0163	63.984	0.5751	0.6818
5.0000	0.	0.0221	0.0436	0.0328	0.0126	0.0603	0.1365	7.551	0.7854	0.0170	63.868	0.5585	0.6922
10.0000	0.	0.0223	0.0447	0.0341	0.0128	0.0521	0.1226	7.380	0.7945	0.0178	63.973	0.5500	0.7113
15.0000	0.	0.0227	0.0461	0.0354	0.0131	0.0447	0.1102	7.199	0.8048	0.0188	64.297	0.5406	0.7278
20.0000	0.	0.0230	0.0475	0.0367	0.0134	0.0381	0.0990	7.018	0.8158	0.0200	64.836	0.5309	0.7422
25.0000	0.	0.0235	0.0491	0.0379	0.0139	0.0322	0.0888	6.843	0.8271	0.0215	65.580	0.5213	0.7546
30.0000	0.	0.0239	0.0509	0.0390	0.0145	0.0270	0.0795	6.678	0.8384	0.0232	66.519	0.5120	0.7651
35.0000	0.	0.0244	0.0529	0.0399	0.0152	0.0225	0.0711	6.525	0.8494	0.0253	67.640	0.5031	0.7739
40.0000	0.	0.0250	0.0553	0.0408	0.0161	0.0185	0.0633	6.384	0.8602	0.0278	68.928	0.4947	0.7810
45.0000	0.	0.0256	0.0581	0.0414	0.0171	0.0151	0.0561	6.254	0.8707	0.0309	70.369	0.4867	0.7865

INLET PREWHIRL (VU/U1) 0.

IMPELLER INLET TIP ABSOLUTE CRITICAL VELOCITY RATIO 0.6280

IMPELLER INLET-EXIT DIAMETER RATIO 0.5500

INLET HUB-TIP DIAMETER RATIO 0.3000

IMPELLER BACKSWEEP	IGV	EFFICIENCY DECREMENTS BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0218	0.0422	0.0291	0.0124	0.0660	0.1422	7.714	0.7894	0.0175	63.747	0.5788	0.6863
5.0000	0.	0.0220	0.0433	0.0304	0.0125	0.0573	0.1282	7.527	0.7989	0.0182	63.612	0.5697	0.7064
10.0000	0.	0.0223	0.0445	0.0317	0.0127	0.0493	0.1156	7.326	0.8099	0.0191	63.696	0.5594	0.7240
15.0000	0.	0.0226	0.0458	0.0329	0.0129	0.0422	0.1042	7.121	0.8220	0.0201	64.000	0.5484	0.7393
20.0000	0.	0.0229	0.0473	0.0341	0.0133	0.0358	0.0939	6.921	0.8346	0.0214	64.520	0.5374	0.7527
25.0000	0.	0.0234	0.0489	0.0352	0.0138	0.0301	0.0846	6.730	0.8473	0.0230	65.247	0.5267	0.7641
30.0000	0.	0.0238	0.0507	0.0363	0.0143	0.0251	0.0760	6.552	0.8600	0.0248	66.172	0.5163	0.7738
35.0000	0.	0.0243	0.0528	0.0372	0.0150	0.0207	0.0682	6.389	0.8724	0.0271	67.282	0.5066	0.7819
40.0000	0.	0.0248	0.0552	0.0380	0.0159	0.0169	0.0609	6.239	0.8845	0.0297	68.564	0.4974	0.7883
45.0000	0.	0.0254	0.0580	0.0387	0.0169	0.0137	0.0542	6.102	0.8961	0.0330	70.006	0.4888	0.7932

INLET HUB-TIP DIAMETER RATIO 0.3500

IMPELLER BACKSWEEP	IGV	EFFICIENCY DECREMENTS BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0216	0.0429	0.0301	0.0123	0.0675	0.1477	7.603	0.7816	0.0169	63.753	0.5724	0.6779
5.0000	0.	0.0218	0.0439	0.0314	0.0124	0.0587	0.1329	7.435	0.7901	0.0175	63.612	0.5643	0.6988
10.0000	0.	0.0221	0.0452	0.0328	0.0126	0.0506	0.1196	7.249	0.8003	0.0184	63.692	0.5547	0.7172
15.0000	0.	0.0225	0.0465	0.0340	0.0129	0.0433	0.1077	7.056	0.8117	0.0194	63.991	0.5444	0.7332
20.0000	0.	0.0228	0.0480	0.0353	0.0132	0.0367	0.0969	6.866	0.8236	0.0207	64.507	0.5338	0.7471
25.0000	0.	0.0232	0.0497	0.0364	0.0137	0.0309	0.0871	6.684	0.8359	0.0222	65.231	0.5235	0.7590
30.0000	0.	0.0237	0.0515	0.0375	0.0143	0.0258	0.0781	6.512	0.8481	0.0240	66.155	0.5134	0.7691
35.0000	0.	0.0242	0.0536	0.0384	0.0150	0.0213	0.0699	6.354	0.8600	0.0261	67.267	0.5039	0.7775
40.0000	0.	0.0248	0.0560	0.0393	0.0158	0.0174	0.0624	6.208	0.8717	0.0287	68.552	0.4950	0.7843
45.0000	0.	0.0254	0.0589	0.0400	0.0168	0.0140	0.0554	6.074	0.8830	0.0318	69.998	0.4865	0.7894

INLET PREWHIRL (VU/U)1 0.

IMPELLER INLET TIP ABSOLUTE CRITICAL VELOCITY RATIO 0.6280

IMPELLER INLET-EXIT DIAMETER RATIO 0.5550

INLET HUB-TIP DIAMETER RATIO 0.3000

IMPELLER BACKSWEEP	IGV	BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
		EFFICIENCY DECREMENTS											
0.	0.	0.0215	0.0426	0.0279	0.0122	0.0643	0.1383	7.607	0.7936	0.0181	63.518	0.5852	0.6931
5.0000	0.	0.0218	0.0437	0.0292	0.0123	0.0557	0.1249	7.405	0.8042	0.0188	63.357	0.5750	0.7124
10.0000	0.	0.0221	0.0449	0.0304	0.0125	0.0478	0.1129	7.192	0.8162	0.0197	63.416	0.5637	0.7294
15.0000	0.	0.0224	0.0463	0.0316	0.0127	0.0408	0.1019	6.978	0.8293	0.0208	63.696	0.5519	0.7443
20.0000	0.	0.0227	0.0476	0.0328	0.0131	0.0344	0.0920	6.769	0.8428	0.0221	64.192	0.5401	0.7571
25.0000	0.	0.0231	0.0494	0.0339	0.0135	0.0288	0.0830	6.572	0.8566	0.0237	64.900	0.5286	0.7681
30.0000	0.	0.0236	0.0513	0.0349	0.0141	0.0239	0.0748	6.389	0.8702	0.0256	65.809	0.5176	0.7774
35.0000	0.	0.0241	0.0534	0.0358	0.0147	0.0196	0.0672	6.221	0.8835	0.0279	66.910	0.5072	0.7851
40.0000	0.	0.0246	0.0559	0.0366	0.0156	0.0159	0.0601	6.067	0.8964	0.0306	68.189	0.4975	0.7913
45.0000	0.	0.0252	0.0588	0.0373	0.0165	0.0127	0.0536	5.927	0.9089	0.0340	69.634	0.4884	0.7959

INLET HUB-TIP DIAMETER RATIO 0.3500

IMPELLER BACKSWEEP	IGV	BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
		EFFICIENCY DECREMENTS											
0.	0.	0.0214	0.0432	0.0285	0.0121	0.0658	0.1436	7.502	0.7855	0.0175	63.525	0.5791	0.6850
5.0000	0.	0.0216	0.0443	0.0302	0.0122	0.0571	0.1294	7.318	0.7951	0.0181	63.359	0.5697	0.7051
10.0000	0.	0.0219	0.0456	0.0315	0.0124	0.0491	0.1167	7.120	0.8064	0.0190	63.412	0.5592	0.7228
15.0000	0.	0.0223	0.0470	0.0327	0.0127	0.0419	0.1053	6.917	0.8187	0.0201	63.687	0.5480	0.7383
20.0000	0.	0.0226	0.0485	0.0339	0.0130	0.0354	0.0949	6.718	0.8317	0.0213	64.180	0.5366	0.7516
25.0000	0.	0.0230	0.0502	0.0351	0.0135	0.0297	0.0855	6.529	0.8449	0.0229	64.885	0.5255	0.7631
30.0000	0.	0.0235	0.0521	0.0361	0.0140	0.0246	0.0768	6.352	0.8580	0.0247	65.793	0.5148	0.7728
35.0000	0.	0.0240	0.0543	0.0370	0.0147	0.0202	0.0689	6.188	0.8709	0.0269	66.895	0.5047	0.7809
40.0000	0.	0.0245	0.0568	0.0379	0.0155	0.0163	0.0616	6.039	0.8834	0.0296	68.176	0.4951	0.7874
45.0000	0.	0.0251	0.0597	0.0386	0.0165	0.0130	0.0548	5.901	0.8955	0.0328	69.625	0.4862	0.7922

INLET PREWHIRL (VU/U1) 0.

IMPELLER INLET TIP ABSOLUTE CRITICAL VELOCITY RATIO 0.6280

IMPELLER INLET-EXIT DIAMETER RATIO 0.5600

INLET HUB-TIP DIAMETER RATIO 0.3000

IMPELLER BACKSWEEP	EFFICIENCY DECREMENTS IGV	BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0213	0.0429	0.0268	0.0120	0.0627	0.1347	7.498	0.7981	0.0187	63.292	0.5914	0.6995
5.0000	0.	0.0216	0.0440	0.0280	0.0121	0.0541	0.1219	7.283	0.8097	0.0195	63.105	0.5801	0.7182
10.0000	0.	0.0219	0.0453	0.0292	0.0123	0.0464	0.1103	7.060	0.8228	0.0204	63.139	0.5678	0.7346
15.0000	0.	0.0222	0.0467	0.0304	0.0125	0.0394	0.0998	6.837	0.8368	0.0215	63.394	0.5552	0.7490
20.0000	0.	0.0225	0.0483	0.0316	0.0129	0.0332	0.0903	6.622	0.8513	0.0228	63.867	0.5426	0.7613
25.0000	0.	0.0229	0.0500	0.0326	0.0133	0.0277	0.0816	6.420	0.8660	0.0245	64.555	0.5303	0.7719
30.0000	0.	0.0234	0.0519	0.0336	0.0138	0.0228	0.0736	6.232	0.8806	0.0264	65.449	0.5187	0.7809
35.0000	0.	0.0239	0.0541	0.0345	0.0145	0.0186	0.0662	6.060	0.8948	0.0287	66.539	0.5077	0.7882
40.0000	0.	0.0244	0.0566	0.0353	0.0153	0.0149	0.0594	5.902	0.9086	0.0315	67.814	0.4974	0.7941
45.0000	0.	0.0250	0.0596	0.0360	0.0162	0.0117	0.0478	5.810	0.9174	0.0350	69.262	0.4911	0.8037

INLET HUB-TIP DIAMETER RATIO 0.3500

IMPELLER BACKSWEEP	EFFICIENCY DECREMENTS IGV	BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0212	0.0435	0.0277	0.0120	0.0642	0.1397	7.400	0.7897	0.0181	63.300	0.5854	0.6917
5.0000	0.	0.0214	0.0447	0.0290	0.0120	0.0555	0.1262	7.202	0.8004	0.0188	63.108	0.5750	0.7111
10.0000	0.	0.0217	0.0460	0.0302	0.0122	0.0476	0.1140	6.992	0.8126	0.0196	63.135	0.5634	0.7282
15.0000	0.	0.0221	0.0474	0.0314	0.0125	0.0405	0.1030	6.780	0.8260	0.0207	63.385	0.5514	0.7431
20.0000	0.	0.0224	0.0490	0.0326	0.0128	0.0341	0.0930	6.574	0.8399	0.0220	63.855	0.5392	0.7560
25.0000	0.	0.0228	0.0508	0.0337	0.0132	0.0284	0.0839	6.379	0.8540	0.0236	64.540	0.5273	0.7671
30.0000	0.	0.0233	0.0527	0.0348	0.0138	0.0235	0.0756	6.197	0.8681	0.0255	65.433	0.5160	0.7764
35.0000	0.	0.0238	0.0550	0.0357	0.0144	0.0191	0.0679	6.029	0.8819	0.0277	66.523	0.5052	0.7841
40.0000	0.	0.0243	0.0575	0.0365	0.0152	0.0153	0.0608	5.875	0.8953	0.0304	67.800	0.4952	0.7902
45.0000	0.	0.0249	0.0606	0.0372	0.0162	0.0121	0.0488	5.787	0.9037	0.0338	69.253	0.4890	0.8002

INLET PREWHIRL (VL/U1)
0.

IMPELLER INLET TIP ABSOLUTE CRITICAL VELOCITY RATIO
0.6280

IMPELLER INLET-EXIT DIAMETER RATIO
0.5650

INLET HUB-TIP DIAMETER RATIO
0.3000

IMPELLER BACKSWEEP	IGV	EFFICIENCY DECREMENTS BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0211	0.0432	0.0258	0.0119	0.0611	0.1312	7.389	0.8028	0.0194	63.068	0.5973	0.7057
5.0000	0.	0.0214	0.0444	0.0269	0.0119	0.0526	0.1190	7.163	0.8154	0.0201	62.856	0.5850	0.7238
10.0000	0.	0.0217	0.0457	0.0281	0.0121	0.0450	0.1079	6.930	0.8295	0.0210	62.864	0.5718	0.7396
15.0000	0.	0.0220	0.0471	0.0293	0.0123	0.0381	0.0978	6.700	0.8445	0.0222	63.094	0.5583	0.7534
20.0000	0.	0.0223	0.0487	0.0304	0.0127	0.0319	0.0886	6.479	0.8600	0.0236	63.544	0.5449	0.7654
25.0000	0.	0.0227	0.0505	0.0314	0.0131	0.0265	0.0802	6.271	0.8756	0.0252	64.212	0.5320	0.7756
30.0000	0.	0.0232	0.0525	0.0324	0.0136	0.0217	0.0725	6.079	0.8911	0.0272	65.089	0.5197	0.7841
35.0000	0.	0.0237	0.0547	0.0333	0.0142	0.0176	0.0653	5.904	0.9063	0.0296	66.168	0.5081	0.7912
40.0000	0.	0.0242	0.0573	0.0341	0.0150	0.0140	0.0535	5.794	0.9165	0.0325	67.439	0.5006	0.8020
45.0000	0.	0.0248	0.0604	0.0348	0.0159	0.0108	0.0473	5.647	0.9307	0.0360	68.889	0.4904	0.8060

INLET HUB-TIP DIAMETER RATIO
0.3500

IMPELLER BACKSWEEP	IGV	EFFICIENCY DECREMENTS BL	SF	DF	RC	VLD	VD	PRESSURE RATIO	SPECIFIC SPEED	B2/D2	ALPHA 2	HEAD COEFFICIENT	TOTAL EFFICIENCY
0.	0.	0.0210	0.0439	0.0266	0.0118	0.0626	0.1361	7.296	0.7941	0.0187	63.076	0.5915	0.6981
5.0000	0.	0.0212	0.0451	0.0278	0.0119	0.0540	0.1232	7.086	0.8058	0.0194	62.859	0.5800	0.7168
10.0000	0.	0.0215	0.0464	0.0291	0.0120	0.0462	0.1115	6.866	0.8191	0.0203	62.861	0.5675	0.7333
15.0000	0.	0.0219	0.0479	0.0302	0.0123	0.0391	0.1009	6.647	0.8334	0.0214	63.086	0.5546	0.7477
20.0000	0.	0.0222	0.0495	0.0314	0.0126	0.0329	0.0913	6.434	0.8483	0.0227	63.532	0.5416	0.7601
25.0000	0.	0.0226	0.0513	0.0325	0.0130	0.0273	0.0825	6.233	0.8634	0.0243	64.197	0.5291	0.7708
30.0000	0.	0.0231	0.0533	0.0335	0.0135	0.0224	0.0744	6.046	0.8784	0.0262	65.073	0.5170	0.7797
35.0000	0.	0.0236	0.0556	0.0344	0.0142	0.0181	0.0670	5.875	0.8931	0.0286	66.153	0.5057	0.7871
40.0000	0.	0.0241	0.0583	0.0353	0.0150	0.0144	0.0547	5.770	0.9028	0.0313	67.425	0.4985	0.7984
45.0000	0.	0.0247	0.0614	0.0360	0.0159	0.0112	0.0483	5.625	0.9167	0.0348	68.879	0.4884	0.8026

ERROR MESSAGES

Two major errors can be encountered in the use of this program. A poor combination of inlet flow velocity, prewhirl velocity ratio, inducer tip speed, impeller inlet tip-exit diameter ratio, and impeller relative velocity ratio will result in impeller exit velocity diagram characteristics for which a velocity triangle cannot be calculated. In this case calculation of the flow solution downstream of the impeller exit is deleted and the printout for the irrational combination of variables is suppressed. The second major error is the lack of convergence of the calculated values of vaned diffuser area ratio required to decelerate the flow to an exit Mach number of 0.2. Values of vaned diffuser inlet blockage and Mach number can result in the interpolation of pressure recovery coefficients for which the specified exit Mach number cannot be attained within an area ratio of 5.0. When this happens, AREA RATIO IS NOT IN BOUNDS is printed out.

FORTRAN PROGRAM

The FORTRAN listing, input and output samples, and definitions of the FORTRAN variables are given in this section. For each combination of input variables the main program calculates overall compressor design point performance from empirical loss estimates and adiabatic flow relations using a mean streamline one-dimensional analysis.

Program Input

Input variables are shown in this section with the definitions of the FORTRAN variables used. These variables appear in the section Main Program FORTRAN Variables and Engineering Symbols but are repeated here for the convenience of the user.

GAM	specific heat ratio, γ
P0P	inlet stagnation pressure, p'_0, N/m^2
T0P	inlet stagnation temperature, T'_0, K
RGAS	gas constant, R, J/(kg)(K)
U1T	inducer tip speed, u_{1T}, m/sec
D1T	inducer tip diameter, D_{1T}, m
MU0	inlet stagnation dynamic viscosity, μ'_0
CF	skin friction coefficient, C_f

VOVCR(I)	inducer tip absolute critical velocity ratio, V_{1T}/V_{cr}
VUT(J)	inlet solid body prewhirl tangential-inducer velocity ratio, $(V_u/u)_1$
DRAT(K)	inlet tip-exit diameter ratio, D_{1T}/D_2
LAM(L)	hub-tip diameter ratio, λ
B2(M)	impeller exit blade angle, β_{2b}
NVOVCR	number of values of V_{1T}/V_{cr} of interest
NVUT	number of values of $(V_u/u)_1$ of interest
NLAM	number of values of λ of interest
NB2	number of values of β_{2b} of interest
W2OW1T	impeller exit-inlet tip relative velocity ratio, W_2/W_{1T}

FORTRAN Listing

```
$IBFTC MAIN
C      FORTRAN PROGRAM FOR CALCULATING TOTAL EFFICIENCY-SPECIFIC SPEED
C      CHARACTERISTICS OF CENTRIFUGAL COMPRESSORS
       DIMENSION VOVCR(8),VUT(8)
       DIMENSION DRAT(16),LAM(16),BETA2(16)
       DIMENSION P3P(20),RARRAY(20),XMARR(20)
       DIMENSION F(20),S(20)
       DIMENSION AMT(4),BARR(6),PREC1(4,6),PREC2(4,6),PREC3(4,6)
       DIMENSION PREC4(4,6),PREC5(4,6)
       EXTERNAL FUNCT
       REAL LAM,MUO,LAMX,LOD
     1 READ(5,510) GAM,RGAS,POP,TOP,U1T,D1T,MUO
       READ(5,510) CF,W2OW1T
       READ(5,511) NVUT,NLAM,NDRAT,NVOVCR,NB2
       READ(5,510) (DRAT(I),I=1,NDRAT)
       READ(5,510) (LAM(I),I=1,NLAM)
       READ(5,510) (BETA2(I),I=1,NB2)
       READ(5,510) (VUT(I),I=1,NVUT)
       READ(5,510) (VOVCR(I),I=1,NVOVCR)
       WRITE(6,520) GAM,RGAS,POP,TOP,U1T,D1T,MUO
       WRITE(6,521) CF,W2OW1T,NVUT,NLAM,NDRAT,NVOVCR,NB2
       WRITE(6,522) (DRAT(I),I=1,NDRAT)
       WRITE(6,523) (LAM(I),I=1,NLAM)
       WRITE(6,524) (BETA2(I),I=1,NB2)
       WRITE(6,525) (VUT(I),I=1,NVUT)
       WRITE(6,526) (VOVCR(I),I=1,NVOVCR)
       DATA(AMT(I),I=1,4)/.2,.4,.6,.8/
       DATA(BARR(I),I=1,6)/.02,.04,.06,.08,.10,.12/
       DATA((PREC1(I,J),I=1,4),J=1,6)/.234,.244,.257,.269,.215,.224,.233,
      1.243,.207,.215,.223,.232,.193,.199,.206,.212,.183,.190,.196,.202,.
      2169,.176,.182,.188/
       DATA((PREC2(I,J),I=1,4),J=1,6)/.644,.670,.696,.722,.620,.638,.656,
```

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1.674,.590,.606,.623,.639,.562,.576,.590,.605,.538,.551,.564,.578,.
2510,.524,.536,.552/
 DATA((PREC3(I,J),I=1,4),J=1,6)/.782,.789,.796,.802,.750,.756,.762,
1.768,.708,.716,.724,.732,.672,.680,.687,.695,.652,.648,.654,.660,.
2604,.612,.619,.626/
 DATA((PREC4(I,J),I=1,4),J=1,6)/.842,.838,.833,.828,.8,.8,.8,.8,.75
12,.756,.760,.763,.710,.713,.716,.719,.675,.678,.680,.683,.630,.635
2,.640,.646/
 DATA((PREC5(I,J),I=1,4),J=1,6)/.878,.865,.852,.838,.832,.825,.818,
1.812,.78,.78,.78,.78,.736,.735,.735,.734,.692,.694,.695,.696,.644,
2.647,.650,.652/
 G2=GAM-1.
 G1=GAM+1.
 CP=GAM*RGAS/G2
 DO 100 I=1,NVOVCR
 DO 100 J=1,NVUT
 OMEGA=2.*U1T*VOVCR(I)/VOVCR(1)/D1T
 VCR=SQRT(2.*GAM/G1*RGAS*TOP)
 V1T=VOVCR(I)*VCR
 AL1=ARSIN(VUT(J)*U1T*VOVCR(I)/VOVCR(1)/V1T)
 SINA=SIN(AL1)
 COSA=COS(AL1)
 VM1=V1T*COSA
 WU1T=U1T*(1.-VUT(J))*VOVCR(I)/VOVCR(1)
 B1=ATAN(WU1T/VM1)
 W1T=VM1**2+WU1T**2
 W1T=SQRT(W1T)
 XKJ=VM1**2+2.*(VUT(J)*U1T*VOVCR(I)/VOVCR(1))**2
 W2=W20W1T*W1T
 DO 100 K=1,NDRAT
 WRITE(6,500)
 WRITE(6,501) VUT(J),VOVCR(I),DRAT(K)
 DRT=1./DRAT(K)
 U2=U1T*VOVCR(I)/VOVCR(1)*DRT
 D2 = D1T*DRT
 DO 100 L=1,NLAM
 WRITE(6,502)
 WRITE(6,503) LAM(L)
 WRITE(6,504)
 LAMX=LAM(L)
 U1H=LAMX*U1T*VOVCR(I)/VOVCR(1)
 D1H=LAMX*D1T
 VU1H=LAMX*VUT(J)*U1T*VOVCR(I)/VOVCR(1)
 VM1H=SQRT(XKJ-2.*VU1H**2)
 WU1H=U1H-VU1H
 B1H=ATAN(WU1H/VM1H)
 W1H=SQRT(VM1H**2+WU1H**2)
 DMF=SQRT(D1T**2*(1.+LAMX**2)/2.)
 U1MF=U1T*VOVCR(I)/VOVCR(1)*DMF/D1T
 VU1MF=DMF/D1T*VUT(J)*U1T*VOVCR(I)/VOVCR(1)
 VM1MF=SQRT(XKJ-2.*VU1MF**2)
 AL1MF=ATAN(VU1MF/VM1MF)
 V1MF=SQRT(VU1MF**2+VM1MF**2)
 WU1MF=U1MF-VU1MF
 W1MF=SQRT(VM1MF**2+WU1MF**2)
 B1MF=ATAN(WU1MF/VM1MF)
 T1M=TOP-V1MF**2/2./CP
 B1AV= (B1+B1MF+B1H)/3.
 DHIGV=0.
```

```
      P1P=POP
      PPCP1=(1.+V1MF**2/2./CP/T1M)**(GAM/G2)
      POPP1=1./PPCP1
      P1=P1P*POPP1
      R1P=P1P/RGAS/TOP
      R1 = R1P*(P1/P1P)**(1./GAM)
      Q=3.14159*D1T**2*(1.-LAMX**2)*VM1MF/4.
      SW=Q*R1
      ROP=POP/RGAS/TOP
      RE=U2*D2/MUO*ROP
      T1PP=T1M+W1MF**2/2./CP
      T2PP=T1PP+(U2**2-U1MF**2)/2./CP
      T2=T2PP-W2**2/2./CP
      A2=SQRT(GAM*RGAS*T2)
      PHI=VM1MF/U2
      WOU2=(PHI**2+(DMF/D2)**2+W2OW1T**2*(PHI**2+DRAT(K)**2))/2.
      IF(VOT(J).LT..01) GO TO 90
      ALSTAG=AL1MF/2.
      SINX=SIN(AL1MF)
      COSX=COS(AL1MF)
      ES=.0076/(COSX-.025)*(1.+COS(ALSTAG)/.7)
      AKE=V1MF**2/2.
      AKEID=AKE/(1.-ES)
      POPP1=(1.-AKE/CP/TOP)**(GAM/G2)
      P1OPPO=(1.-AKEID/CP/TOP)**(GAM/G2)
      P1P=POP*P1OPPO/POPP1
      R1P=P1P/RGAS/TOP
      P1=P1P*POPP1
      R1 = R1P*(P1/P1P)**(1./GAM)
      SW=Q*R1
      RV=R1*VM1MF
      PARA=RV/ROP/VCR
      AMSTAR=0.10
   11 Y=FUNCT(AMSTAR,G1,G2)-PARA
      AMSTAR=AMSTAR+.001
      IF(Y.LT.0.) GO TO 11
      VO=AMSTAR*VCR
      AMU=9.7965E-7*T1M**1.5/(T1M+110.4)
      REO=SW/AMU/D1T
      DHIGV=0.4*SINX*(VO**2+V1MF**2)/2./COSX/REO**.2
   90 CONTINUE
      DO 101 M=1,NB2
      B2X=BETA2(M)*.01745
      Z=6.5*(1.+DMF/D2)/(1.-DMF/D2)*COS((B1AV+B2X)/2.)
      EPSLIM=1./EXP(8.16*COS(B2X)/Z)
      VSL=SQRT(COS(B2X))*U2/Z**.7
      IF((DMF/D2).GT.EPSLIM) VSL=U2*(SQRT(COS(B2X))/Z**.7)*(1.-((DMF/D2-
     1EPSLIM)/(1.-EPSLIM))**3)+U2*((DMF/D2-EPSLIM)/(1.-EPSLIM))**3
      IF((VSL*COS(B2X)/W2).GT.1.) GO TO 101
      DELTA=ARSIN(VSL*COS(B2X)/W2)
      W2ID=W2*COS(B2X+DELTA)/COS(B2X)
      VU2=U2-VSL-W2ID*SIN(B2X)
      VM2=W2ID*COS(B2X)
      IF(VM2.LT.0.) GO TO 101
      IF(VU2.LT.0.) GO TO 101
      AL2=ATAN(VU2/VM2)
      WU2=U2-VU2
      V2=SQRT(VU2**2+VM2**2)
      T2P=T2+V2**2/2./CP
```

```
      DHAERO=CP*TOP*(T2P/TOP-1.)
      QTH=DHAERO/U2**2
      DF=  W1T/U2*(Z/3.14159*(1.-D1T/D2)+2.*D1T/D2)
      DF=1.-W2OW1T+0.75*QTH/DF
      DHBL=0.05*DF**2*U2**2
      DHRC=0.02*SQRT(TAN(AL2))*DF**2*U2**2
      LOD=(1.-DMF/.3048)/COS(B2X)/2.
      R2G=R1*(T2/T1M)**(1./G2)
   50 RHO2=R2G
      DHDF=.013561*RHO2*U2**3*D2**2/SW/RE**.2
      B2=SW/(3.14159*RHO2*D2*VM2)
      DHYD=Z/3.14159/COS(B2X)+D2/B2
      DHYD=1./DHYD+D1T/D2/(2./(1.-LAMX)+2.*Z/3.14159/(1.+LAMX)
     1*SQRT(1.+(1.+LAMX**2)/2.*(TAN(B1))**2))
      DHSF=5.6*CF*LOD/DHYD*WOU2*U2**2
      DHACT=DHAERO+DHDF+DHRC
      DHID=DHAERO-DHIGV-DHBL-DHSF
      ETAR=DHID/DHAERO
      TX=ETAR*DHAERO/CP/TOP+1.
   51 P2P=TX**(GAM/G2)*P1P
      P2=P2P*(T2P/T2)**(-GAM/G2)
      R2G=P2/RGAS/T2
      IF(ABS((R2G-RHO2)/R2G).GT..001) GO TO 50
      XM2= V2/A2
      R2=D2/2.
      AMU=9.7965E-7*T2**1.5/(T2+110.4)
      ANU=AMU/R2G
      B0=1.
      XM=XM2
      ALPHA=AL2
      NO=1
      R=1.0
      F(1)=XM2**3/(1.+G2/2.*XM2**2)**(GAM/G2)*R
      P3P(1)=P2P
      RARRAY(1)=1.0
      XMARR(1)=XM2
      DELTAR=0.02
      ZETA=CF*R2/B2
   20 NO=NO+1
      JAN=1
      XM1=XM
      ALPH1=ALPHA
   21 DELTAS=0.37*DELTAR*R2/8./COS(ALPHA)/(V2*DELTAR*R2/COS(ALPHA)/ANU)*
     1*.2
      B=B0-2.*DELTAS/B2
      DELTAB=B0-B
      VARM=-2.*(1.+G2/2.*XM**2)/(XM**2-1./COS(ALPHA)**2)*((GAM*XM**2-TAN
     1(ALPHA)**2)*ZETA/B0/COS(ALPHA)-1./B0*DELTAB/DELTAR-1./COS(ALPHA)**
     22/R)*XM**2*DELTAR
      VARAL=1./COS(ALPHA)**2/(XM**2-(1./COS(ALPHA))**2)*((1.+G2/2.*XM**2
     1)*ZETA/B0/COS(ALPHA)-1./B0*DELTAB/DELTAR-XM**2/R)*TAN(ALPHA)*DELTA
     2R
      B0=B
      IF(JAN.EQ.1) VARAL1=VARAL
      IF(JAN.EQ.1) VARM1=VARM
      IF(JAN.EQ.2) GO TO 22
      XM=XM**2+VARM
      XM=SQRT(XM)
      TALPH=TAN(ALPHA)+VARAL
```

```
      ALPHA=ATAN(TALPH)
      JAN=JAN+1
      R=R+DELTAR
      GO TO 21
   22 VARAL=(VARAL1+VARAL)/2.
      TALPH=TAN(ALPH1)+VARAL
      ALPHA=ATAN(TALPH)
      VARM=(VARM1+VARM)/2.
      XM=XM1**2+VARM
      XM=SQRT(XM)
      ACOUSR=1./(1.+G2/2.*XM**2)
      RHOR=1./(1.+G2/2.*XM**2)**(1./G2)
      F(NO)=XM**3*ACOUSR*RHOR*R
      IF(NO.EQ.2) S(NO)=(F(NO)+F(NO-1))*0.5*DELTAR
      IF(NO.EQ.2) GO TO 23
      CALL FNTGRL(NO,.02,F,S)
   23 TPL=1./(1.+GAM*CF*R2*S(NO)/COS(AL2)/B2/XM2*(1.+G2/2.*XM2**2)**(GAM
     1/G2))
      PP=TPL*P2P
      P3P(NO)=PP
      RARRAY(NO)=R
      XMARR(NO)=XM
      IF(XM.GT.0.8) GO TO 20
      RVANE=(XMARR(NO-1)-0.8)/(XMARR(NO-1)-XMARR(NO))*(RARRAY(NO)-RARRAY
     1(NO-1))+RARRAY(NO-1)
      PTHP=(RVANE-RARRAY(NO-1))/.02*(P3P(NO-1)-P3P(NO))
      PTHP=P3P(NO-1)-PTHP
      XMACH=(RVANE-RARRAY(NO-1))/.02*(XMARR(NO-1)-XMARR(NO))
      XMACH=XMARR(NO-1)-XMACH
      IF(XMARR(1).LE.0.8) XMACH=XMARR(2)
      IF(XMARR(1).LE.0.8) PTHP=P3P(2)
      PTH=PTHP/(1.+G2/2.*XMACH**2)**(GAM/G2)
      DHVLD=CP*T2P*((PTH/PTHP)**(G2/GAM)-(PTH/P2P)**(G2/GAM))
      BT=1.-B
      AR=XMACH/0.2*((1.+G2/2.*0.04)/(1.+G2/2.*XMACH**2))**(G1/2./G2)
      PPEXIT=PTHP
   70 AR1=AR
      ARNUM=AR*PPEXIT
      IF((AR-1.2).GT.0..AND.(AR-2.).LT.0.) GO TO 60
      IF((AR-2.).GT.0..AND.(AR-3.).LT.0.) GO TO 61
      IF((AR-3.).GT.0..AND.(AR-4.).LT.0.) GO TO 62
      IF((AR-4.).GT.0..AND.(AR-5.).LT.0.) GO TO 63
      WRITE(6,110)
  110 FORMAT(28H AREA RATIO IS NOT IN BOUNDS)
      GO TO 102
   60 CALL LININT (XMACH,BT,AMT,BARR,PREC1,4,6,F1)
      CALL LININT (XMACH,BT,AMT,BARR,PREC2,4,6,F2)
      CPSTAR=(AR-1.2)/.8*(F2-F1)+F1
      GO TO 68
   61 CALL LININT (XMACH,BT,AMT,BARR,PREC2,4,6,F2)
      CALL LININT (XMACH,BT,AMT,BARR,PREC3,4,6,F3)
      CPSTAR=(AR-2.)*(F3-F2)+F2
      GO TO 68
   62 CALL LININT (XMACH,BT,AMT,BARR,PREC3,4,6,F3)
      CALL LININT (XMACH,BT,AMT,BARR,PREC4,4,6,F4)
      CPSTAR=(AR-3.)*(F4-F3)+F3
      GO TO 68
   63 CALL LININT (XMACH,BT,AMT,BARR,PREC4,4,6,F4)
      CALL LININT (XMACH,BT,AMT,BARR,PREC5,4,6,F5)
      CPSTAR=(AR-4.)*(F5-F4)+F4
```

```
68 PEXIT=CPSTAR*(PTHP-PTH)+PTH
   PPEXIT=PEXIT*(1.+G2/2.*0.04)**(GAM/G2)
   AR=ARNUM/PPEXIT
   IF(ABS(AR1-AR).LT..001) GO TO 69
   GO TO 70
69 DHVD =T2P*CP*((PEXIT/PPEXIT)**(G2/GAM)-(PEXIT/PTHP)**(G2/GAM))
   ETAD=(DHAERO-DHSF-DHBL-DHVLD-DHVD-DHIGV)/DHACT
   B2D2=B2/D2
   PR=PPEXIT/POP
   HID=ETAD*DHAERO
   PSI=HID/U2**2
   XNS=OMEGA*SQRT(Q)/HID**.75
   DEIGV=DHIGV/DHACT
   DEBL=DHBL/DHACT
   DESF=DHSF/DHACT
   DEDF=DHDF/DHACT
   DERC=DHRC/DHACT
   DEVLD=DHVLD/DHACT
   DEVD=DHVD/DHACT
   AL2=AL2*57.29577
   WRITE(6,505) BETA2(M),DEIGV,DEBL,DESF,DEDF,DERC,DEVLD,DEVD,PR,XNS,
  1B2D2,AL2,PSI,ETAD
500 FORMAT(   23H1INLET PREWHIRL (VU/U)1,5X,51HIMPELLER INLET TIP ABSO
   1LUTE CRITICAL VELOCITY RATIO,5X,34HIMPELLER INLET-EXIT DIAMETER RA
   2TIO)
501 FORMAT(10X,F10.4,32X,F10.4,32X,F10.4)
502 FORMAT(39X,29H INLET HUB-TIP DIAMETER RATIO)
503 FORMAT(48X,F10.4)
504 FORMAT(9H IMPELLER,2X,54H----------------EFFICIENCY DECREMENTS----
   1-------------,3X,8HPRESSURE,3X,8HSPECIFIC,25X,4HHEAD,9X,5HTOTAL/,1
   20H BACKSWEEP,3X,3HIGV,5X,2HBL,6X,2HSF,6X,2HDF,6X,2HRC,6X,3HVLD,6X,
   32HVD,6X,5HRATIO,7X,5HSPEED,4X,5HB2/D2, 4X,7HALPHA 2,2X,11HCOEFFICI
   4ENT,2X,10HEFFICIENCY)
505 FORMAT(F10.4,1X,F6.4,2X,F6.4,2X,F6.4,2X,F6.4,2X,F6.4,2X,F6.4,2X,F6
   1.4,3X,F8.3,3X,F8.4,3X,F6.4,3X,F7.3,2X,F10.4, 5X,F6.4)
510 FORMAT(8F10.4)
511 FORMAT(5I4)
520 FORMAT(4X,3HGAM,12X,4HRGAS,12X,3HPCP,12X,3HTCP,12X,3HU1T,12X,3HD1T
   1,12X,3HMU0/,1X,F10.4,5X,F10.4,5X,F10.3,5X,F10.4,5X,F10.4,5X,F10.4,
   25X,F10.8)
521 FORMAT(4X,2HCF,12X,6HW2QW1T,10X,4HNVUT,11X,4HNLAM,11X,5HNDRAT,10X,
   16HNVOVCR,10X,3HNB2/,1X,F10.4,5X,F10.4,8X,I4,11X,I4,12X,I4,11X,I4,1
   20X,I4)
522 FORMAT(1X,11H DRAT ARRAY/5X,8F10.4/5X,8F10.4)
523 FORMAT(1X,10H LAM ARRAY/5X,8F10.4/5X,8F10.4)
524 FORMAT(1X,12H BETA2 ARRAY/5X,8F10.4/,5X,8F10.4)
525 FORMAT(1X,10H VUT ARRAY/5X,8F10.4)
526 FORMAT(1X,12H VOVCR ARRAY/5X,8F10.4)
102 CONTINUE
101 CONTINUE
100 CONTINUE
    GO TO 1
    END
```

Function FUNCT(AMSTAR, G1, G2)

This routine calculates $(\rho V/\rho' V_{cr})_0$ for an estimated V_0 upstream of the impeller inlet guide vanes. The solution obtained by trial-and-error process is used to compute the total pressure loss across the inlet guide vanes.

FUNCT	$(\rho V/\rho' V_{cr})_0$
AMSTAR	V_0/V_{cr}
G1	$\gamma + 1$
G2	$\gamma - 1$

```
$IBFTC FUNCT

      FUNCTION FUNCT(AMSTAR,G1,G2)
      FUNCT=(1.-G2/G1*AMSTAR**2)**(1./G2)*AMSTAR
      RETURN
      END
```

Subroutine LININT(X1, Y1, X, Y, TN, MX, MY, F)

This subroutine interpolates a value of maximum pressure recovery coefficient C_p^{**} from a table of vaned diffuser throat Mach numbers and aerodynamic blockage given as input.

X1	input, vaned diffuser throat Mach number
Y1	input, throat aerodynamic blockage
X	input array of throat Mach numbers
Y	input array of throat blockages
TN	input two-dimensional array of C_p^{**} corresponding to throat Mach numbers and blockages
MX	input, number of throat Mach numbers
MY	input, number of throat blockages
F	output, interpolated value of C_p^{**}

```
$IBFTC LININT
      SUBROUTINE LININT(X1,Y1,X,Y,TN,MX,MY,F)
      DIMENSION X(MX),Y(MY),TN(MX,MY)
      DO 10 J3=2,MX
   10 IF(X1.LE.X(J3)) GO TO 20
      J3=MX
   20 DO 30 J4=2,MY
   30 IF(Y1.LE.Y(J4)) GO TO 40
      J4=MY
   40 J1=J3-1
      J2=J4-1
      EPS1=(X1-X(J1))/(X(J3)-X(J1))
      EPS2=(Y1-Y(J2))/(Y(J4)-Y(J2))
      EPS3=1.-EPS1
      EPS4=1.-EPS2
      F=TN(J1,J2)*EPS3*EPS4+TN(J3,J2)*EPS1*EPS4+TN(J1,J4)*EPS2*EPS3+
     1TN(J3,J4)*EPS1*EPS2
      RETURN
      END
```

Subroutine FNTGRL(NO,.02,F,S)

This integration subprogram from the IBM scientific subroutine package is used to integrate the function $M^3(\rho a/\rho' a')$ in the vaneless diffuser.

NO number of equally spaced radii

.02 radius ratio between stations

F $M^3(\rho a/\rho' a')$

S integral of $M^3(\rho a/\rho' a')$

Main Program FORTRAN Variables and Engineering Symbols

ACOUSR a/a'

AKE KE

AKEID KE_{id}

ALPHA α inside vaneless diffuser

ALPH1 temporary storage

ALSTAG α_{st}

AL1 α_{1T}

AL1MF α_{1MF}

AL2	α_2
AMSTAR	M^*
AMT	array of throat Mach numbers
AMU	μ
ANU	ν
AR	AR
ARNUM	ARp'_4
AR1	temporary storage
A2	a_2
B	B
BT	vaned diffuser inlet blockage
BARR	array of vaned diffuser inlet blockage
BETA2	β_{2b} array
B0	B_0
B1	β_{1T}
B1AV	β_{1AV}
B1H	β_{1H}
B1MF	β_{1MF}
B2	b_2
B2D2	b_2/D_2
B2X	β_{2b}
CF	C_f
COSA	$\cos \alpha_{1T}$
COSX	$\cos \alpha_{1MF}$
CP	C_p
CPSTAR	C_p^{**}
DEBL	$\Delta\eta_{BL}$
DEDF	$\Delta\eta_{DF}$
DEIGV	$\Delta\eta_{IGV}$
DELTA	δ

DELTAB	ΔB
DELTAR	$\Delta \overline{R}$
DELTAS	$\Delta \delta^*$
DERC	$\Delta \eta_{RC}$
DESF	$\Delta \eta_{SF}$
DEVD	$\Delta \eta_{VD}$
DEVLD	$\Delta \eta_{VLD}$
DF	D_f
DHACT	Δh_{act}
DHAERO	Δh_{aero}
DHBL	Δh_{BL}
DHDF	Δh_{DF}
DHID	ΔH_{id}
DHIGV	Δh_{IGV}
DHRC	Δh_{RC}
DHSF	Δh_{SF}
DHVD	Δh_{VD}
DHVLD	Δh_{VLD}
DHYD	D_{hyd}/D_2
DMF	D_{MF}
DRAT	D_{1T}/D_2 array
DRT	D_2/D_{1T}
D1H	D_{1H}
D_{1T}	D_{1T}
D2	D_2
EPSLIM	ϵ_{lim}
ES	e_s
ETAD	η_{AD}
ETAR	η_R
F	$M^3(a/a')(\rho/\rho')$ array

F1	C_p^{**} at vaned diffuser area ratio of 1.2
F2	C_p^{**} at vaned diffuser area ratio of 2.0
F3	C_p^{**} at vaned diffuser area ratio of 3.0
F4	C_p^{**} at vaned diffuser area ratio of 4.0
F5	C_p^{**} at vaned diffuser area ratio of 5.0
GAM	γ
G1	$\gamma + 1$
G2	$\gamma - 1$
HID	H_{id}
JAN	iteration counter
LAM	λ array
LAMX	λ
LOD	L/D_2
MU0	μ_0'
NB2	iteration limit
NDRAT	iteration limit
NLAM	iteration limit
NO	increment counter
NVOVCR	iteration limit
NVUT	iteration limit
OMEGA	ω
PARA	$(\rho V/\rho' V_{cr})_0$
PEXIT	p_4
PHI	φ
POPP1	$(p/p')_1$
PP	p'
PPEXIT	p_4'
PPOP1	$(p'/p)_1$
PR	p_4'/p_0'
PREC1	array of C_p^{**} at area ratio 1.2

PREC2	array of C_p^{**} at area ratio 2.0
PREC3	array of C_p^{**} at area ratio 3.0
PREC4	array of C_p^{**} at area ratio 4.0
PREC5	array of C_p^{**} at area ratio 5.0
PSI	ψ
PTH	p_3
PTHP	p_3'
P0P	p_0'
P1	p_{1MF}
P1OPP0	p_{1MF}/p_0'
P1P	p_{1MF}'
P2	p_2
P2P	p_2'
P3P	p_3'
Q	Q
QTH	q_{th}
R	$\overline{R}$
RARRAY	temporary storage
RE	Re
RE0	Re based on inlet stagnation conditions
RGAS	R
RHOR	ρ/ρ'
RHO2	ρ_2
RV	$(\rho V)_{1MF}$
RVANE	r_3
R0P	ρ_0'
R1	ρ_{1MF}
R1P	ρ_{1MF}'
R2	r_2
R2G	ρ_{2est}

S	integral of $M^3(\rho a/\rho' a')$
SINA	$\sin \alpha_{1T}$
SINX	$\sin \alpha_{1MF}$
SW	w
TALPH	$\tan \alpha$
TPL	p'/p'_2
TX	$\eta_R \Delta h_{aero}/C_p T'_0 + 1$
T0P	T'_0
T1M	T_{1MF}
T1PP	T''_1
T2	T_2
T2P	T'_2
T2PP	T''_2
U1H	u_{1H}
U1MF	u_{1MF}
U1T	u_{1T}
U2	u_2
VARAL	$\Delta \tan \alpha$
VARAL1	temporary storage
VARM	ΔM^2
VARM1	temporary storage
VCR	V_{cr}
VM1	V_{m1T}
VM1H	V_{m1H}
VM1MF	V_{m1MF}
VM2	V_{m2}
VOVCR	V_{1T}/V_{cr} array
VSL	V_{SL}
VUT	$(V_u/u)_1$ array
VU1H	V_{u1H}
VU1MF	V_{u1MF}
VU2	V_{u2}
V0	V_0

V1MF	V_{1MF}
V1T	V_{1T}
V2	V_2
WOU2	$(W/u_2)^2_{av}$
WU1H	W_{u1H}
WU1MF	W_{u1MF}
WU1T	W_{u1T}
WU2	W_{u2}
W1H	W_{1H}
W1MF	W_{1MF}
W1T	W_{1T}
W2	W_2
W2ID	W_{2id}
W2OW1T	W_2/W_{1T}
XKJ	K
XM	M
XM1	temporary storage
XM2	M_2
XMACH	M_3
XMARR	array of vaneless diffuser M's
XNS	N_s
Y	dummy variable
Z	Z
ZETA	ζ

Lewis Research Center,
National Aeronautics and Space Administration,
and
U.S. Army Air Mobility R&D Laboratory,
Cleveland, Ohio, April 18, 1972,
132-15.

APPENDIX A

SYMBOLS

AR area ratio

a local acoustic velocity, m/sec

B diffuser effective depth ratio

B_t vaned diffuser throat aerodynamic blockage

b blade height, m

C_f skin friction coefficient

C_p specific heat at constant pressure, J/(kg)(K)

C_p^{**} maximum pressure recovery coefficient at a given area ratio

D diameter, m

D_f diffusion factor

e_s inlet guide vane loss coefficient

H overall compressor enthalpy, J/kg

Δh incremental compressor enthalpy, J/kg

K constant of integration

KE kinetic energy, J/kg

L blade length, m

M Mach number

N_s specific speed

PR total pressure ratio

p pressure, N/m^2

Q volume flow rate, m^3/sec

q dimensionless enthalpy (eq. (B75))

R gas constant, J/(kg)(K)

$\overline{R}$ radius ratio

Re Reynolds number

r radius, m

T temperature, K

u blade speed, m/sec

V absolute gas velocity, m/sec

W relative gas velocity, m/sec

w mass flow rate, kg/sec

Z number of blades

α absolute flow angle, deg from meridional

β relative flow angle, deg from meridional

β_b blade angle, deg from meridional

γ specific heat ratio

δ deviation angle between flow and blade, deg

$\Delta\delta^*$ incremental boundary layer displacement thickness, m

ϵ_{lim} limiting impeller diameter ratio for slip calculations

ζ vaneless diffuser loss coefficient

η efficiency

$\Delta\eta$ decrement in efficiency

λ inducer hub-tip diameter ratio

μ dynamic viscosity, $(N)(sec)/m^2$

ν kinematic viscosity, m^2/sec

ρ gas density, kg/m^3

φ flow coefficient

ψ head coefficient

ω angular velocity, sec^{-1}

Subscripts:

AD adiabatic

act actual

aero aerodynamic

av average

BL blade loading

cr critical state

DF disk friction

est	estimated
H	hub
hyd	hydraulic
id	ideal
IGV	inlet guide vane
m	meridional
MF	rms
R	rotor
RC	recirculation
SF	skin friction
SL	slip
st	stagger
T	tip
th	theoretical
u	tangential
VD	vaned diffuser
VLD	vaneless diffuser
0	station just upstream of inlet guide vanes
1	impeller inlet
2	impeller exit
3	vaned diffuser inlet
4	vaned diffuser exit

Superscripts:

'	absolute stagnation
''	relative stagnation

APPENDIX B

EQUATIONS

The following are the equations listed in the order solved in the FORTRAN program:

$$\omega = \frac{2u_{1T}}{D_{1T}} \tag{B1}$$

$$V_{cr} = \sqrt{\frac{2\gamma}{\gamma + 1} RT'_0} \tag{B2}$$

$$V_{1T} = \frac{V_{1T}}{V_{cr}} V_{cr} \tag{B3}$$

$$\alpha_{1T} = \sin^{-1}\left[\left(\frac{V_u}{u}\right)_1 \frac{u_{1T}}{V_{1T}}\right] \tag{B4}$$

$$V_{m1T} = V_{1T} \cos \alpha_{1T} \tag{B5}$$

$$W_{u1T} = u_{1T}\left[1 - \left(\frac{V_u}{u}\right)_1\right] \tag{B6}$$

$$\beta_{1T} = \tan^{-1}\left(\frac{W_{u1T}}{V_{m1T}}\right) \tag{B7}$$

$$W_{1T} = \sqrt{W^2_{u1T} + V^2_{m1T}} \tag{B8}$$

$$K = V^2_{m1T} + 2V^2_{u1T} = \text{constant} \tag{B9}$$

$$W_2 = \left(\frac{W_2}{W_{1T}}\right) W_{1T} \tag{B10}$$

$$u_2 = \frac{u_{1T}}{\left(\frac{D_{1T}}{D_2}\right)} \tag{B11}$$

$$D_2 = \frac{D_{1T}}{\left(\frac{D_{1T}}{D_2}\right)} \tag{B12}$$

$$u_{1H} = \lambda u_{1T} \tag{B13}$$

$$D_{1H} = \lambda D_{1T} \tag{B14}$$

$$V_{u1H} = \lambda u_{1T}\left(\frac{V_u}{u}\right)_1 \tag{B15}$$

$$V_{m1H} = \sqrt{K - 2V_{u1H}^2} \tag{B16}$$

$$W_{u1H} = u_{1H} - V_{u1H} \tag{B17}$$

$$\beta_{1H} = \tan^{-1}\left(\frac{W_{u1H}}{V_{m1H}}\right) \tag{B18}$$

$$W_{1H} = \sqrt{V_{m1H}^2 + W_{u1H}^2} \tag{B19}$$

$$D_{1MF} = \sqrt{\frac{1}{2} D_{1T}^2(1 + \lambda^2)} \tag{B20}$$

$$u_{1MF} = \frac{u_{1T}D_{1MF}}{D_{1T}} \tag{B21}$$

$$V_{u1MF} = \frac{u_{1T}D_{1MF}}{D_{1T}}\left(\frac{V_u}{u}\right)_1 \tag{B22}$$

$$V_{m1MF} = \sqrt{K - 2V_{u1MF}^2} \tag{B23}$$

$$\alpha_{1MF} = \tan^{-1}\left(\frac{V_{u1MF}}{V_{m1MF}}\right) \tag{B24}$$

$$V_{1MF} = \sqrt{V_{u1MF}^2 + V_{m1MF}^2} \tag{B25}$$

$$W_{u1MF} = u_{1MF} - V_{u1MF} \tag{B26}$$

$$W_{1MF} = \sqrt{V_{m1MF}^2 + W_{u1MF}^2} \tag{B27}$$

$$\beta_{1MF} = \tan^{-1}\left(\frac{W_{u1MF}}{V_{m1MF}}\right) \tag{B28}$$

$$T_{1MF} = T_0' - \frac{V_{1MF}^2}{2C_p} \tag{B29}$$

$$\beta_{1av} = \frac{\beta_{1T} + \beta_{1MF} + \beta_{1H}}{3} \tag{B30}$$

$$\left(\frac{p}{p'}\right)_{1MF} = \left(1 + \frac{V_{1MF}^2}{2C_pT_{1MF}}\right)^{-\gamma/(\gamma-1)} \tag{B31}$$

$$p_{1MF} = p_{1MF}'\left(\frac{p}{p'}\right)_{1MF} \tag{B32}$$

$$\rho_{1MF}' = \frac{p_{1MF}'}{RT_0'} \tag{B33}$$

$$\rho_{1MF} = \rho_{1MF}'\left(\frac{p}{p'}\right)_{1MF}^{1/\gamma} \tag{B34}$$

$$Q = \frac{\pi}{4} D_{1T}^2(1 + \lambda^2)V_{m1MF} \tag{B35}$$

$$w = \rho_{1MF}Q \tag{B36}$$

$$\rho_0' = \frac{p_0'}{RT_0'} \tag{B37}$$

$$Re = \frac{u_2 D_2}{\mu_0' \rho_0'} \tag{B38}$$

$$T_1'' = T_{1MF} + \frac{W_{1MF}^2}{2C_p} \tag{B39}$$

$$T_2'' = T_1'' + \frac{u_2^2 - u_{1MF}^2}{2C_p} \tag{B40}$$

$$T_2 = T_2'' - \frac{W_2^2}{2C_p} \tag{B41}$$

$$a_2 = \sqrt{\gamma RT_2} \tag{B42}$$

$$\varphi = \frac{V_{m1MF}}{u_2} \tag{B43}$$

$$\left(\frac{W}{u_2}\right)_{av}^2 = \frac{1}{2}\left\{\varphi^2 + \left(\frac{D_{1MF}}{D_2}\right)^2 + \left(\frac{W_2}{W_{1T}}\right)^2 \left[\varphi^2 + \left(\frac{D_{1T}}{D_2}\right)^2\right]\right\} \tag{B44}$$

When inlet swirl is prescribed, equations (B45) to (B60) are solved instead of equations (B31) to (B44).

$$\alpha_{st} = \frac{\alpha_{1MF}}{2} \tag{B45}$$

$$e_s = \left(\frac{0.0076}{\cos\alpha_{1MF} - 0.025}\right)\left(1 + \frac{\cos\alpha_{st}}{0.7}\right) \tag{B46}$$

$$KE = \frac{V_{1MF}^2}{2} \tag{B47}$$

$$KE_{id} = \frac{KE}{1 - e_s} \tag{B48}$$

$$\left(\frac{p}{p'}\right)_{1MF} = \left[1 - \frac{KE}{C_p T_0'}\right]^{\gamma/(\gamma-1)} \tag{B49}$$

$$\frac{p_{1MF}}{p_0'} = \left(1 - \frac{KE_{id}}{C_p T_0'}\right)^{\gamma/(\gamma-1)} \tag{B50}$$

$$p_{1MF}' = p_0' \frac{\left(\frac{p_{1MF}}{p_0'}\right)}{\left(\frac{p}{p'}\right)_{1MF}} \tag{B51}$$

$$\rho_{1MF}' = \frac{p_{1MF}'}{RT_0'} \tag{B52}$$

$$p_{1MF} = p_{1MF}'\left(\frac{p}{p'}\right)_{1MF} \tag{B53}$$

$$\rho_{1MF} = \rho_{1MF}'\left(\frac{p}{p'}\right)_{1MF}^{1/\gamma} \tag{B54}$$

$$w = \rho_1 Q \tag{B55}$$

$$(\rho V)_{1MF} = \rho_{1MF} V_{m1MF} \tag{B56}$$

$$\left(\frac{\rho V}{\rho' V_{cr}}\right)_{1MF} = \left[1 - \frac{\gamma - 1}{\gamma + 1}\left(\frac{V}{V_{cr}}\right)_0^2\right]^{1/(\gamma-1)} \left(\frac{V}{V_{cr}}\right)_0 \tag{B57}$$

$$V_0 = \left(\frac{V}{V_{cr}}\right)_0 V_{cr} \tag{B58}$$

$$\mu = \frac{9.796\times10^{-7}\ T_{1MF}^{1.5}}{T_{1MF} + 110.4} \tag{B59}$$

$$Re = \frac{w}{\mu D_{1T}} \tag{B60}$$

$$\Delta h_{IGV} = \frac{0.4 \sin \alpha_{1MF}}{2 \cos \alpha_{1MF}\ Re^{0.2}} \left(V_0^2 + V_{1MF}^2\right) \tag{B61}$$

$$Z = 6.5\ \frac{1 + \left(\frac{D_{1MF}}{D_2}\right)}{1 - \left(\frac{D_{1MF}}{D_2}\right)} \cos\left(\frac{\beta_{1av} + \beta_{2b}}{2}\right) \tag{B62}$$

$$\epsilon_{lim} = e^{-(8.16 \cos \beta_{2b}/Z)} \tag{B63}$$

$$V_{SL} = \frac{u_2\sqrt{\cos \beta_{2b}}}{Z^{0.7}} \tag{B64}$$

If $(D_{1MF}/D_2) > \epsilon_{lim}$, then the slip velocity is expressed as

$$V_{SL} = u_2 \frac{\sqrt{\cos \beta_{2b}}}{Z^{0.7}} \left\{ \frac{\left[1 - \left(\frac{D_{1MF}}{D_2} - \epsilon_{lim}\right)\right]}{(1 - \epsilon_{lim})} \right\}^3 + u_2 \left[\frac{\left(\frac{D_{1MF}}{D_2} - \epsilon_{lim}\right)}{(1 - \epsilon_{lim})} \right]^3 \tag{B65}$$

$$\delta = \sin^{-1}\left(\frac{V_{SL} \cos \beta_{2b}}{W_2}\right) \tag{B66}$$

$$W_{2id} = W_2 \frac{\cos(\beta_{2b} + \delta)}{\cos \beta_{2b}} \tag{B67}$$

$$V_{u2} = u_2 - V_{SL} - W_{2id} \sin \beta_{2b} \tag{B68}$$

$$V_{m2} = W_{2id} \cos \beta_{2b} \tag{B69}$$

$$\alpha_2 = \tan^{-1}\left(\frac{V_{u2}}{V_{m2}}\right) \tag{B70}$$

$$W_{u2} = u_2 - V_{u2} \tag{B71}$$

$$V_2 = \sqrt{V_{m2}^2 + V_{u2}^2} \tag{B72}$$

$$T_2' = T_2 + \frac{V_2^2}{2C_p} \tag{B73}$$

$$\Delta h_{aero} = C_p T_0' \left(\frac{T_2'}{T_0'} - 1\right) \tag{B74}$$

$$q_{th} = \frac{\Delta h_{aero}}{u_2^2} \tag{B75}$$

$$D_f = 1 - \frac{W_2}{W_{1T}} + \frac{0.75\, q_{th}}{\frac{W_2}{W_{1T}}\left[\frac{Z}{\pi}\left(1 - \frac{D_{1T}}{D_2}\right) + 2\frac{D_{1T}}{D_2}\right]} \tag{B76}$$

$$\Delta h_{BL} = 0.05\, D_f^2 u_2^2 \tag{B77}$$

$$\Delta h_{RC} = 0.02\, D_f^2 u_2^2 \sqrt{\tan \alpha_2} \tag{B78}$$

$$\frac{L}{D_2} = \frac{1 - \frac{D_{1MF}}{0.3048}}{2 \cos \beta_{2b}} \tag{B79}$$

Using the isentropic density rise as the first approximation, we solve equations (B80) to (B90) iteratively for the impeller exit density.

$$\rho_{2est} = \rho_{1MF}\left(\frac{T_2}{T_{1MF}}\right)^{1/(\gamma-1)} \tag{B80}$$

$$\Delta h_{DF} = \frac{0.01356\, \rho_{2est}\, u_2^2 D_2^2}{w\, Re^{0.2}} \tag{B81}$$

$$b_2 = \frac{w}{\pi D_2 V_{m2} \rho_{2est}} \tag{B82}$$

$$\frac{D_{hyd}}{D_2} = \frac{1}{\frac{Z}{\pi \cos \beta_{2b}} + \frac{D_2}{b_2}} + \frac{\frac{D_{1T}}{D_2}}{\frac{2}{1 - \lambda} + \frac{2Z}{\pi(1 + \lambda)}\sqrt{1 + \frac{1 + \lambda^2}{2} \tan^2 \beta_{1T}}} \tag{B83}$$

$$\Delta h_{SF} = 5.6\ C_f \frac{\dfrac{L}{D_2}}{\dfrac{D_{hyd}}{D_2}} \left(\frac{W}{u_2}\right)^2_{av} u_2^2 \tag{B84}$$

$$\Delta h_{act} = \Delta h_{aero} + \Delta h_{DF} + \Delta h_{RC} \tag{B85}$$

$$h_{id} = \Delta h_{aero} - \Delta h_{BL} - \Delta h_{SF} - \Delta h_{IGV} \tag{B86}$$

$$\eta_R = \frac{h_{id}}{\Delta h_{aero}} \tag{B87}$$

$$p_2' = \left(\frac{\eta_R\ \Delta h_{aero}}{C_p T_0'} + 1\right)^{\gamma/(\gamma-1)} p_{1MF}' \tag{B88}$$

$$p_2 = p_2'\left(\frac{T_2'}{T_2}\right)^{-\gamma/(\gamma-1)} \tag{B89}$$

$$\rho_{2est} = \frac{p_2}{RT_2} \tag{B90}$$

$$M_2 = \frac{V_2}{a_2} \tag{B91}$$

$$r_2 = \frac{D_2}{2} \tag{B92}$$

$$\mu = \frac{9.7965\times10^{-7}\ T_2^{1.5}}{T_2 + 110.4} \tag{B93}$$

$$\nu = \frac{\mu}{\rho_2} \tag{B94}$$

$$B_0 = 1.0 \tag{B95}$$

$$F(1) = \frac{M_2^3 \overline{R}}{\left(1 + \frac{\gamma - 1}{2} M_2^2\right)^{\gamma/(\gamma-1)}} \tag{B96}$$

$$\zeta = \frac{C_f r_2}{b_2} \tag{B97}$$

$$\Delta\delta^* = \frac{\left(\frac{0.37}{8} \frac{r_2 \Delta\overline{R}}{\cos\alpha}\right)}{\left(\frac{V_2 r_2 \Delta\overline{R}}{\nu \cos\alpha}\right)^{0.2}} \tag{B98}$$

$$B = B_0 - \frac{2\Delta\delta^*}{b_2} \tag{B99}$$

$$\Delta B = B_0 - B \tag{B100}$$

$$\Delta M^2 = \frac{-2\left(1 + \frac{\gamma - 1}{2} M^2\right)}{(M^2 - \sec^2\alpha)} \left[(\gamma M^2 - \tan^2\alpha) \frac{\zeta}{B_0 \cos\alpha} - \frac{1}{B_0} \frac{\Delta B}{\Delta\overline{R}} - \frac{\sec^2\alpha}{\overline{R}}\right] M^2 \Delta\overline{R} \tag{B101}$$

$$\Delta \tan\alpha = \frac{\sec^2\alpha}{(M^2 - \sec^2\alpha)} \left[\left(1 + \frac{\gamma - 1}{2} M^2\right) \frac{\zeta}{B_0 \cos\alpha} - \frac{1}{B_0} \frac{\Delta B}{\Delta\overline{R}} - \frac{M^2}{\overline{R}}\right] \tan\alpha \, \Delta\overline{R} \tag{B102}$$

$$\frac{p'}{p_2'} = \frac{1}{1 + \frac{\gamma C_f r_2 \int_1^R M^3 \left(\frac{\rho}{\rho'}\right)\left(\frac{a}{a'}\right) d\overline{R}}{b_2 M_2 \cos\alpha_2} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}} \tag{B103}$$

Equations (B98) to (B103) are solved by the numerical technique described in reference 6 with increments in radius ratio of 0.02 until a Mach number of 0.8 or less is attained.

$$p_3 = \frac{p_3'}{\left(1 + \frac{\gamma - 1}{2} M_3^2\right)^{\gamma/(\gamma-1)}} \tag{B104}$$

$$\Delta h_{VLD} = C_p T_2' \left[\left(\frac{p_3}{p_3'}\right)^{(\gamma-1)/\gamma} - \left(\frac{p_3}{p_2'}\right)^{(\gamma-1)/\gamma}\right] \tag{B105}$$

$$B_t = 1 - B \tag{B106}$$

$$p_4' = p_3' \tag{B107}$$

$$AR = \frac{M_3}{0.02}\left(\frac{1 + \frac{\gamma - 1}{2} 0.04}{1 + \frac{\gamma - 1}{2} M_3^2}\right)^{(\gamma+1)/2(\gamma-1)} \tag{B108}$$

$$ARNUM = p_4' \, AR \tag{B109}$$

$$p_4 = C_p^{**}(p_3' - p_3) + p_3 \tag{B110}$$

$$p_4' = p_4\left(1 + \frac{\gamma - 1}{2} 0.04\right)^{\gamma/(\gamma-1)} \tag{B111}$$

$$AR = \frac{ARNUM}{p_4'} \tag{B112}$$

Equations (B108) to (B112) are iterated until successive approximations of area ratio agree within 0.001.

$$\Delta h_{VD} = C_p T_2' \left[\left(\frac{p_4}{p_4'} \right)^{(\gamma-1)/\gamma} - \left(\frac{p_4}{p_3'} \right)^{(\gamma-1)/\gamma} \right] \tag{B113}$$

$$\eta_{AD} = \frac{h_{id} - \Delta h_{VLD} - \Delta h_{VD}}{\Delta h_{act}} \tag{B114}$$

$$PR = \frac{p_4'}{p_0'} \tag{B115}$$

$$H_{id} = \eta_{AD} \, \Delta h_{aero} \tag{B116}$$

$$\psi = \frac{H_{id}}{u_2^2}$$

$$N_s = \frac{\omega \sqrt{Q}}{H_{id}^{3/4}} \tag{B118}$$

$$\Delta \eta_{BL} = \frac{\Delta h_{BL}}{\Delta h_{act}} \tag{B119}$$

$$\Delta \eta_{SF} = \frac{\Delta h_{SF}}{\Delta h_{act}} \tag{B120}$$

$$\Delta \eta_{DF} = \frac{\Delta h_{DF}}{\Delta h_{act}} \tag{B121}$$

$$\Delta \eta_{RC} = \frac{\Delta h_{RC}}{\Delta h_{act}} \tag{B122}$$

$$\Delta \eta_{VLD} = \frac{\Delta h_{VLD}}{\Delta h_{act}} \tag{B123}$$

$$\Delta\eta_{VD} = \frac{\Delta h_{VD}}{\Delta h_{act}} \tag{B124}$$

$$\Delta\eta_{IGV} = \frac{\Delta h_{IGV}}{\Delta h_{act}} \tag{B125}$$

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