Proceedings of the International Gas Turbine Congress 2003 Tokyo
November 2-7, 2003

IGTC2003Tokyo TS-093

Thermodynamic Table for Performance Calculations in Gas Turbine Engine

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ABSTRACT

The purpose of this study is to simplify the programming process by minimizing the iteration calculation steps. To achieve the aim, one dimensional isentropic compressible-flow function table was integrated with thermodynamic table to yield a subroutine program, which can be utilized in the programming work relating with performance calculations in gas turbine engine. The table, written in Fortran, covers for the temperature range ; 0 ~ 5000 (K) , mixture strength ; air~stoichiometric, and mach number ; 0~25. The table work also for the calculation with constant specific heat ratio; κ. The table was arranged to work for the following three systems of units; (1) SI unit, (2) metric unit and (3) British unit to be chosen. The program is hoped to be utilized through the GTSJ if it is permitted.

NOMENCLATURE

A	sectional area	(cm^2)
a	air/fuel ratio at stoichiometric	
Cp	specific heat at constant pressure	(kJ/kg K)
Cv	specific heat at constant volume	(kJ/kg K)
Cpm	$=\Delta h/\Delta T$	(kJ/kg K)
F	fuel/air ratio	
G	mass flow rate	(kg/sec)
g	gravity	(m/sec^2)
$\overline{H}$	proportion of hydrogen	
h	enthalpy	(kJ/kg)
M	molecular weight	(kg/kg-mol)
Ma	molecular weight of air	(kg/kg-mol)
Mn	Mach number	
P	pressure	(MPa)
Pr	relative pressure	
Q	$G\sqrt{T}/APt$	$(kg/sec\sqrt{K})/cm^2MPa$
Qs	$G\sqrt{T}/APs$	$(kg/sec\sqrt{K})/cm^2MPa$
R	gas constant	(kJ/kg K)
T	temperature	(K)
u	internal energy	(kJ/kg)
V	velocity	(m/sec)
$V/\sqrt{T}$	velocity(normalized)	$(m/sec)/\sqrt{K}$
φ	entropy function	(kJ/kg K)
φ_f	relative fuel/air ratio	
κ	specific heat ratio	
ρ	density	(kg/m^3)
$\Re$	universal gas constant	(kJ/kmol K)
ND	no. of unit systems	
CK	constant κ	
CJK	conversion factor	= 4.1868

Subscripts

a	air
p	combustion products
t, s, m	total, static, mean
st	stoichiometric

INTRODUCTION

One dimensional isentropic compressible-flow functions are often required to be handled in the programming work relating to performance estimation, data analyzing, and cycle calculation program etc. engaged with turbomachineries. It is rather tedious part of job to solve the required flow function each time during the main programming work. The subroutine program was studied intending to simplify these programming processes. There are many thermodynamic tables published, however few have the polynomial coefficients to be utilized for programming work. Chappell's table has the polynomial coefficients together with thermodynamic tables, and the coefficients are reproduced also in the IGTI publication(1991). This study based on Chappell's coefficients for the temperature range from 250 to 2200 K. For the temperature range less than 250 K, it was obtained based on Keenan's table(1945) for air, and on JANAF table(1985) for mixture. For the temperature range higher than 2200 K, both of air and mixture were obtained based on Chemkin Data Base(1994) up to 5000 K. Chappell's table has no relative pressure; Pr and relative volume; Vr, therefor they were defined and obtained in this study to be convenient for performance calculation. The thermodynamic table covers the temperature range from 0 to 5000 K, and air to stoichiometric mixture. With the thermodynamic table, the flow function table was arranged to cover the Mach number up to 25. The accuracy was checked by comparing the table obtained with the several other tables published having various units of systems, and it was considered to be acceptable for the purpose of this study. Dissociation was not taken into account in this study, however the effects were checked briefly with GE table(1954).

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Manuscript Received on March 31, 2003

THERMODYNAMIC TABLE

DRY AIR

The composition of dry air for the purpose of computing air properties was assumed by Keenan and Kays(1945), as N_2: 78.03, O_2: 20.99 and Ar: 0.98 per cent by volume, to yield the molecular weight of air then as 28.970(kg/kmol).
The molecular weights for the related species have been reviced since then, therefor applying the recent values to the above composition, the molecular weight of air was obtained as 28.967 which is equivalent with that of real air (JSME, 1985).

The above composition and molecular weight of dry air were used in this study as the base to obtain the thermodynamic characteristics of air and mixture.

STANDARD FUEL

It has been studied that if the proportion of hydrogen contained in hydrocarbon fuel (denoted as $\overline{H}$) is 0.1392, the gas constant: R of the products of combustion becomes equal to that of air, irrespective of the mixture strength. The fuel is called as 'standard fuel' which is equivalent to $CH_{1.927.}$ The standard fuel has been widely used for performance calculations in gas turbine engine to simplify calculations, since gas constant for air: R can also be used for combustion gases with this fuel. The standard fuel is chosen in this study to simplify to obtain the flow characteristics.

THERMODYNAMIC FUNCTIONS

Based on the air and fuel chosen as above, the thermodynamic characteristics of air and stoichiometric gases can be obtained by using the following equations respectively(Hodge,1955).

$$(Cp)_a = 0.7546(Cp)_{N2} + 0.2319(Cp)_{O2} + 0.0135(Cp)_{Ar} \quad \text{------ (1)}$$

$$(Cp)_{ST} = 0.7064(Cp)_{N2} + 0.0126(Cp)_{Ar} + 0.0795(Cp)_{H2O} + 0.2015(Cp)_{CO2} \quad \text{-------(2)}$$

The Chemkin Data Base presents the polynomial coefficients for thermodynamic properties of various species. For the species concerned in this study are given for the temperature range of T=(300-1000)K and (1000-5000)K separately(Chemkin,1994).
Specific heat: Cp, enthalpy: h and entropy function: ϕ were obtained for the related species such as N_2, O_2, Ar, H_2O and CO_2.
The obtained values were checked by comparing with JANAF's table, which covers for the temperature range of (0-6000)K (JANAF,1985).

The enthalpy obtained from Chemkin Data Base becomes negative value at T=298.15 which is defined as 0 in JANAF, therefor the difference were adjusted to meet with JANAF, and also it was further adjusted to be h=0 at T=0 (K), by using JANAF table. The thermodynamic characteristics of the species obtained were checked by comparing with Keenan's table in which the enthalpy were defined as h=0 at T=0 and it covers for T=(300-5380)R (Keenan,1945). These characteristics obtained as above for the related species, are applied into Eq.(1) to obtain air characteristics, and into Eq(2) for the stoichiometric gases.

For the temperature range lower than 300 K, no polynomial coefficients published were found, therefor the coefficients for air were obtained based on Keenan's air table, and coefficients for species were obtained based on JANAF data. They were applied into Eq(2) to obtain the coefficients of stoichiometric gases for this temperature range.

On the other hand, Chappell's thermodynamic table covers for the temperature range of (200-2200)K with three systems of units, together also with the polynomial coefficients(Chappell,1974). The coefficients were also reproduced in the IGTI publication, therefor the table have been widely utilized (IGTI,1991). Considering not to affect on the data already obtained, the Chappell's coefficients were tried to use in this study for the temperature range of (200-2200)K. This table are divided into the two temperature ranges for (200-800) and (800-2200)K.

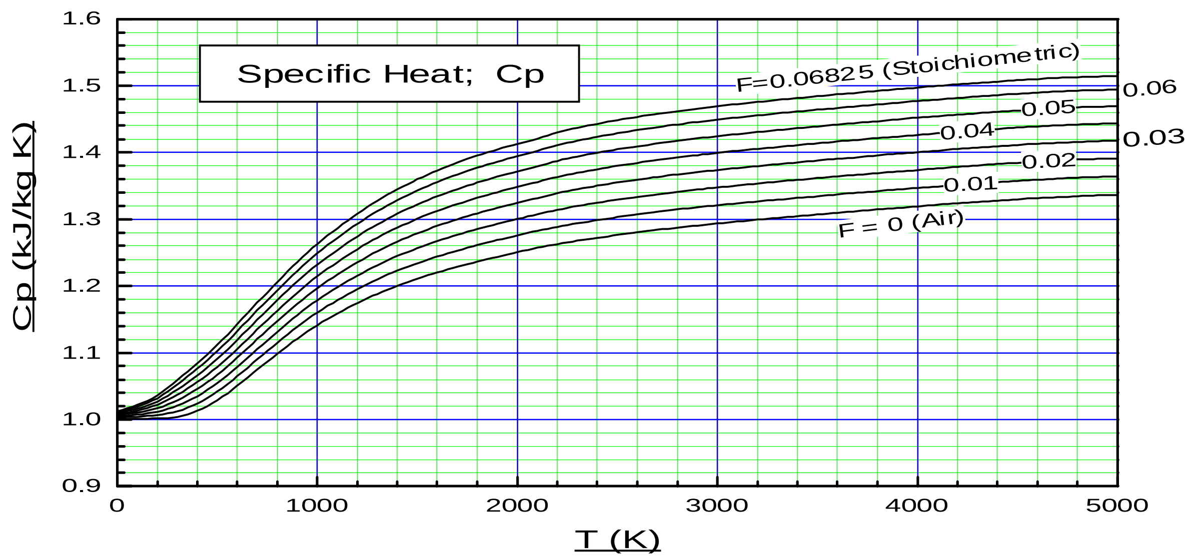

Fig.1 Specific heat characteristics

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Table 1 Thermodynamic functions

		To Obtain						
		T	Cp	h	Φ	u	Pr	Vr
From	T		① CPT	② HFT	③ SFT	⑦ UFT	④ PRT	⑧ VRT
	Cp							
	h	⑤ TFH					⑮ PRH	⑯ VRH
	Φ							
	u	⑨ TFU					⑱ PRU	⑰ VRU
	Pr	⑥ TPR		⑪ HPR		⑫ UPR		
	Vr	⑭ TVR		⑩ HVR		⑬ UVR		

Comparing the table obtained for (0-300)K as above with the Chappell's table, the latter showed a slightly different characteristics for the range of (200-250)K, probably because of the very end of the temperature range studied. Therefor, the table for (0-300)K is used for (0-250)K, and Chappell's for (250-800)K. The characteristics for (0-300)K table were slightly adjusted to meet with Chappell's at T=250 K by changing the constants.

The higher temperature range had no such problem, therefor the table (1000-5000)K are used to cover the range of (2200-5000) K though the constants obtained for (1000-5000)K were also slightly adjusted to meet Chappell's at T=2200 K.

With the characteristics for air and stoichiometric gases obtained as above, the characteristics for combustion gases at arbitrary mixture strength were obtained by using the following equations.

$$\mathrm{Cp} = \mathrm{Cp}_{a} + \frac{f}{1+f}(1+a)(\mathrm{Cp}_{st} - \mathrm{Cp}_{a})$$

$$= \mathrm{Cp}_{a} + \frac{f}{1+f}\theta_{Cp} ---------- (3)$$

$$\theta_{Cp} = (1+a)(\mathrm{Cp}_{st} - \mathrm{Cp}_{a}) -------- (4)$$

The enthalpy: h and entropy function ϕ were also obtained in the similar manner. The specific heat : Cp obtained is shown in Fig. 1.

RELATIVE PRESSURE AND VOLUME

Relative pressure: Pr and relative volume: Vr can be obtained as;

$$\Pr = \exp\left(\frac{1}{R/M}(\phi - \phi_0)\right) -------- (5)$$

$$Vr = \exp\left(-\frac{\phi - \phi_0}{R/M} + \ln(\frac{T}{T_0})\right) ------ (6)$$

Where $\phi_0 \equiv \phi$ at $T_0 \equiv 273.15$ K assumed.

Both of the Pr and Vr become 1.0 at T=273.15 K according to the above definition. However, Pr increases as temperature increases, but the Vr reduces, as the result the Vr becomes too small in value for the practical temperature range. To avoid this inconvenience, the Vr is redefined in this study as:

$$Vr = \frac{T}{\Pr} ---------- (7)$$

With this definition of Vr, the value becomes convenient level in use, and also it is easy to obtain the values when Pr is known.

SUB-PROGRAM ARRANGEMENT

The thermodynamic table is arranged as shown in Table 1 which consists of 18 sub-functions as;

Cp, k, h, u, ϕ , Pr, Vr = f (T, F)

T, Pr, Vr =f (h, F), T, Pr, Vr = f (u, F)

T, h, u =f (Pr, F), T , h , u =f (Vr, F)

The function names of sub-programs are defined as ;

(1) CPT(T, F, Cp, κ) = ' obtain Cp from T ' ,

(2) HFT(T, F, h) = ' obtain h from T ' and so on.

A specific feature of this table is, a corresponding temperature: T can be obtained as a function of h (⑤ TFH), or as a function of Pr (⑥ TPR). These functions are effective to reduce the iteration calculations which will be required otherwise.

Table 2 Accuracy check on Cp (kJ/kg K) for air

--- compared with Keenan's table

Temp. (K)	SYTBL	K & K	Diff (%)
55.55	1.00109	1.00148	−0.039
111.11	1.00108	1.00148	−0.040
222.22	1.00156	1.00190	−0.034
500	1.02908	1.02912	−0.003
1000	1.14118	1.14090	0.024
1444.44	1.20524	1.20496	0.023
2000	1.25060	1.25018	0.034
3000	1.29371	1.29372	−0.001
3555.56	1.30856	1.30963	−0.082

The most of sub-programs were checked to work satisfactorily for the temperature range of (0-5000) K , from air to stoichiometric mixture. However, the sub-program, ⑥;TPR, T=f (Pr) and ⑩ HVR,T=f(Vr) failed to yield reliable results for the temperature range less than 4 K, which affected on the functions of ⑪;HPR, ⑫; UPR and ⑭TVR as seen in Fig. 2. This was caused because the relative pressure; Pr and volume; Vr become too small or too big respectively to be handled for the low temperature range. The outputs for specific heat: Cp, enthalpy: h and entropy function: ϕ for air were compared with Keenan's table and the differences between them were checked in Fig.3, Tables 2 and 3. The difference are small enough as shown which considered to be satisfactory for the purpose of this study. The same comparisons were made for combustion gases at 200 % air condition in Table 4, since Keenan's table has no stoichiometric condition. The function number are used to clarify the location of program among the sub-programs as shown in Fig. 2.

Table 3 Accuracy check for air
----Compared with Keenan's table

Enthalpy; h

Temp. (K)	SYTBL	K & K	Diff (%)
60	59.857	59.662	0.327
100	99.900	99.762	0.138
200	200.016	199.966	0.010
500	503.070	503.021	0.010
1000	1046.083	1046.025	0.006
1500	1635.971	1635.992	−0.001
2000	2252.043	2252.056	−0.001
3000	3527.131	3526.542	0.017
3500	4177.442	4177.217	0.005

Entropy function; ϕ

Temp. (K)	SYTBL	K & K	Diff (%)
60	5.0905	5.0883	0.043
100	5.6019	5.6001	0.033
200	6.2958	6.2944	0.022
500	7.2197	7.2183	0.020
1000	7.9680	7.9663	0.021
1500	8.4454	8.4437	0.021
2000	8.7996	8.7978	0.020
3000	9.3159	9.3139	0.022
3500	9.5164	9.5144	0.021

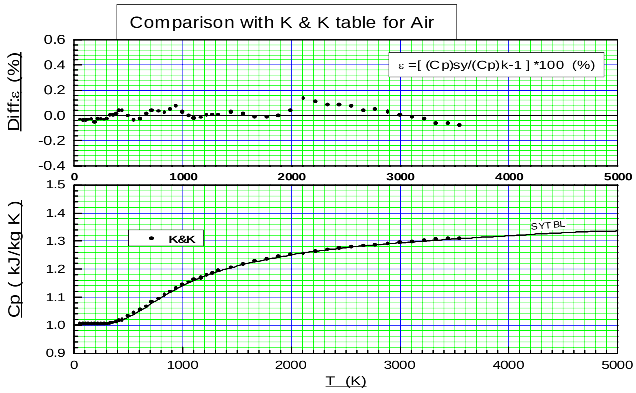

Fig. 3 Cp compared with Keenan's table for air

Table 4 Cp, h compared with Keenan's table
---- for combustion products (200 % air)

Specific heat; Cp

Temp. (K)	SYTBL	K & K	Diff (%)
166.67	1.01623	1.01581	0.042
500	1.07195	1.07160	0.033
1000	1.20383	1.20356	0.023
1500	1.28791	1.28869	−0.061
2000	1.33441	1.33668	−0.170
2222.22	1.35044	1.35171	−0.094

Enthalpy; h

Temp. (K)	SYTBL	K & K	Diff (%)
166.67	168.339	168.361	−0.013
500	202.262	202.295	−0.017
1000	514.924	514.953	−0.006
1500	1084.606	1084.589	0.002
2000	1709.819	1709.855	−0.002
2222.22	2367.105	2367.185	−0.003

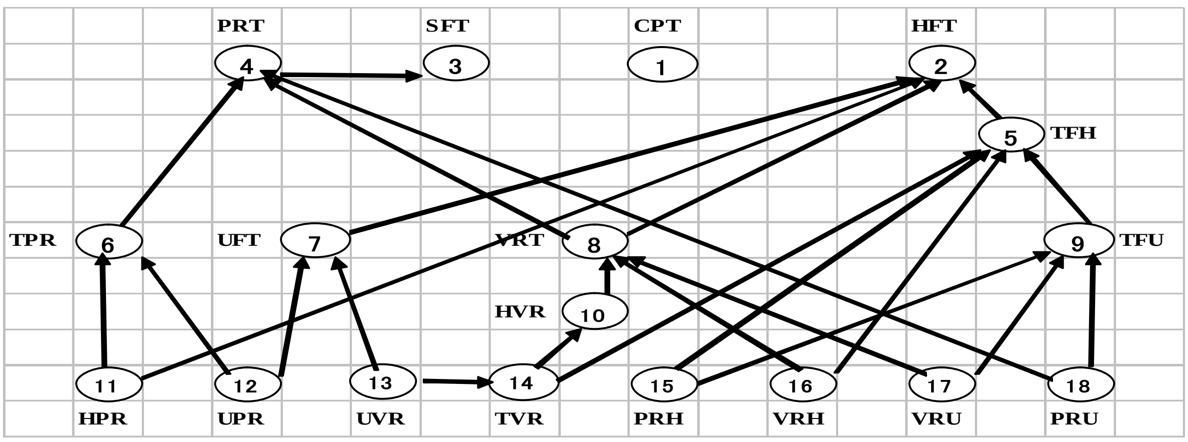

Fig.2 Interrelations among thermodynamic functions

Thermodynamic Functions

$$Cpa = C_0 + C_1T + C_2T^2 + C_3T^3 + C_4T^4 \qquad (1)$$

$$h_a = \int_0^T CpadT$$

$$= C_0T + \frac{C_1}{2}T^2 + \frac{C_2}{3}T^3 + \frac{C_3}{4}T^4 + \frac{C_4}{5}T^5 + CH \qquad (2)$$

$$\varphi a = \int_0^T \frac{Cp}{T}dT$$

$$= C_0 \ln(T) + C_1T + \frac{C_2}{2}T^2 + \frac{C_3}{3}T^3 + \frac{C_4}{4}T^4 + CF \qquad (3)$$

$$\theta_{Cp} = (1+a)(Cp_{st} - Cp_a) \qquad (4)$$

$$\theta h = (1+a)(h_{st} - h_a) \qquad (5)$$

$$\theta_\Phi = (1+a)(\varphi_{st} - \varphi_a) \qquad (6)$$

$$Cp = Cpa + \frac{f}{1+f}\theta_{Cp} \qquad (7)$$

$$h = h_a + \frac{f}{1+f}\theta h \qquad (8)$$

$$\varphi = \varphi a + \frac{f}{1+f}\theta_\Phi \qquad (9)$$

$$\theta_{Cp} = CP_0 + CP_1T + CP_2T^2 + CP_3T^3 + CP_4T^4 + CP_5T^5 \qquad (10)$$

$$\theta h = H_0 + H_1T + H_2T^2 + H_3T^3 + H_4T^4 + H_5T^5 \qquad (11)$$

$$\theta_\Phi = F_0 + F_1T + F_2T^2 + F_3T^3 + F_4T^4 + F_5T^5 \qquad (12)$$

The equations used for the thermodynamic functions are shown above and the coefficients obtained are tabulated in Table 5. The 4 data sources are used to obtain the coefficients as shown in Fig. 4.

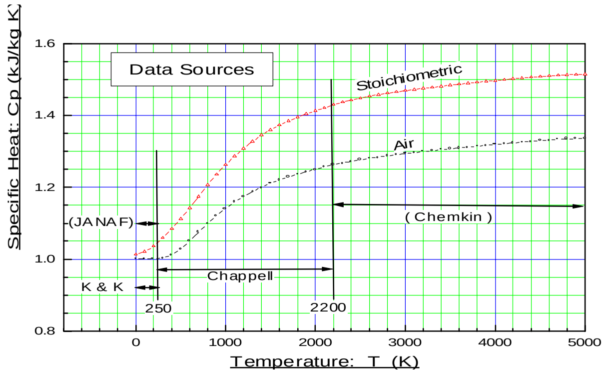

Fig. 4 Data Sources

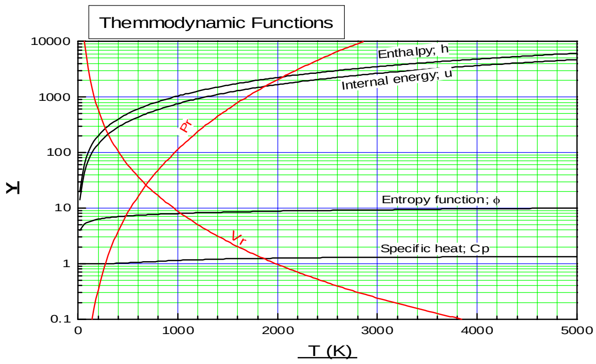

Fig. 5 Thermodynamic Functions / Characteristics

Table 5 Coefficients for Thermodynamic Functions (kJ, kg, K)

Symbol	T= (0-250) K	T= (250-800) K	T= (800-2200) K	T= (2200-5000) K	Equation
C0	1.00142E+00	1.0189134E+00	7.9865509E-01	8.857846E-01	1, 2, 3
C1	-1.17384E-05	-1.3783636E-04	5.3392159E-04	3.702210E-04	
C2	1.40847E-07	1.9843397E-07	-2.2881694E-07	-1.349033E-07	
C3	-7.49559E-10	4.2399242E-10	3.7420857E-11	2.368343E-11	
C4	1.64621E-12	-3.7632489E-13	0.0000000E+00	-1.580984E-15	
CH	-2.14700E-01	-1.6984633E+00	4.7384653E+01	1.515862E+01	2
CF	9.90870E-01	9.1992640E-01	2.0190882E+00	1.539254E+00	3
CP0	7.62900E-02	-3.5949415E-01	1.0887572E+00	-8.471030E-04	10
CP1	1.55000E-03	4.5163995E-03	-1.4158834E-04	2.714380E-03	
CP2	-5.19768E-06	2.8116360E-06	1.9160159E-06	-1.017066E-06	
CP3	4.78012E-08	-2.1708731E-08	-1.2400934E-09	1.722610E-10	
CP4	-7.18487E-11	2.8688783E-11	3.0166946E-13	-1.103124E-14	
CP5	0.00000E+00	-1.2226336E-14	-2.6117109E-17	0.000000E+00	
H0	9.27910E-01	6.2637417E+01	-1.7683851E+02	1.531204E+02	11
H1	1.88590E-01	-5.2903044E-01	8.3690644E-01	-8.471030E-04	
H2	4.64088E-04	3.2226232E-03	3.6476207E-04	1.357190E-03	
H3	1.13387E-06	-2.1670253E-06	2.5155448E-07	-3.390221E-07	
H4	1.12841E-09	2.4951704E-10	-1.2541337E-10	4.306526E-11	
H5	0.00000E+00	3.4891819E-13	1.6406268E-14	-2.206248E-15	
F0	-1.58142E+00	-7.1269837E-01	-1.2645360E+00	-6.811900E-01	12
F1	2.93141E-02	-2.2950186E-04	4.4686731E-03	2.670000E-03	
F2	-4.07579E-04	1.3154132E-05	-2.8538183E-06	-4.797580E-07	
F3	2.81833E-06	-2.5531817E-08	1.6403464E-09	4.890310E-11	
F4	-8.89157E-09	2.2390992E-11	-5.3143142E-13	-1.517310E-15	
F5	1.04291E-11	-7.6071855E-15	6.9884610E-17	-7.104190E-20	

FLOW FUNCTION TABLE

One dimensional isentropic compressible-flow functions can be written as the functions of Mach number; Mn and specific heat ratio: κ , thus;

$$\frac{T_t}{T_S} = 1 + \frac{\kappa - 1}{\kappa} Mn^2 \quad \text{--- for } \kappa = \text{const. assumed}$$

$$= 1 + \left(\frac{\kappa_S}{\kappa_m}\right)\left(\frac{\kappa_m - 1}{2}\right) Mn^2 \quad \text{--- for } \kappa = \text{variable}$$

Where κ = specific heat ratio

κ_S = specific heat ratio corresponding to Ts,

κ_m = mean specific heat ratio defined as;

$$= \frac{1}{(1 - R/Cp_m)} \quad \text{where } Cp_m = \frac{\Delta h}{\Delta T}$$

These functions may be summarized as;

$$\{Mn, Ps/Pt, Pt/Ps, Ts/Tt, \rho_S/\rho_t, A/Ach\} = f(Mn) \quad \text{-----------} \quad (8)$$

$$\{\frac{V}{\sqrt{T}}, \ Q, \ Q_S\} = f(R, Mn) \quad \text{----------} \quad (9)$$

where ;

$$Q = \frac{G\sqrt{T}}{APt} \quad \text{and} \quad Qs = \frac{G\sqrt{T}}{APs} \quad \left[\frac{kg/s\sqrt{K}}{cm_2 MPa}\right]$$

The Eq.(8) is for non-dimensional parameters and Eq.(9) for dimensional which is directly affected by the value of gas constant; R. The flow function table studied consists of the 9 sub-programs as shown in Eq. (8) and (9). The table is arranged to obtain the 9 parameters, i.e. { Mach number; Mn, pressure ratio; Ps/Pt, Pt/Ps, temperature ratio; Ts/Tt, density ratio; ρ_s/ρ_t , velocity; $V/\sqrt{T}$, volume flow rate; Q, Qs, and area ratio; A/Ach } as function of the one of those 9 parameters together with fuel/air ratio; F and temperature; T.

The arrangement of flow function tables is shown in Fig. 6 schematically. The function names of sub-programs are defined as;

(21) FMN; Function of Mn (MN)
(22) PSR; Pressure, Static, Ratio =Ps/Pt
(23) PTR; Pressure, Total , Ratio =Pt/Ps etc.

The input formats are shown in Table 5 and output format are in Table 6. The related 9 parameters such as AMNX, VRTX,QX etc , can be obtained from one parameter inputted in main program as;

' CALL PSR (Ps/Pt ,F, T) '.

SUB-PROGRAM ARRANGEMENT

To obtain the 9 parameters corresponding to a parameter inputted, the Mach number corresponding to the inputted parameter has to be obtained. In the other word, the following relation has to be solved.

Mn = f (Ps/Pt . F, T)

Obtaining Mach number; Mn as above, are sometimes not easy depending upon the value inputted. The accuracy of the Mach number obtained are checked through the following manners.

(Step-1); The values of 9 parameters are obtained for a Mach number inputted.

(Step-2); The Mach number obtained for the parameters obtained in the (Step-1).

The accuracy is checked by comparing the Mach number obtained in (Step-2) with the Mach number inputted in the (Step-1). There are some difficulties existed for the range as Mach number approaches to near zero, since every parameters become so small to yield reliable values. The error will be less than 0.16% for the parameters corresponding to Mach number; Mn =0.01. That is, the table are not able to work for the Mach number range of ; 0< Mn <0.01. The error for the velocity is shown in Fig. 7..

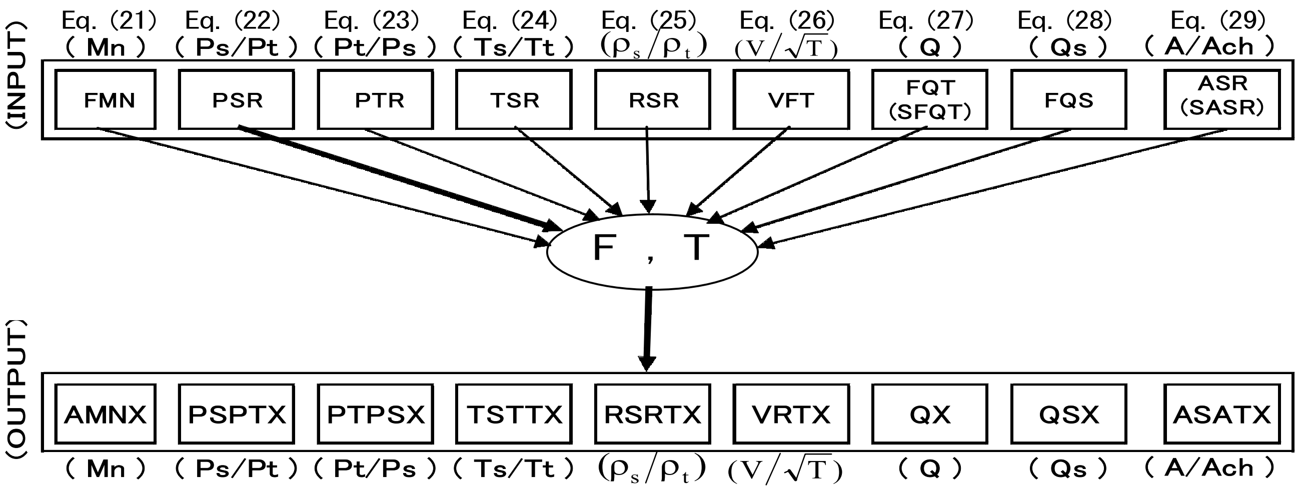

Fig. 6 Flow function table arrangement

Similar difficulties existed also at around Mn=1.0. The errors in this area are 0.92% at Mn=0.999, and 0.0022 (%) at Mn=1.001.

The flow function characteristics are shown in Fig. 8 in which the dimensional parameters are shown in red. The volume flow rate; Q has its maximum value and area ratio; A/Ach has minimum value at Mn=1.0. That is, two Mach numbers exist for a parameter inputted for those two functions.

The two function names are used for these sub-programs as shown in Fig. 9. These are;

$$Q \equiv \frac{G\sqrt{T}}{APt} = FQT\,(Mn\,,F,T) \quad \text{--- for sub-sonic.}$$

$$= SFQT\,(Mn\,,F,T) \quad \text{------ for super-sonic condition.}$$

Similarly,

A/ Ach = ASR (Mn, F, T) --- for sub-sonic

= SASR (Mn, F, T) --- for super-sonic condition.

These functions are also shown in Eq. (27) and Eq.(29), in Fig. 6.

Table 6 Input Formats

(21):	FMN (Mn, F, T)	Y= f(Mn)
(22);	PSR (Ps/Pt, F, T)	Y= f (Ps/Pt)
(23):	PTR(Pt/Ps, F, T)	Y= f (Pt/Ps)
(24);	TSR (Ts/Tt, F, T)	Y= f (Ts/Tt)
(25);	RSR (ρ_s / ρ_t , F, T)	Y= f (ρ_s / ρ_t)
(26);	VFT ($V/\sqrt{T}$, F, T)	Y= f ($V/\sqrt{T}$)
(27);	FQT (Q, F, T) SFQT (Q, F, T)	Y=f (Q)
(28);	FQS (Qs)	Y= f (Qs)
(29);	ASR (A/A_{ch}, F, T) SASR (A/A_{ch}, F, T)	Y =f(A/A_{ch})

Table 7 Output Formats

Y = Mn (AMNX),	Ps/Pt (PSPTX)
Pt/Ps (PTPSX),	Ts/Tt (TSTTX)
ρ_s / ρ_t (RSRTX),	$V/\sqrt{T}$ (VRTX)
Q (QX),	Qs (QSX)
A / Ach (ASATX)	

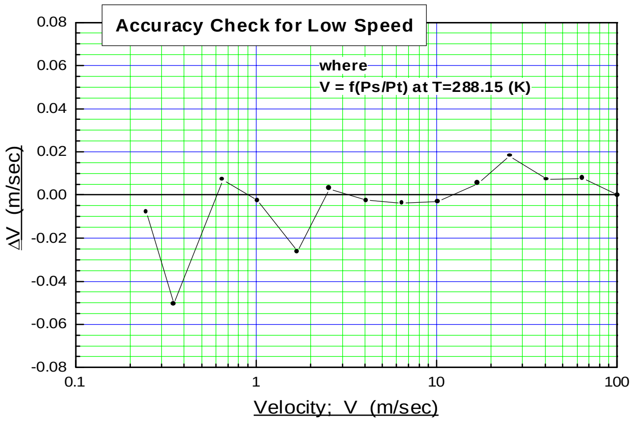

Fig. 7 Accuracy check for low speed

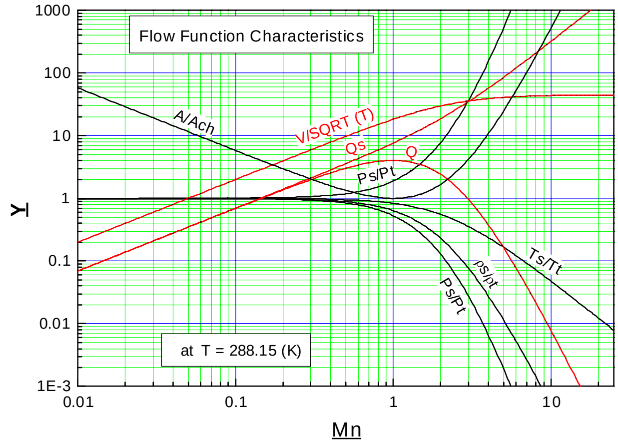

Fig. 8 Flow function characteristics

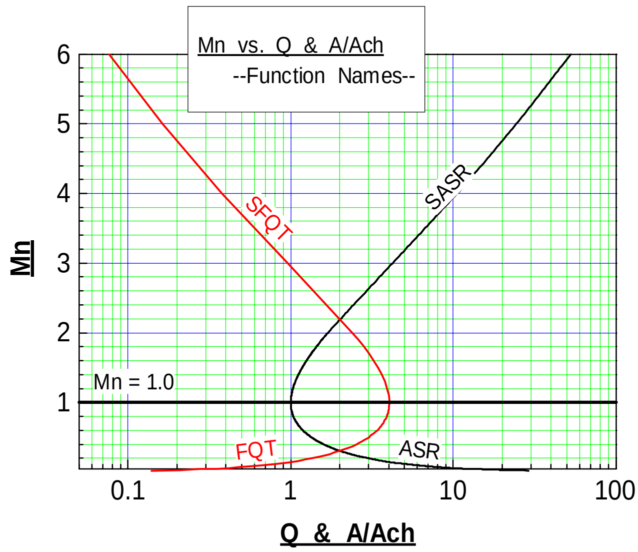

Fig. 9 Characteristics of volume flow rate; Q

APPLICATION AND REMARKS

The table developed consists of 18 thermodynamic sub-programs as shown in Table 1 and 9 flow function sub-programs as shown in Fig.6. The table, written in Fortran, is hoped to be a convenient tool when used as a subroutine program as the manner shown in Fig.9. It will be done simply by adding about 10 lines in the top of main program as described in Table 9.

FUEL/AIR RATIO

Fuel/air ratio is arranged to be taken as shown in Table 8 according to the value inputted.

Table 8　Fuel /Air ratio;　F

F =	f / a	for	$0 \leqq F < 0.09$
=	Φ	for	$0.09 \leqq F \leqq 2$
=	a / f	for	$2 < F$

THREE SYSTEMS OF UNITS

The symbol; ND (stands for Number of Dimension) in the Table 9, is the number to choose a system of units for SI, Metric and British unit as shown in Table 10, and the CK (stands for Constant Kappa) is prepared to cope with constant κ caluculation. For example, ND=3, CK=1.40 will yield the table for κ =1.4 with British unit.
These functions such as the ND and CK, will work as useful tools when numerical check is required for a reference document written in various units of systems. Most of the parameters of flow function are non-dimensional except the three functions shown in Eq. (9) which are shown in red lines in Fig. 8. These dimensional parameters will be specifically useful to check data. Table 11 shows an example of the dimensional parameters for a same condition with different systems of units.

Table 9　Formats to be added into main program

```
DEBUG
C    -----Main Program Format to use the Subroutine   -----

       COMMON/SYIAE/RM,R,AFST,CK,ND,G,CJK,AKR
       COMMON/SHEN/TSX,CPMX,AKMX,AKRMX
      / VRTX,QX,QSX,ASATX
C
       UR=8.31433          !      (kJ/kmol K)
       AM=28.967           !      (kg/kmol)
C
       G=9.80665
       CJK=4.1868          !      (kJ/kcal)
C
       R=UR/AM             !      (kJ/kg K)
       RM=R/CJK            !      (kcal/kg K)
C
C      ND=1! ND=1 for SI, 2 for Metric,3 for British Units.
C      CK=0.0              !  for Constant k
```

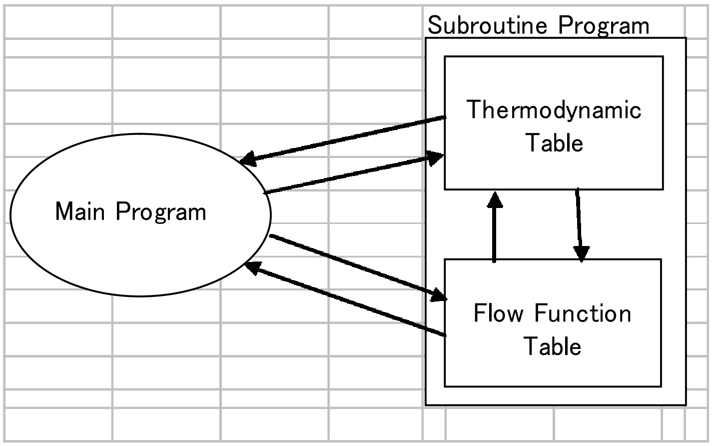

Fig. 10　Flow Chart/ Schematic

Table 10　Three systems of units

ND unit	1 SI	2 Metric	3 British
A	cm^2	cm^2	in^2
Cp, Cv, Φ	kJ/kg K	kcal/kg K	Btu/lb R
G	kg/sec	kg/sec	lb/sec
h, u	kJ/kg	kcal/kg	Btu/lb
L	m	m	ft
P	MPa	kg/cm^2	psia
T	K	K	R
V	m/sec	m/sec	ft/sec
ρ	kg/m^3	kg/m^3	lb/ft^3
$\frac{V}{\sqrt{T}}$	$\frac{m/sec}{\sqrt{K}}$	$\frac{m/sec}{\sqrt{K}}$	$\frac{ft/sec}{\sqrt{R}}$
Q , Qs	$\frac{\frac{kg}{sec}\sqrt{K}}{cm^2\,MPa}$	$\frac{(\frac{kg}{sec})\sqrt{K}}{cm^2(\frac{kg}{cm^2})}$	$\frac{\frac{lb}{sec}\sqrt{R}}{in^2\,psi}$

Table-11　Dimensional parameters for air at　Mn=1.0　T=288.15 (K)

ND	$V/\sqrt{T}$	Q	Qs
1; S I	18.3045	4.04287	7.65691
2; Metric	18.3045	0.39647	0.75089
3; British	44.7616	0.53192	1.00743

SUMMARY

A subroutine program, written in Fortran, is developed to make the programming work easy, relating to performance estimation, data analyzing and cycle calculation program etc. engaged with turbomachineries. The program consists of two parts, thermodynamic table and flow function table, the both are integrated together. The thermodynamic table is basically after Chappell's table(1974), of which the temperature range is extended to cover o-5000 (K) since it is required to work for the wider mach number range in the flow table. It has been done with the help of Keenan and Kay's table, JANAF's table and Chemkin Data Base. The table covers for air to stoichiometric condition. Relative pressure: Pr and relative volume: Vr are also obtained. The thermodynamic table consists of 18 sub-functions which arranged as below.

$$Cp,\ k,\ h,\ u,\ \phi,\ Pr,\ Vr = f(T,\ F)$$

$$T,\ Pr,\ Vr = f(h,\ F), \qquad T,\ Pr,\ Vr = f(u,\ F)$$

$$T,\ h,\ u = f(Pr,\ F), \qquad T,\ h,\ u = f(Vr,\ F)$$

The flow function table, is arranged to cover the mach number up to 25, by using the above thermodynamic table. The table consists of 9 sub-functions of which 6 are for non-dimensional and 3 are for dimensional parameters as shown below.

$$\{Mn,\ Ps/Pt,\ Pt/Ps,\ Ts/Tt,\ \rho_S/\rho_t,\ A/Ach\} = f(Mn)$$

$$\{\frac{V}{\sqrt{T}},\ Q,\ Q_S\} = f(R,\ Mn)$$

where ;

$$Q = \frac{G\sqrt{T}}{APt} \quad \text{and} \quad Qs = \frac{G\sqrt{T}}{APs} \qquad \left[\frac{kg/s\sqrt{K}}{cm_2 MPa}\right]$$

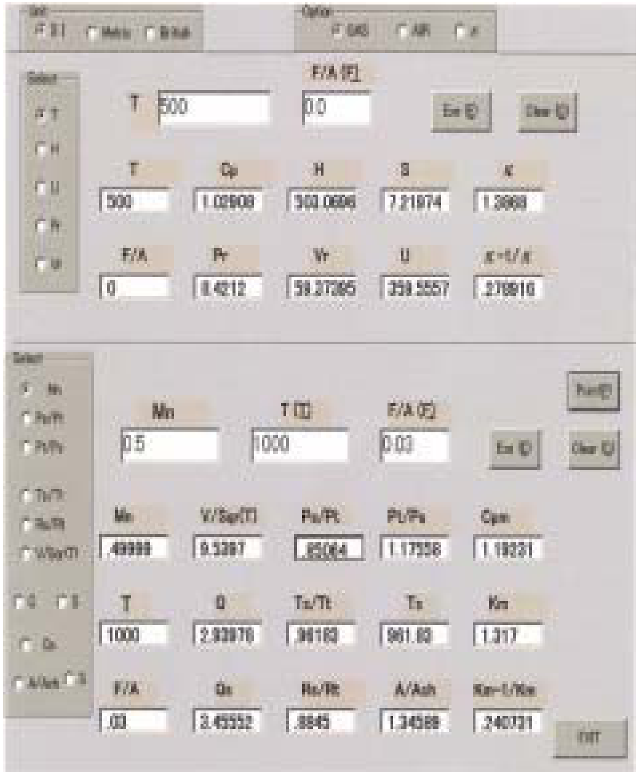

Fig. 11 VB Version for Hand Cal.

In the table, the functions such as Y=f (Ps/Pt, F, T), for example, are obtained where the Y denotes the above 9 parameters.

The both of thermodynamic and flow function tables are arranged to work for the three systems of units such as ;.

(1): S I , (2): Metric and (3): British unit

They are able also to work for constant κ. These functions , the three systems of units and constant κ, will work as a useful tool to check data numerically for documents written in various units.

The non-dimensional parameters in flow table will be specifically useful to check measured data. Most of text books are written with constant-κ such as, for example, $\eta=1/\varepsilon^{\kappa-1}$ for piston engine. On the other hand the relative pressure: Pr and relative volume Vr are used in practical work. A theoretical equation as above can be checked numerically by using the relative pressure: Pr and/or relative volume :Vr, with the constant κ option in this program. The result can be compared with air-cycle and/or fuel/air cycle calculations in the same manner with this table.

The function of the table will best be described with the Visual Basic Version as shown in Fig.11, which arranged for hand calculation. The upper half in the figure is for thermodynamic table and the lower half for flow function table. The subroutine program is hoped to be utilized by whom interested.

ACKNOWLEDGMENTS

The author has been looking for the chance to accomplish the table for personal use. The study was summarized in the Shenyang Institute of Aeronautical Engineering (SYIAE) in China. The author would like to acknowledge the generosity of Professor Rui Xiao-miao, President Office, for his encouragement to accomplish the study. The author appreciate Professor Xu Rang-shu and also Associate Professor Fu Li-xin, Department of Power Engineering ,to provide various supports during the course of study.

[Note]

Essence of this study is in the software. It will be shared with whom interested. Please contact to the author by e-mail.

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