ABSTRACT

Title of Thesis: One-Dimensional Compressible Flow Analysis - Isentropic And Normal Shock.

Su-Bo Wong, Master of Science in Mechanical Engineering 1983.

Thesis Directed by: Rong-yaw Chen
Professor of Mechanical Engineering

A computer program to compute and analyse one-dimensional isentropic compressible flow through variable cross-sectional area with or without a normal shock is developed. The program is written in the "FORTRAN LANGUAGE".

In this work, the area change is the predominant cause of change of flow condition. One of the advantage of this program is set on general uses for isentropic flow. In common practice, the values of the isentropic flow property ratios were tabulated or graphically presented as function of the Mach number with a specified specific heat ratio, K (normally K=1.40 was presented). With todays technology, the most versatile method is by implementation of computer programming method.

The computer program presented can solve all the one-dimensional isentropic flow problems and to analyse the flow characteristic and the flow patterns in converging nozzle and

converging-diverging nozzle. The value of K can be assigned as any value as one's requirement. All the solutions are computed within 0.1 % error. For solving Mach number and location of normal shock inside the nozzle, ITERATION method is employed instead of numerical method. In most cases, a few iterations (less than ten) may arise a reasonable solutions.

ONE-DIMENSIONAL COMPRESSIBLE FLOW ANALYSIS - ISENTROPIC AND NORMAL SHOCK

by

Su-Bo Wong

Thesis submitted to the Faculty of the Graduate School
of the New Jersey Institute of Technology in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering

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NOTATION

a	Speed of sound
A	Cross-sectional area of duct
h	Specific enthalpy
K	Specific gas ratio
M	Mach number
$\dot{M}$	Mass flow rate
MF	Mass flux = $\dot{M}/A$
P	Static pressure
R	Specific heat constant
s	Specific entropy
T	Static temperature
V	Velocity of the fluid flow
v	Specific volume
X	Position coordinate
ρ	Density
max	Maximum
o	Stagnation condition
*	Condition at M = 1

1. INTRODUCTION

Fluid mechanics is that study of fluid motion involving a rational method of approach based on general physical laws and consistent with the results of modern experimental study. There is hardly a branch of engineering that is not concerned with fluids or does not make use of them. Real economy and value are achieved in studying at one time the same principles underlying the flow of different fluids. Such a study tends to develop a sound background and to make one versatile in approaching new problems.

A fluid may be considered as compressible or incompressible. As an example in the compressible flow, when the relative velocity of the fluid with respect to the immersed body became high, the results of the analysis for the pressure coefficient began to depart from that based on incompressible flow. Also, when the speed of the fluid relative to the immersed body approached the speed of sound in the flowing medium, owing to the compressibility of the fluid, the deviation from incompressible flow analysis become pronounced.

The fact that the flow is compressible indicates that the density, ρ of the flowing medium is a sensitive function of the pressure. The introduction of this new variable ρ into the equations of motion will necessitate the study of its relationship to the other properties of the medium. This need then invokes the principles of thermodynamics which represent a separate and independent approach from the dynamic equations of motion. Since a new variable ρ has been added, this independent approach is necessary for the solution of the problem, and the concepts of thermodynamics will play an important role in the theory of compressible flow.

Friction, heat transfer,area change and electromagnatic fields have a great effect on compressible flow. In most physical situations, more than one of these effects occur simultaneously; for example, flow in a rocket nozzle involves area change, friction,and heat transfer. However, one of the effects is usually predominant; in the rocket nozzle, area change is the factor having greatest influence on the flow. The frequent predominance of one factor provides a justification for separating the effects, including them one at a time in the equations of motion, and studying the resultant property variations.

Whereas a certain loss of generality is incurred by treating each of the effects individually, this procedure does simplify the equations of motion so that the results of each of the effects can be easily appreciated. Further, this simplification enables approximate solutions to be derived for a wide range of problems in compressible flow; such solutions are sufficiently accurate for many engineering applications. Attempts to include all the effects simultaneously in the equations of motion lead to mathematical complexities that mask the physical situation. In many cases exact solutions to these generalized equations of motion are impossible.

This study is concerned with compressible, isentropic flow through varying area ducts, such as nozzles passages. Friction and heat transfer are negligible for this isentropic flow; variation in properties are brought about by area change. One-dimensional steady flow of a perfact gas is assumed in order to reduce the equetions to a workable form. Since this is a study of gas flows, changes in potential energy and gravitational forces are neglected.

The intention on this study has been to provide a good understanding of the physical behaviour of compressibe fluid flow and an adequate appreciation of the principles behind the design of modern engines such as nozzles and their equivalent form a very important item of all turbine and jet devices. In this work, a computer program is implemented to solve most of the engineering problems arising from isentropic compressible flow.

In general, the changing variable properties are To,Po,T,P,

ρ_o, ρ, M, V, m/A (MF), K, R. Since K and R are the properties of the gas and usually listed in most of the science or engineering data booklets. The remainder nine properties at which three properties must be given in order to obtain the rest of the variable properties, this gives the initial cross-section (station 1) properties. The program may proceed further to consider any other sections of the duct with no discontinuities or shock wave occurs inbetween. since the stagnation properties are remains constant at any sections of the duct, by giving one properties from T, P, M, V, ρ, AR (A1/A2 - area ratio), the other properties can be obtained.

To shows the great effect of mach number and wisely needed in engineering applications; converging nozzle and converging-diverging nozzle were chosen to demonstrate on this study . The program is constructed to consider a fluid stored in a large reservoir and is discharged through a converging nozzle; by varying the back pressure to analyse the characteristics and compute the properties of the fluid flow at the exit plane. For converging-diverging nozzle, it is desired to consider the pressure distribution in the nozzle over a range of values of Pb/Po with Po maintained constant (except across the shock wave). The phenomenon of the choked or unchoked, shock wave occurs inside or outside the nozzle , overexpansion , underexpansion or designed condition; all those situations will be detected and printed at the output of the solutions.

The main fundamental concepts are discussed in Chapter 2, which include the analysis, governing equations for isentropic flow and flow across the normal shock wave and the features of the fluid flows through the converging nozzle and converging-diverging nozzle.

Chapter 3 is the method of solutions which explain the techniques of writting this program and the procedures of inputing the data.

Conclusions are presented in Chapter 4 and suggested recommendations are in Chapter 5. Appendix - A, is the computer program and Appendix - B, is the sample of examples. Finally, the References.

2. ANALYSIS

2.1 Fundamental Concepts

Four basic laws can be readily applied in studying the flow of compressible fluids. These fundamental laws or principles upon which the analysis presented in this study depend directly or indirectly are :

(A) The law of conservation of mass

$$\rho VA = constant$$

(B) Newton's second law of motion

$$1/\rho \; dp + V \; dV = 0$$

(C) The first law of thermodynamics

$$h + V^2/2 = conatant$$

(D) The second law of thermodynamics

$$T \; ds = dh - v \; dp$$

In any flow analysis some information about the properties of the fluid must be known. This information (such as equation of state of a perfact gas) is used in connection with the basic laws to provide maximum knowledge of the flow. Compressible flow can be treated at various levels of complexity. In this work, the most elementary level possible was taken and the results by virtue of their simplicity, are among the most instructive.

The basic approximations are that the flow is steady and one-dimensional or, more precisely, steady and quasi-one-dimensional. By this we mean that the flow can be treated according to a one-dimensional model even though the 'real' flow is in fact three-dimensional.

2.2 Classification of Compressible Flows

There are large differences in flow patterns with compressible flows. General behaviour of the flow depends on whether the fluid velocity is greater or less than the local velocity of sound. Thus , the compressible flows may be classified as follows :

(1) $M < 1$ ---- Subsonic flow ;

(2) $M = 1$ ---- Sonic flow ;

(3) $M > 1$ ---- Supersonic flow.

A transonic flow is defined as a flow having regions in which the flow speed changes from subsonic to supersonic. For example, transonic flows can occur in converging-diverging nozzles and in flow over bodies.

A hypersonic flow is a supersonic flow at high mach number (often defined as a flow whose mach number is greater than 5) . Hypersonic flows are so called because they require treatment somewhat different from low mach number supersonic flows.

2.3 Assumptions on The Flow Through a Normal Shock Wave

The assumptions are made as follows:

(1) The boundary surface forming the stream tube is far removed from the boundary layers adjacent to any solid surface. Since all friction forces may be assumed to be confined to the shearing stresses in the boundary layer, the configuration under discussion is a frictionless duct.

(2) The shock process takes place at constant area; that is, the streamlines forming the boundary of the stream tube are parallel.

(3) The shock wave is perpendicular to the streamlines.

(4) The flow process, including the shock wave is adiabatic, no external work is performed, and the effects of body forces are negligible.

2.4 Governing Equations

(A) For Isentropic Flow:

The ratio of the speed of the fluid at a point to the local speed of sound at that point is a useful index for identifying the flow. this ratio is called the Mach number, M.;

$$M = \frac{V}{a} \qquad (1)$$

For isentropic flow,

$$a^2 = \left(\frac{\partial P}{\partial \rho}\right)_s$$

Where subscript s denotes constant entropy.

For an ideal gas under isentropic process P^{-K} =const.

Thus,

$$a = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_s} = \sqrt{\frac{KP}{\rho}} = \sqrt{KRT} \qquad (2)$$

$$\therefore \quad M = \frac{V}{\sqrt{KRT}} \qquad (3)$$

The stagnation temperature, To is the temperature where the speed of the fluid is zero. With the energy equation for isentropic flow, we get

$$To = T\left(1 + \frac{K-1}{2} M^2\right) \qquad (4)$$

The stagnation pressure Po and the stagnation temperature To are related by

$$\frac{Po}{P} = \left(\frac{To}{T}\right)^{\frac{K}{K-1}} \qquad (5a)$$

$$\text{or} \quad \frac{Po}{P} = \left(1 + \frac{K-1}{2} M^2\right)^{\frac{K}{K-1}} \qquad (5b)$$

The stagnation or total density, ρ_o is the density corresponding to the stagnation temperature and pressure.

From the thermal equation of state,

$$Po = \rho_o R T \qquad (6a)$$

$$\text{or} \quad P = \rho R T \qquad (6b)$$

Substituting equations (4) & (5) into equation (6) yields

$$\frac{\rho_o}{\rho} = \left(1 + \frac{K-1}{2} M^2\right)^{\frac{1}{(K-1)}} \qquad (7)$$

The continuity equation may be transformed to read

$$\frac{\dot{M}}{A} = \rho V = \frac{PV}{RT} \qquad (8a)$$

Substituting equation (3) into equation (8a) yields

$$\frac{\dot{M}}{A} = \frac{PV}{RT} = \frac{PV}{(KRT)^{1/2}} \left(\frac{K}{RT}\right)^{1/2}$$

$$= PM\left(\frac{K}{RT}\right)^{1/2} \qquad (8b)$$

From equation (4), we have

$$T = \frac{To}{\left(1 + \frac{K-1}{2} M^2\right)}$$

Hence, in terms of the stagnation temperature To ; equation (8b) becomes

$$\frac{\dot{M}}{A} = PM\left[\frac{K}{RTo}\left(1 + \frac{K-1}{2} M^2\right)\right]^{1/2} \qquad (8c)$$

From equation (5b), it follows that

$$P = Po\left[1 + \frac{K-1}{2} M^2\right]^{-\frac{K}{K-1}}$$

Hence, the continuity equation expressed in terms of the stagnation pressure Po for the actual flow becomes

$$\frac{\dot{M}}{A} = MPo\left(\frac{K}{RTo}\right)^{1/2} \cdot \left[1 + \frac{K-1}{2} M^2\right]^{\frac{-(K+1)}{2(K-1)}} \qquad (8d)$$

or in terms of T, we have

$$\frac{\dot{M}}{A} = MPo\left(\frac{K}{RT}\right)^{1/2} \cdot \left(1 + \frac{K-1}{2} M^2\right)^{\frac{K}{1-K}} \tag{8e}$$

(B) For Normal Shock Wave:

In below is the application of the equations developed in the above to normal shock wave.

Since To is a constant, therefore equation (4) gives

$$\frac{T_2}{T_1} = \frac{1 + \frac{K-1}{2} M_1^2}{1 + \frac{K-1}{2} M_2^2} \tag{9}$$

From equation (8a), as $\dot{M}/A$ = Const., we can derived that

$$\frac{V_2}{V_1} = \frac{\rho_1}{\rho_2} = \frac{P_1 T_2}{P_2 T_1} \tag{10}$$

Substituting equation (3) into equation (10) gives

$$\frac{P_2}{P_1} = \frac{M_1}{M_2}\left(\frac{1 + \frac{K-1}{2} M_1^2}{1 + \frac{K-1}{2} M_2^2}\right)^{1/2} \tag{11}$$

Introducing the momentum equation,

$$P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2 = \text{constant.} \tag{12a}$$

or $$P_1\left(1 + \frac{\rho_1 V_1^2}{P_1}\right) = P_2\left(1 + \frac{\rho_2 V_2^2}{P_2}\right) \tag{12b}$$

From equation (2), noting that $a^2 = KP/\rho$,equation (12b) yields

$$\frac{P_2}{P_1} = \frac{1 + KM_1^2}{1 + KM_2^2} \tag{13}$$

Equating the right-hand sides of equation (11) and (13), We can obtained that

$$\frac{M_1\left(1 + \frac{K-1}{2} M_1^2\right)^{1/2}}{1 + KM_1^2} = \frac{M_2\left(1 + \frac{K-1}{2} M_2^2\right)^{1/2}}{1 + KM_2^2} \tag{14}$$

Squaring both sides of equation (14) and solving for M2 yields

$$M_2 = M_1 \tag{15a}$$

or

$$M_2^2 = \frac{M_1^2 + \frac{2}{K-1}}{\frac{2K}{K-1} M_1^2 - 1} \tag{15b}$$

Equation (15a) expresses the trival result that no change occurs across the normal shock wave; that is, the latter has infinitestimal strength. Equation (15b) gives the solution for a normal shock wave of finite strength.

For a normal shock wave to occur, the mach number, M1 must be greater than unity and equation (15b) shows that as M1 in front of the normal shock wave is increased infinitely, the mach number, M2 in back of the normal shock wave continually decreases but approaches the limiting value $\sqrt{(k-1)/2K}$. The limiting value for M2 depends only on the specific heat ratio for the gas. For air and diatomic gases, k=1.40 and $\sqrt{(k-1)/2K}$ =0.378. (Note that the computer program presented is permitted to put any value of k as one's necessity).

The property ratios across a normal shock wave may be expressed in terms of the mach number ahead of the shock wave M1 by substituting equation (15b) into equations (9), (10) and (13) to eliminate M2. Thus

$$\frac{T_2}{T_1} = \left(\frac{2K}{K+1} M_1^2 - \frac{K-1}{K+1}\right)\left[\frac{K-1}{K+1} + \frac{2}{(K+1)\ M_1^2}\right] \tag{16}$$

$$\frac{\rho_2}{\rho_1} = \frac{(K+1)\ M_1^2}{2+(K-1)\ M_1^2} \qquad (17)$$

$$\frac{P_2}{P_1} = \frac{2}{K+1}\ M_1^2 - \frac{K-1}{K+1} \qquad (18)$$

$$\frac{Po_2}{Po_1} = \left\{ \left(\frac{K-1}{K+1} + \frac{2}{(K+1)M_1^2} \right)^K \cdot \left[\frac{2K}{K+1}\ M_1^2 - \frac{K-1}{K+1} \right] \right\}^{\frac{-1}{K-1}} \qquad (19)$$

It follows from equation (17) that as the mach number M1 approaches infinity, the density ratio ρ/ρ_o approaches (k+1)/(k-1) as a limiting value. (i.e. = 6, for k=1.40). On the other hand, the pressure ratio P2/P1 (see equation (18)) increases continuously with M1.

The flow conditions immediately in front of and in back of the normal shock wave are isentropic, thus all the governing equations derived for isentropic flow can be applied to those sections.

2.5 Performance of Converging Nozzle

Consider the configuration shown in fig.2.1., where a simple converging duct discharges into a region where the back pressure Pb is controlled by a valve. Let Pe be the pressure in the exit plane of the nozzle and Po the reservoir pressure (stagnation pressure for isentropic flow).

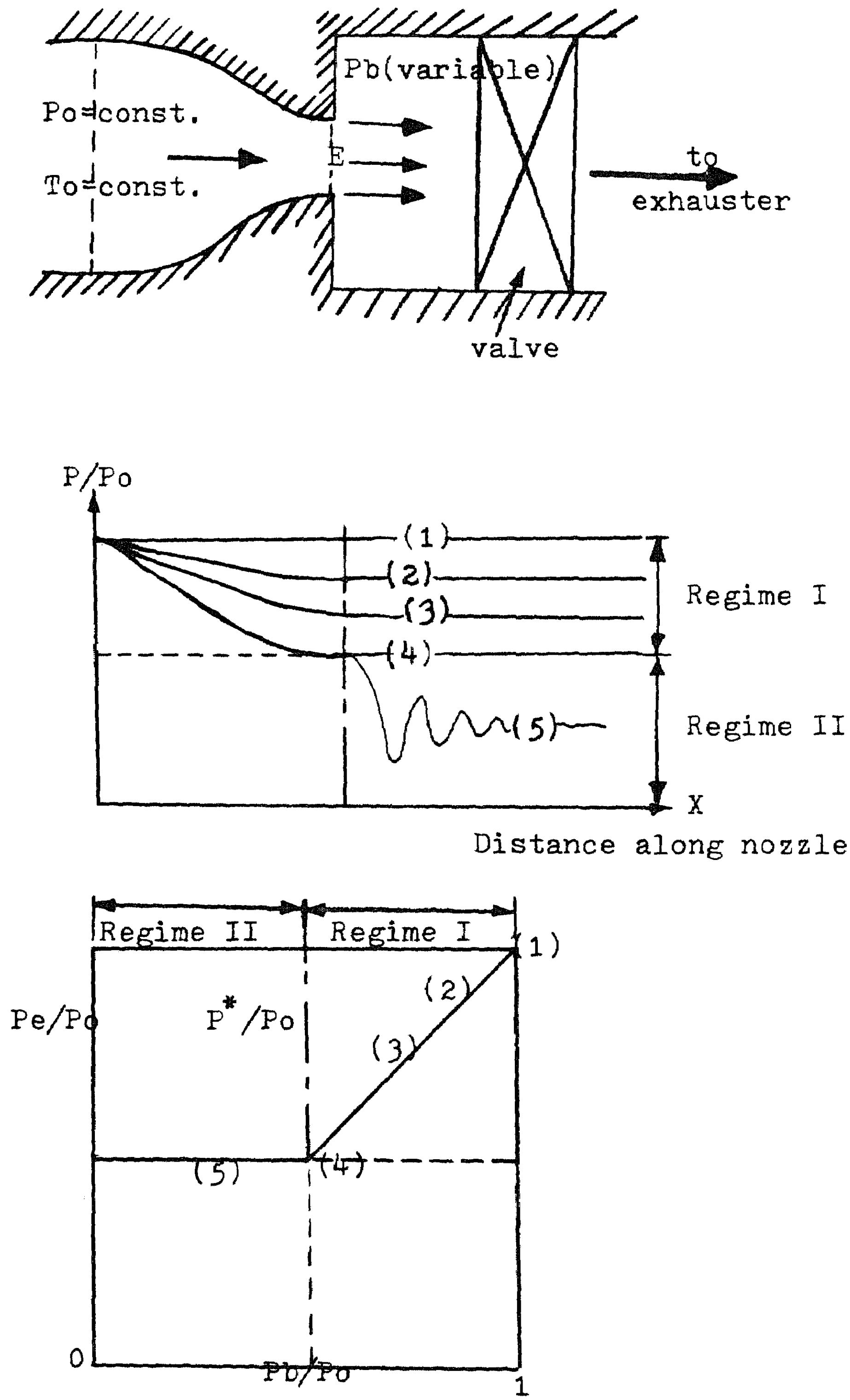

fig.2.1. Flow Through a Converging nozzle

If $P_b/P_o = 1$ (at condition 1, fig.2.1) then the pressure is constant throughout the nozzle and there is no flow. If Pb is slightly reduced from this value (condition 2, fig.2.1) a subsonic flow will be established with the exit pressure Pe equal to the back pressure Pb. If Pb is reduced further to condition 3, the flow remains subsonic with Pb=Pe, but the mass flow rate increases. This increase continues until Pb/Po reaches the critical pressure ratio ($P_b/P_o = P^*/P_o = P_e/P_o$) where Me = 1, i.e. condition 4. If Pb is reduced further, (condition 5), the pressure Pe can not become less than P since Me stays at 1. Therefore the flow rate remains constant and pressure distribution inside the nozzle remains the same as for condition 4. The pressure distribution in the chamber outside the nozzle for Pb/Pe can not be predicted accurately by a one-dimensional model and is indicated by a wavy line.

The maximum mass flux, (MF)max can be found from equation (8c) with Me = 1, gives

$$\left(\frac{\dot{M}}{A}\right)_{max} = Po\sqrt{\frac{K}{RTo}\left(\frac{2}{K+1}\right)^{\frac{K+1}{K-1}}} \qquad (20)$$

and from equation (5b),

$$\frac{P^*}{Po} = \left(\frac{2}{K+1}\right)^{\frac{K}{K-1}} \qquad (21)$$

For $k = 1.40$, $P^*/Po = 0.5283$

2.6 Performance of Converging-Diverging Nozzle

Consider the case in which a fluid stored in a large reservoir is to be discharged through a converging-diverging nozzle. The experiment can be carried out similar to the above case (converging nozzle) by controlling the valve to vary the back pressure, Pb. It was pointed out that for certain ratios of back pressure to supply pressure, isentropic, one-dimensional solutions to the equations of motion are not possible. However, it is sufficient to analyse the normal shock occured inside or at the exit plane and studied in details. It is desired to find the pressure distribution in the nozzle over a range of values of Pb/Po, with Po maintained constant.(see fig.2.3a)

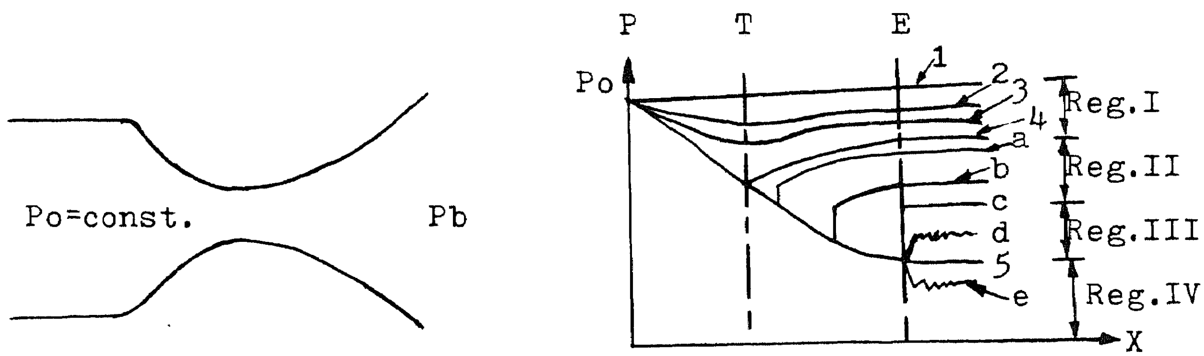

fig.2.3a

With Pb = Po, there is no flow in the nozzle. As Pb is reduced below Po, subsonic flow is induced through the nozzle with pressure decreasing to the throat then increasing in the diverging portion of the nozzle. When the back pressure is lowered to that of curve 4, sonic flow occurs at the nozzle throat. Further reductions in back pressure can induced no more flow through the nozzle. As the back pressure is reduced below that of curve 4, a normal shock appears in the nozzle just downstream of the throat (curve a). Further reductions in back pressure cause the shock to move downstream (curve b), until for a low enough back pressure, the normal shock positions itself at the nozzle exit plane (curve c). Consider in detail a curve of P versus X with a shock in the nozzle (fig.2.3b). the static pressure decreases in the converging portion of the nozzle, with M = 1 at the throat. In the diverging portion, with the flow supersonic, the pressure continues to decrease up to the normal shock. After the shock, flow in the diverging part of the nozzle is subsonic, the static pressure increasing to the exit plane pressure. With subsonic flow at the exit, the exit plane pressure is equal to the back pressure.

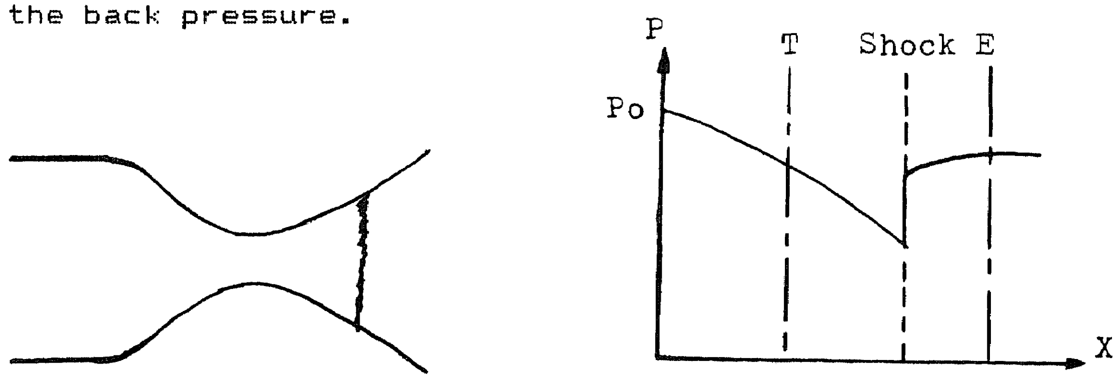

fig.2.3b

As the back pressure is lowered below that of curve c, a shock wave inclined at an angle to the flow appears at the exit plane of the nozzle (fig.2.3c). This shock wave, weaker than a normal shock is called an oblique shock. Further reductions in back pressure cause the angle between the shock and the flow to decrease, thus decreasing the shock strength (fig.2.3d) until eventually the isentropic case, curve 5, is reached. Curve 5 corresponds to the design condition in which the flow is perfectly expanded in the nozzle to the back pressure.

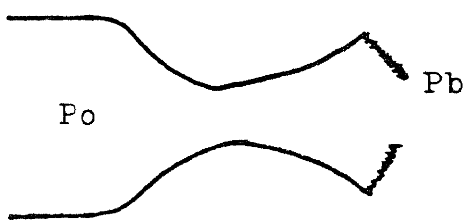

fig.2.3c

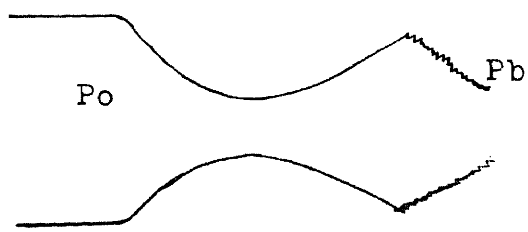

fig.2.3d

For back pressure below that of curve 5, exit plane pressure is greater than the back pressure. A pressure decrease occurs outside the nozzle in the form of expansion waves (fig.2.3e). Oblique shock waves and expansion waves represent flows which are not one-dimensional and can not be treated directly with the equations derived before.

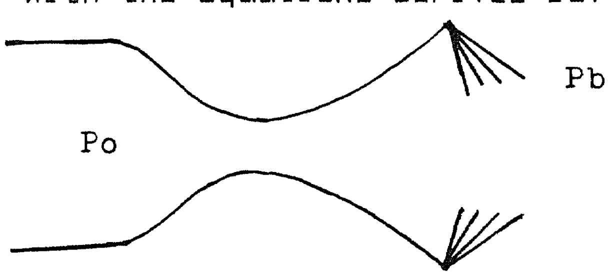

fig.2.3e

It is important to realize that for all back pressures below that of curve c the flow adjusts to the back pressure outside the nozzle. Over this range of back pressures (below c), flow inside the nozzle remains unchanged as the back pressure is varied. For example, the exit plane pressure and exit velocity are the same for all back pressures below c. If a rocket nozzle is designed to operate isentropically at sea level, the rocket exhaust velocity and exit plane pressure do not change as the rocket moves upwards through the atmosphere (assuming constant chamber temperature and pressure).

Fig.2.3f depicts the variation of exit plane pressure with back pressure. For subsonic flow at the exit plane (curves 1,2,3,4, a,b,c), and for the design condition (curve 5), the exit plane pressure is equal to the back pressure. For supersonic flow at the exit plane (curve d,5,e) the exit plane pressure is equal to that for the design condition. For back pressure between c and 5, the exit plane pressure is less than the back pressure, so that the nozzle is termed overexpanded. For back pressure below 5, with the exit plane pressure greater than the back pressure, the nozzle is termed underexpanded.

Fig.2.3g shows the variation of pressure at the throat with back pressure, when back pressure is in between 1 and 4, the pressure at throat varies with back pressure (i.e. unchoked condition). Till back pressure equals or less than 4, choked condition, Pt always remain at P (i.e. critical stage).

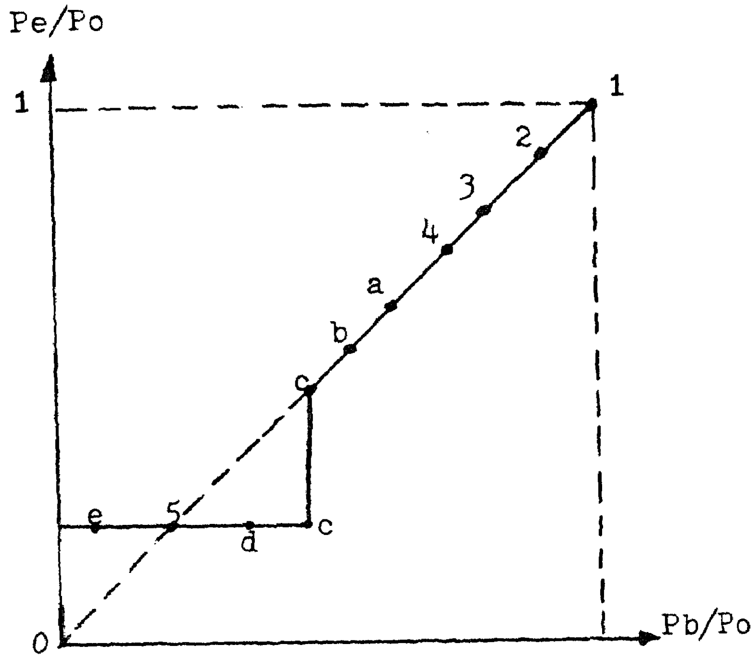

fig.2.3f

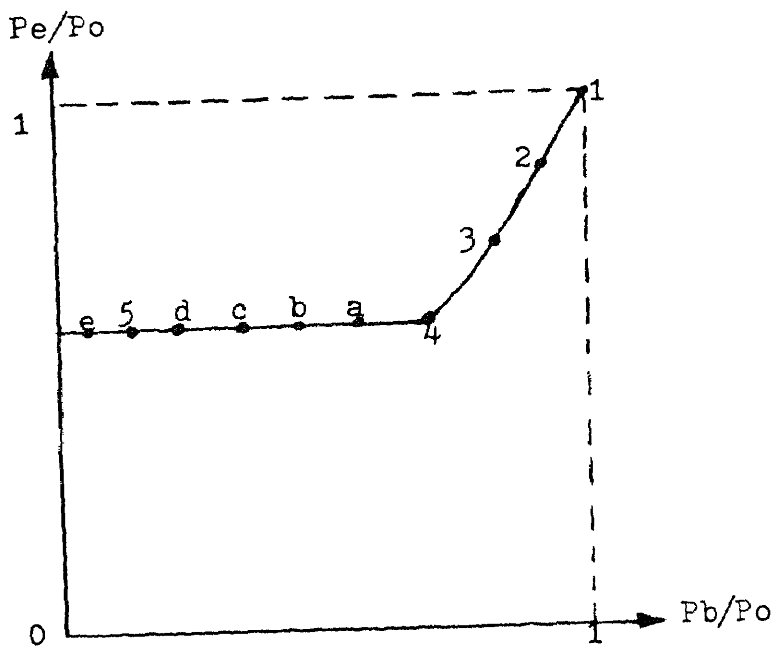

fig.2.3g

Summarising, there are four regimes of flow :

(I) Subsonic flow throughout the duct, maximum velocity is reached at the throat.

(II) Subsonic flow at the throat, then supersonic up to the normal shock, following by subsonic compression.

(III) Subsonic flow to the throat, followed by supersonic flow to the exit plane. Non-isentropic re-compression outside the duct though oblique shock waves.

(IV) Flow in the duct identical to (III), supersonic jet expanding out of the nozzle exit.

The nozzle is choked in regimes (II),(III) & (IV). The mass flow rate, M is independent of the back pressure and is a maximum. Only in regime (I) can the mass flow rate be changed by variation in the back pressure.

3. METHOD OF SOLUTIONS

3.1 Introduction

By use of the governing equations developed in Chapter 2, we can express the flow property ratios (T/To, P/Po, etc.) in a steady one-dimensional isentropic flow as a function of the local flow mach number, M for a given value of the specific heat ratio, k. In most of the engineering compressible text books, the values of the isentropic flow property ratios are tabulated or grapically presented as function of the mach number for k = 1.40. It has been a common practice of using table or graphs, whenever possible, in solving steady one-dimensional flow problems.

In most cases, the initial conditions at the inlet cross-section of the passage are specified. Using those conditions, the corresponding values of T/To, P/Po, ρ/ρ_o ,etc. may be read directly from tables or graphs. The reference condition To, Po, ρ_o , A may than be calculated.

One condition at the exit cross-section of the flow passage must be known, so that tables or graphs may be employed for determine the property ratios, and hence the flow properties at the exit cross-section. Many problems of the practical interest are not that straight-forward, and may be too complicated for a closed-form mathematical solution. A numerical solution is required and the most versatile method is by implementation of computer programming method. With present-days technology, computer is common and wisely used. It may solves the problem in shortest time with great efficient and high merit of accuracy. In this work, a computer program is developed to solve the isentropic flow problems instead of traditional method by using tables or graphs to compute and analyse the flow pattern. Also, it can be used for any different values of specific heat ratio, k.

One of the advantages of setting the program on general purpose is that many of the solution steps are common to all application area. For instant, the procudure for solving problems in converging or converging-diverging nozzle involve many of the same steps found in general program; i.e. for given three properties and compute the remainder properties.

3.2 Techniques of Programming the Program

A genaral computer flow diagram is presented in fig.3.1. This flow diagram is specifically for the one-dimensional isentropic flow with variable cross-sectional area and is

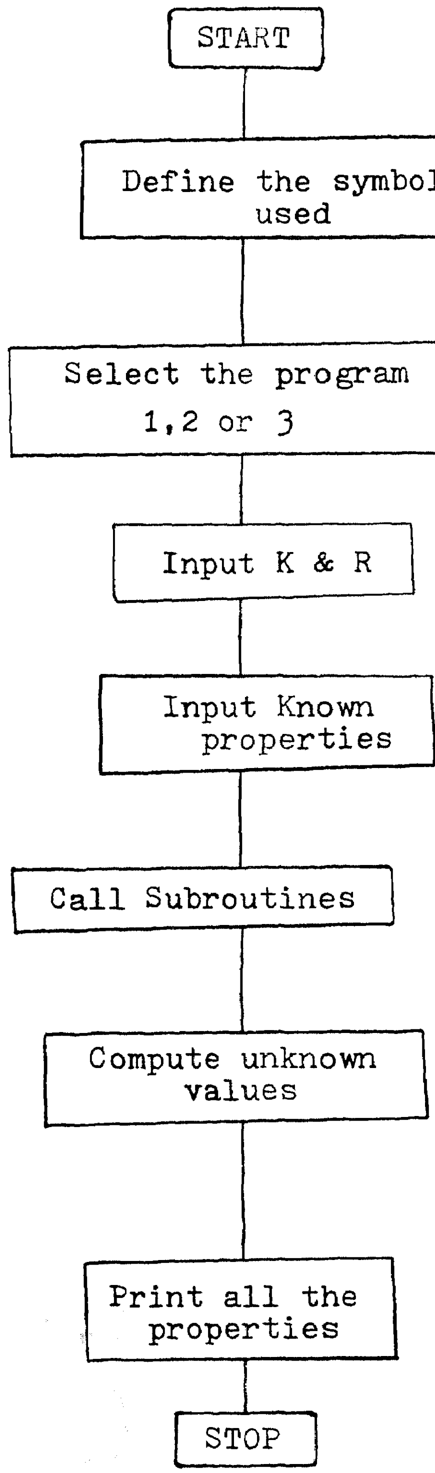

fig.3.1. A General Flow Diagram

valid for all of the application areas discussed in Chapter 2. Each major step of the flow chart will be discussed in genaral terms rather than with respect to a specific example.

Firstly, the general program was established. In general, the changing variable flow properties are To, Po, T, P, ρ, ρ_o M, V, MF, K and R. Since K and R are the properties of the gas and usually listed in most of the text books. The remainder nine properties at which three must be given to make the solution possible.

From the knowledge of mathematical statistics, if one is interested only in what particular objects are selected when r objects are chosen from n objects (where r and n are any arbitrary numbers), without regard to their arrangement in a line, then the unloaded selection is called a "COMBINATION ".

Employing the formula with r = 3 and n = 9 ;

Combination formula :

$$\binom{n}{r} = \frac{n}{r!\ (n-r)!}$$

$$\text{i.e.}\quad \binom{9}{3} = \frac{9!}{3!\ (9-3)!} = \underline{84}.$$

From the above, it is understood that there are 84 ways of setting the problems.

Mass flux, MF is a most common property that either known or unknown value. This property is taken as a reference and divide the program into two parts. i.e. (1) Given two properties with mass flux, MF ; or (2) Given three properties without MF.

Using the same combination knowledge, we get in case (I) is 28 ways and 56 ways in case (II). Due to certain properties gives in the combination is exactly the terms of the governing equation, it is unable or should say not enough information to solve the problem. Such as occured in case (I) has two cases and eight cases in case (II). When this situation appears, the output will print " NOT ENOUGH INFORMATION".

The logical If statement is used as a transfer control for the given condition. A pattern of entering the code number is fixed by entering the code number in ascending order.

For example, The coding as follows:

To - 1	T - 3	DN - 5	M - 7
Po - 2	P - 4	DNO- 6	V - 8

For given To,Po,P then enter 124 without any punctuation in between the numbers.

One of the most tedious part in the program is to solve for

M by trial and error. Here, ITERATION method is used instead of other numerical method, like Newton-Raphson method, because numerical method may easily diverged and make the solution impossible.

For instant, given MF,Po and To from equation (8c), we have

$$MF = M\,Po\left(\frac{K}{RTo}\right)^{1/2}\left(1 + \frac{K-1}{2}M^2\right)^{-\frac{(K+1)}{2(K-1)}}$$

Solving for M,

$$M = \frac{MF\left(1+\frac{K-1}{2}M^2\right)^{\frac{(K-1)}{2(K-1)}}}{Po\left(\frac{k}{RTo}\right)^{1/2}}$$

By iteration, the DO-LOOP being employed. The Fortran statement may be written as follows :

```
      DUMMY=PO*SQRT(K/R/TO)
      M=MF*(1+C2)**PW5/DUMMY
      DO 111 I=1,30
      MP=MF*(1+C2*M*M)**PW5/DUMMY
      EP=ABS(1-MP/M)
      IF (EP.LT.0.00001) GO TO 1000
      M=MP
111   CONTINUE
1000  --------
      --------
```

In most cases, only a few iterations (normally less than 10) may gives the reasonable solution within 0.001 % error.

Due to many solution steps are common in most of the cases, in preparing the program, one must solve all the 84 cases at one time to search where the solution steps are common. By grouping those steps together to form the SUBROUTINE. In this program, eleven subroutines were employed.

3.3 Comments on the Computer Program

When the program get started, it prints the NOTATION of the symbols used then follows by select program:

(1) Given three properties of a flow in a duct, find the other properties of the flow;

(2) Converging nozzle flow from reservoir;

(3) Converging-Diverging nozzle.

3.3.1 Program (1)

1. Select either (a) Given mass flux with two properties

   or (b) Given three properties without mass flux.
2. Input K and R.
3. Input the known properties with the coding specified in ascending order.
4. Input the values of the known properties.

5. The computer may compute the unknown properties at this initial section and print out the solutions.

6. It may proceed further to compute any section of the duct by entering one known properties.

7. The program may keep on repeated until all the section of the required properties are obtained

3.3.2 Program (2)

1. Input K and R

2. Input To,Po and Pb (Back pressure)

3. The computer may detect the characteristic of the flow pattern through the nozzle. Refer to Chapter two, fig.2.1.

(i) Po = Pb

(ii) Regime I (Po < Pb < P(iv))

(iii) Regime II (Pb < P(iv))

(iv) Pb = P(iv)

4. Print the properties at the exit plane.

3.3.3 Program (3)

1. Input K and R

2. Input To,Po and Pb (Back pressure)

3. Input area ratio between exit and throat (Ae/At)

4. The program is able to detect the charecteristic of the flow pattern. Refer to fig.3.2 in below :

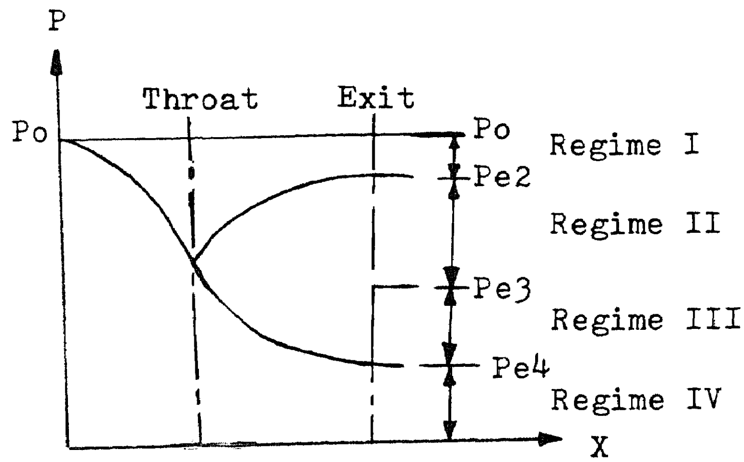

fig.3.2

(i) Find Me2 and Me4

(ii) Determine Pe2, Pe3 and Pe4

(iii) Using Logical IF to classify the flow pattern. Generally, it consists of the following cases. (Note : All the details had been included in Chapter 2).

(a) Po = Pb

(b) Regime I (Po > Pb > Pe2)

(c) Pb = Pe2

(d) Regime II (Pe2 > Pb > Pe3)

(e) Pb = Pe3

(f) Regime III (Pe3 > Pb > Pe4)

(g) Pb = Pe4

(h) Regime IV (Pe4 > Pb)

In the above eight cases,themost difficult part of the program is in Regime II (i.e. to locate normal shock inside the nozzle).There are many ways of solving this problem. Here, the iteration method is employed to find the area ratio AR, where the normal shock occurs. The program is constructed as follows:

(i) By averaging the area ratios AR at throat and exit to assume the normal shock wave occurs half way between the throat and the exit plane.

(ii) Fromthe throat condition with M = 1 and the known Po,To. Using subroutine with estimated AR to compute the properties before the normal shock occurs.

(iii) Compute the properties after normal shock wave occurs.

(iv) Using subroutine to determine the properties at the exit plane.

(v) To compare is the computed exit pressure Pe = Pb ?

(vi) (a) If Pe > Pb ; take AR as the average of the estimated AR and area ratio at the throat.

(b) If Pe < Pb ; take AR as the average of the estimated AR and the area ratio at the exit.

(vii) Repeating the procedures by taking the average until Pe within 0.1 % error equals to Pb. In most cases, within ten iterations the solution may arise.

(5) Print all the necessary solutions. i.e

(i) Throat properties;

(ii) exit plane properties;

(iii) normal shock, before and after.

The program constructed in the above are three programs that are commonly needed for studying one-dimensinal isentropic compressible flow with variable cross-sectional area. The program may be modified or extended to fit others requirement.

4. CONCLUSION

A computer program to aid the analysis of one-dimensional isentropic compressible flow through variable cross-sectional area, and discharges of gas from a reservoir through a converging or converging-diverging nozzle has been developed . The program was written in FORTRAN LANGUAGE.

In this work, the area change is the predominant cause of change of flow condition. One of the advantage of this program is set on general uses for isentropic cases. Three application solutions on fluid flow through a variable cross-sectional area duct are described and had demonstrated how those problems being solved. The three applications are :

(1) Three properties of the initial conditions at the inlet cross-section or any particular section of the flow passage are specified, the corresponding properties can be computed and proceed further with one condition given at any section or at the exit cross-section of the flow passage, all other required properties are computed.

(2) A fluid stored in a large reservoir with given Po and To is discharged through a converging nozzle and by varying the back pressure to analyse the features and the patterns of the flow, choked or unchoked and compute the properties at the exit plane.

(3) A fluid stored in a large reservoir with given Po and To is discharged through a converging-diverging nozzle. The fluid flow has been carefully considered in all flow patterns,i.e.subsonic or supersonic. It can detect the shock occured inside, outside or at the exit plane. Furthermore it analyses the flow at design condition, overexpansion or underexpansion, and choked or unchoked conditions. It also computes all the necessary properties at throat, exit plane, before and after the normal shock wave. Especially, it can locate the position of the normal shock wave occured inside the nozzle.

The computer program presented in Appendex A is not limited to solving these three types of applications, instead it can be easily extended to fit all other applications or any section of the isentropic compressible flow. In genaral, graphs or tables for K = 1.40 is attached at the textbook for solving isentropic flow. In this program, value of K can be assigned as any value as one's requirement.

5. RECOMMENDATIONS

(1) Nozzle design and operation have been studied up to this point by means of a one-dimensional flow analysis. Although this method of analysis is adequate for the solution of many engineering problems, certain limitations become apparent. For example, in the design of a supersonic nozzle, area ratios can be determined for a given supersonic Mach number. But the length of the nozzle or the rate of change of area with axial distance cannot be prescribed from one-dimensional flow considerations. Further, due to presence of boundary layers on the nozzle walls, the area available to the main flow is somewhat reduced; the areas calculated from a one-dimensional flow analysis may have to be enlarged to account for boundary layers. For an advanced and complete analysis of the operation and design of a converging or converging-diverging nozzle, a study of two- and three-dimensional analysis is required.A good engineering approximations may then be obtained for the solution of a wide range of compressible flow problems.

(2) Compressible flow in ducts was analyzed for the case in which changes in flow properties were brought about solely by area change. In a real flow situation, however, frictional forces are present and may have a decisive effect on the resultant flow characteristic. Naturally, the inclusion of friction terms in the equations of motion makes

the resultant analysis more complex. For this reason, to study the effect of friction on compressible flow in ducts, certain restrictions may be placed on the flow. (a) By considering compressible flow with friction in constant-area insulated ducts, which eliminate the effects of area change and heat addition. In a practical sense, these restrictions limit the applicability of the resultant analysis; however, certain problems such as flow in short ducts can be handled, and furthermore an insight is provided into the general effects of friction on a compressible flow. (b) Dealing with the flow with friction in constant-area ducts, in which the fluid temperature is assumed constant, this approximates the flow of a gas through a long uninsulated pipe line. Thus these two cases cover a wide range of frictional flows and are consequently of great significance.

(3) Flow assumed to be adiabatic and study the effects on a gas flow of area change and friction. Here, the effect of heat addition or loss on a gas flow may be investigated. Flows with heat transfer occur in a wide variety of situations, for example, combustion chambers, in which the heat addition is supplied internally by a chemical reaction, or heat exchangers, in which heat flow occurs the system boundaries.

(4) Furthermore, the investigation may be ventured into the case of flow with applied electric and magnetic fields. Under certain conditions, however, a gas can be made into an electrically conducting fluid, possessing electrical

properties similar to a solid conductor. If such a conducting gas stream is allowed to pass through a magnetic field aligned perpendicular to the flow, an electrical field is induced normal to the flow direction and the magnetic field. Since the gas is able to conduct electrically, the electric field can be used to generate a current between electrodes placed in the fluid, and this current is able to produce work through an external load.

APPENDIX A

FORTRAN IV COMPUTER PROGRAM

```
C-------------------------------
C       MAIN  PROGRAM
C-------------------------------
C     ----------------------------------------------------------------
C     *  PROGRAM FOR SOLVING ONE-DIMENSIONAL ISENTROPIC         *
C     *     COMPRESSIBLE FLOW, INCLUDING FLOW THROUGH           *
C     *     CONVERGING NOZZLE AND CONVERGING-DIVERGING          *
C     *                        NOZZLE                           *
C     ----------------------------------------------------------------
      COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
      REAL*4 MF,M,K,MP,ME2,ME3,ME4,ME5,MB1,MB2,MFB1,MFB2
      WRITE(2,1)
1     FORMAT(1X,'TO DEFINE THE SYMBOLS USED :')
      WRITE(2,2)
2     FORMAT(//,7X,'MF = MASS FLUX',//,
     $6X,' R  = SPEC.HEAT CONST.',//,
     $6X,' K  = SPEC.GAS RATIO.',//,
     $6X,' M  = MACH NO.',//,
     $6X,' T  = STATIC TEMPERATURE',//,
     $6X,' P  = STATIC PRESSURE',//,
     $6X,' DN = STATIC DENSITY',//,
     $6X,' V  = LOCAL FLUID VELOCITY',//,
     $6X,' TO = STAGNATION TEMPERATURE',//,
     $6X,' PO = STAGNATION PRESSURE',//,
     $6X,' DNO= STAGNATION DENSITY')
      WRITE(2,31)
31    FORMAT(//,2X,'SELECT PROGRAM :',
     $//,7X,'1 - GIVEN THREE PROPERTIES OF A FLOW IN A DUCT,',
     $/,15X,'FIND THE OTHER PROPERTIES OF THE FLOW',
     $//,7X,'2 - CONVERGING NOZZLE FLOW FROM RESERVOIR',
     $//,7X,'3 - CONVERGING-DIVERGING NOZZLE',/)
      READ ,J1
9999  IF (J1.EQ.1) WRITE (2,10)
10    FORMAT(//,1X,'SELECT EITHER :',//,
     $6X,'1 - GIVEN MASS FLUX WITH TWO PROPERTIES',//,
     $2X,'OR  2 - GIVEN THREE PROPERTIES WITHOUT MASS FLUX',//)
      JJ=0
      IF (J1.EQ.1) READ ,JJ
      WRITE(2,6)
6     FORMAT(//,3X,'ENTER K,R')
      READ ,K,R
      WRITE(2,17) K,R
17    FORMAT(//,3X,'SPECIFIC HEAT RATIO=',F12.4,//,
     $3X,'SPECIFIC GAS CONSTANT=',F12.4,//)
      IF (JJ.EQ.1) WRITE (2,5)
```

```
5       FORMAT(//,3X,'ENTER MF')
        IF (JJ.EQ.1) READ ,MF
        C1=2/(K-1)
        C2=(K-1)/2
        C3=(K-1)/(K+1)
        C4=2/(K+1)
        PW1=K-1
        PW2=1/(K-1)
        PW3=K/(K-1)
        PW4=(K-1)/K
        PW5=(K+1)/(2*(K-1))
        KNOR=0
        IF ((J1.EQ.2).OR.(J1.EQ.3)) GO TO 2001
        WRITE(2,3)
3       FORMAT(//,1X,'SELECT THE CONDITIONS :',//,
       $3X,'ENTERING THE CODE OF THE GIVEN CONDITIONS IN ASCENDI
        NG ORDER',
       $//,12X,'###    CODES    ###',//,
       $11X,'TO - 1',6X,'DN - 5',//,
       $11X,'PO - 2',6X,'DNO- 6',//,
       $11X,'T  - 3',6X,' M - 7',//,
       $11X,'P  - 4',6X,' V - 8',//)
        READ ,N
        WRITE(2,4)N
4       FORMAT(//,1X,'THE CONDITIONS GIVEN ARE CODES ##',1X,I4,1
        X,'##',//)
        KK=1
        IF ((JJ.EQ.1).AND.(N.GT.100)) GO TO 9996
        IF ((JJ.EQ.2).AND.(N.GT.100)) GO TO 9998
        IF ((JJ.EQ.2).AND.(N.LT.100)) GO TO 9996
C      -----------------------------------------
C      PROGRAM FOR GIVEN MF & TWO PROPERTIES
C      -----------------------------------------
        IF (N.EQ.12) GO TO 100
        IF (N.EQ.14) GO TO 150
        IF (N.EQ.23) GO TO 200
        IF (N.EQ.34) GO TO 250
        IF (N.EQ.35) GO TO 300
        IF (N.EQ.45) GO TO 350
        IF (N.EQ.38) GO TO 400
        IF (N.EQ.48) GO TO 450
        IF (N.EQ.13) GO TO 500
        IF (N.EQ.15) GO TO 520
        IF (N.EQ.18) GO TO 540
        IF (N.EQ.78) GO TO 560
        IF (N.EQ.57) GO TO 580
        IF (N.EQ.17) GO TO 600
        IF (N.EQ.37) GO TO 620
        IF (N.EQ.28) GO TO 640
        IF (N.EQ.25) GO TO 660
        IF (N.EQ.24) GO TO 680
        IF (N.EQ.27) GO TO 700
```

```
      IF (N.EQ.47) GO TO 720
      IF (N.EQ.67) GO TO 740
      IF (N.EQ.56) GO TO 760
      IF (N.EQ.68) GO TO 780
      IF (N.EQ.16) GO TO 782
      IF (N.EQ.26) GO TO 785
      IF (N.EQ.36) GO TO 787
      IF (N.EQ.46) GO TO 1111
      IF (N.EQ.58) GO TO 1111
100   CONTINUE
      WRITE(2,8)
8     FORMAT(1X,'INPUT TO,PO')
      READ, TO,PO
      CALL ISEN7
      GO TO 2222
150   WRITE(2,15)
15    FORMAT(1X,'INPUT TO,P')
      READ ,TO,P
      M=MF/SQRT(1+C2)/(P*SQRT(K/R/TO))
      DO 155 I=1,30
      MP=MF/SQRT(1+C2*M*M)/(P*SQRT(K/R/TO))
      EP=ABS(1-MP/M)
      IF (EP.LT.0.00001) GO TO 1500
      M=MP
155   CONTINUE
1500  T=TO/(1+C2*M*M)
      CALL ISENT1
      PO=P*(1+C2*M*M)**PW3
      GOTO 2222
200   WRITE(2,20)
20    FORMAT(1X,'INPUT PO,T')
      READ , PO,T
      M=MF*(1+C2)**PW3/(PO*SQRT(K/R/T))
      DO 205 I=1,30
      MP=MF*(1+C2*M*M)**PW3/(PO*SQRT(K/R/T))
      EP=ABS(1-MP/M)
      IF(EP.LT.0.00001) GO TO 2000
      M=MP
205   CONTINUE
2000  TO=T*(1+C2*M*M)
      CALL ISENT1
      P=PO/(1+C2*M*M)**PW3
      GO TO 2222
250   WRITE(2,25)
25    FORMAT(1X,'INPUT T,P')
      READ ,T,P
      M=MF/(P*SQRT(K/R/T))
      CALL ISENT1
      PO=P*(1+C2*M*M)**PW3
      TO=T*(1+C2*M*M)
```

```
      GO TO 2222
300   CONTINUE
      WRITE(2,30)
30    FORMAT(1X,'INPUT T,DN')
      READ ,T,DN
      P=DN*R*T
36    M=MF/(P*SQRT(K/R/T))
      V=M*SQRT(K*R*T)
      DNO=DN*(1+C2*M*M)**PW2
      PO=P*(1+C2*M*M)**PW3
      TO=T*(1+C2*M*M)
      GO TO 2222
350   WRITE(2,35)
35    FORMAT(1X,'INPUT P,DN')
      READ ,P,DN
      T=P/(DN*R)
      GO TO 36
400   WRITE(2,40)
40    FORMAT(1X,'INPUT T,V')
      READ , T,V
      DN=MF/V
      P=DN*R*T
46    M=V/(K*R*T)**0.5
      PO=P*(1+C2*M*M)**PW3
      TO=T*(1+C2*M*M)
      DNO=DN*(1+C2*M*M)**PW2
      GO TO 2222
450   WRITE(2,45)
45    FORMAT(1X,'INPUT P,V')
      READ ,P,V
      DN=MF/V
      T=P/(DN*R)
      GO TO 46
500   WRITE(2,50)
50    FORMAT(1X,'INPUT TO,T')
      READ ,TO,T
      TOT=TO/T
      M=((2*(TOT-1))/(K-1))**0.5
      V=M*(K*R*T)**0.5
      DN=MF/V
      CALL ISENT2
      GO TO 2222
520   WRITE(2,52)
52    FORMAT(1X,'INPUT TO,DN')
      READ ,TO,DN
      V=MF/DN
55    M=SQRT(V*V/((TO*K*R)-(V*V*C2)))
      T=TO/(1+C2*M*M)
      CALL ISENT2
      GO TO 2222
```

```
540     WRITE(2,54)
54      FORMAT(1X,'INPUT TO,V')
        READ ,TO,V
        DN=MF/V
        GO TO 55
560     WRITE(2,56)
56      FORMAT(1X,'INPUT M,V')
        READ ,M,V
        DN=MF/V
59      T=V*V/(M*M*K*R)
        TO=T*(1+C2*M*M)
        CALL ISENT2
        GO TO 2222
580     WRITE(2,58)
58      FORMAT(1X,'INPUT DN,M')
        READ ,DN,M
        V=MF/DN
        GO TO 59
600     WRITE(2,60)
60      FORMAT(1X,'INPUT TO,M')
        READ ,TO,M
        CALL ISEN8
        GO TO 2222
620     WRITE(2,62)
62      FORMAT(1X,'INPUT T,M')
        READ ,T,M
790     TO=T*(1+C2*M*M)
        CALL ISEN8
        GO TO 2222
640     WRITE(2,641)
641     FORMAT(1X,'INPUT PO,V')
        READ ,PO,V
        DN=MF/V
662     M=V*(1+C2)**(0.5*PW3)*SQRT(DN/PO/K)
        DO 644 I=1,30
        MP=V*(1+C2*M*M)**(0.5*PW3)*SQRT(DN/PO/K)
        EP=ABS(1-MP/M)
        IF (EP.LT.0.00001) GO TO 645
        M=MP
644     CONTINUE
645     P=PO/(1+C2*M*M)**PW3
        T=P/(DN*R)
        TO=T*(1+C2*M*M)
        DNO=DN*(1+C2*M*M)**PW2
        GO TO 2222
660     WRITE(2,661)
661     FORMAT(1X,'INPUT PO,DN')
        READ ,PO,DN
        V=MF/DN
        GO TO 662
```

```
680   WRITE(2,681)
681   FORMAT(1X,'INPUT PO,P')
      READ ,PO,P
      M=SQRT(C1*((PO/P)**PW4-1))
688   T=M*M*P*P*K/(MF*MF*R)
      V=M*SQRT(K*R*T)
      TO=T*(1+C2*M*M)
      DN=MF/V
      DNO=DN*(1+C2*M*M)**PW2
      GO TO 2222
700   WRITE(2,701)
701   FORMAT(1X,'INPUT PO,M')
      READ ,PO,M
      P=PO/(1+C2*M*M)**PW3
      GO TO 688
720   WRITE(2,721)
721   FORMAT(1X,'INPUT P,M')
      READ ,P,M
      PO=P*(1+C2*M*M)**PW3
      GO TO 688
740   WRITE(2,741)
741   FORMAT(1X,'INPUT DNO,M')
      READ , DNO,M
      DN=DNO/(1+C2*M*M)**PW2
766   V=MF/DN
      T=V*V/(M*M*K*R)
      TO=T*(1+C2*M*M)
      P=DN*R*T
      PO=P*(1+C2*M*M)**PW3
      GO TO 2222
760   WRITE(2,761)
761   FORMAT(1X,'INPUT DN,DNO')
      READ ,DN,DNO
767   DU=(DNO/DN)**(K-1)-1
      M=SQRT(2*DU/(K-1))
      GO TO 766
780   WRITE(2,781)
781   FORMAT(1X,'INPUT DNO,V')
      READ ,DNO,V
      DN=MF/V
      GO TO 767
782   WRITE(2,783)
783   FORMAT(1X,'INPUT TO,DNO')
      READ ,TO,DNO
      PO=DNO*R*TO
      CALL ISEN7
      GO TO 2222
785   WRITE(2,786)
786   FORMAT(1X,'INPUT PO,DNO')
      READ ,PO,DNO
```

```
      TO=PO/R/DNO
      CALL ISEN7
      GO TO 2222
787   WRITE(2,788)
788   FORMAT(1X,'INPUT T,DNO')
      READ ,T,DNO
      M=MF*(1+C2)**PW2/(DNO*SQRT(K*R*T))
      DO 789 I=1,30
      MP=MF*(1+C2*M*M)**PW2/(DNO*SQRT(K*R*T))
      EP=ABS(1-MP/M)
      IF (EP.LT.0.00001) GO TO 790
      M=MP
789   CONTINUE
C    ------------------------------------------------------------
C    PROGRAM FOR GIVEN THREE PROPERTIES WITHOUT MASS FLUX
C    ------------------------------------------------------------
9998  CONTINUE
      IF (N.EQ.123) GO TO 800
      IF (N.EQ.134) GO TO 802
      IF (N.EQ.135) GO TO 804
      IF (N.EQ.136) GO TO 806
      IF (N.EQ.137) GO TO 1111
      IF (N.EQ.138) GO TO 1111
      IF (N.EQ.246) GO TO 808
      IF (N.EQ.248) GO TO 810
      IF (N.EQ.247) GO TO 1111
      IF (N.EQ.234) GO TO 812
      IF (N.EQ.245) GO TO 814
      IF (N.EQ.456) GO TO 816
      IF (N.EQ.256) GO TO 818
      IF (N.EQ.356) GO TO 820
      IF (N.EQ.156) GO TO 822
      IF (N.EQ.568) GO TO 824
      IF (N.EQ.567) GO TO 1111
      IF (N.EQ.125) GO TO 826
      IF (N.EQ.126) GO TO 1111
      IF (N.EQ.128) GO TO 828
      IF (N.EQ.127) GO TO 832
      IF (N.EQ.124) GO TO 834
      IF (N.EQ.345) GO TO 1111
      IF (N.EQ.346) GO TO 836
      IF (N.EQ.348) GO TO 838
      IF (N.EQ.347) GO TO 842
      IF (N.EQ.146) GO TO 844
      IF (N.EQ.168) GO TO 846
      IF (N.EQ.167) GO TO 848
      IF (N.EQ.145) GO TO 850
      IF (N.EQ.148) GO TO 852
      IF (N.EQ.147) GO TO 855
      IF (N.EQ.236) GO TO 857
```

```
      IF (N.EQ.235) GO TO 860
      IF (N.EQ.238) GO TO 863
      IF (N.EQ.237) GO TO 866
      IF (N.EQ.158) GO TO 868
      IF (N.EQ.157) GO TO 871
      IF (N.EQ.258) GO TO 873
      IF (N.EQ.257) GO TO 878
      IF (N.EQ.268) GO TO 880
      IF (N.EQ.267) GO TO 882
      IF (N.EQ.358) GO TO 885
      IF (N.EQ.357) GO TO 887
      IF (N.EQ.368) GO TO 889
      IF (N.EQ.237) GO TO 892
      IF (N.EQ.458) GO TO 894
      IF (N.EQ.457) GO TO 896
      IF (N.EQ.468) GO TO 898
      IF (N.EQ.467) GO TO 903
      IF (N.EQ.178) GO TO 1111
      IF (N.EQ.378) GO TO 1111
      IF (N.EQ.478) GO TO 905
      IF (N.EQ.278) GO TO 907
      IF (N.EQ.578) GO TO 913
      IF (N.EQ.678) GO TO 910
800   WRITE(2,801)
801   FORMAT(1X,'INPUT TO,PO,T')
      READ ,TO,PO,T
      M=SQRT(C1*(TO/T-1))
      P=PO/(1+C2*M*M)**PW3
      CALL ISEN1
      GO TO 2222
802   WRITE(2,803)
803   FORMAT(1X,'INPUT TO,T,P')
      READ ,TO,T,P
      M=SQRT(C1*(TO/T-1))
      PO=P*(1+C2*M*M)**PW3
      CALL ISEN1
      GO TO 2222
804   WRITE(2,805)
805   FORMAT(1X,'INPUT TO,T,DN')
      READ ,TO,T,DN
920   M=SQRT(C1*(TO/T-1))
      P=DN*R*T
      PO=P*(1+C2*M*M)**PW3
      CALL ISEN1
      GO TO 2222
806   WRITE(2,807)
807   FORMAT(1X,'INPUT TO,T,DNO')
      READ ,TO,T,DNO
      M=SQRT(C1*(TO/T-1))
      DN=DNO/(1+C2*M*M)**PW2
```

```
      P=DN*R*T
      CALL ISEN2
      GO TO 2222
808   WRITE(2,809)
809   FORMAT(1X,'INPUT PO,P,DNO')
      READ ,PO,P,DNO
      M=SQRT(C1*((PO/P)**PW4-1))
      DN=DNO/(1+C2*M*M)**PW2
      CALL ISEN5
      GO TO 2222
810   WRITE(2,811)
811   FORMAT(1X,'INPUT PO,P,V')
      READ ,PO,P,V
      M=SQRT(C1*((PO/P)**PW4-1))
      T=V*V/(M*M*K*R)
      TO=T*(1+C2*M*M)
      CALL ISEN1
      GO TO 2222
812   WRITE(2,813)
813   FORMAT(1X,'INPUT PO,T,P')
      READ ,PO,T,P
      M=SQRT(C1*((PO/P)**PW4-1))
      TO=T*(1+C2*M*M)
      CALL ISEN1
      GO TO 2222
814   WRITE(2,815)
815   FORMAT(1X,'INPUT PO,P,DN')
      READ ,PO,P,DN
      M=SQRT(C1*((PO/P)**PW4-1))
972   DNO=DN*(1+C2*M*M)**PW2
      CALL ISEN5
      GO TO 2222
816   WRITE(2,817)
817   FORMAT(1X,'INPUT P,DN,DNO')
      READ ,P,DN,DNO
      M=SQRT(C1*((DNO/DN)**PW1-1))
      PO=P*(1+C2*M*M)**PW3
      CALL ISEN5
      GO TO 2222
818   WRITE(2,819)
819   FORMAT(1X,'INPUT PO,DN,DNO')
      READ ,PO,DN,DNO
      M=SQRT(C1*((DNO/DN)**PW1-1))
      P=PO/(1+C2*M*M)**PW3
      CALL ISEN5
      GO TO 2222
820   WRITE(2,821)
821   FORMAT(1X,'INPUT T,DN,DNO')
      READ ,T,DN,DNO
      M=SQRT(C1*((DNO/DN)**PW1-1))
```

```
      TO=T*(1+C2*M*M)
      CALL ISEN2
      GO TO 2222
822   WRITE(2,823)
823   FORMAT(1X,'INPUT TO,DN,DNO')
      READ ,TO,DN,DNO
922   M=SQRT(C1*((DNO/DN)**PW1-1))
      T=TO/(1+C2*M*M)
      CALL ISEN2
      GO TO 2222
824   WRITE(2,825)
825   FORMAT(1X,'INPUT DN,DNO,V')
      READ ,DN,DNO,V
      M=SQRT(C1*((DNO/DN)**PW1-1))
      T=V*V/(M*M*K*R)
      TO=T*(1+C2*M*M)
      CALL ISEN2
      GO TO 2222
826   WRITE(2,827)
827   FORMAT(1X,'INPUT TO,PO,DN')
      READ ,TO,PO,DN
      DNO=PO/(R*TO)
      M=SQRT(C1*((DNO/DN)**PW1-1))
      CALL ISEN3
      GO TO 2222
828   WRITE(2,829)
829   FORMAT(1X,'INPUT TO,PO,V')
      READ ,TO,PO,V
      DNO=PO/R/TO
841   CALL ISENM1
831   DN=DNO/(1+C2*M*M)**PW2
      CALL ISEN3
      GO TO 2222
832   WRITE(2,833)
833   FORMAT(1X,'INPUT TO,PO,M')
      READ ,TO,PO,M
      CALL ISEN6
      GO TO 2222
834   WRITE(2,835)
835   FORMAT(1X,'INPUT TO,PO,P')
      READ ,TO,PO,P
2004  CONTINUE
      M=SQRT(C1*((PO/P)**PW4-1))
      T=TO/(1+C2*M*M)
      CALL ISEN1
      IF (J1.EQ.2) GO TO 2005
      IF (J1.EQ.3) GO TO 2042
      GO TO 2222
836   WRITE(2,837)
837   FORMAT(1X,'INPUT T,P,DNO')
```

```
      READ ,T,P,DNO
      DN=P/R/T
      M=SQRT(C1*((DNO/DN)**PW1-1))
      CALL ISEN4
      GO TO 2222
838   WRITE(2,839)
839   FORMAT(1X,'INPUT T,P,V')
      READ ,T,P,V
      DN=P/R/T
      M=V/SQRT(K*R*T)
840   DNO=DN*(1+C2*M*M)**PW2
      CALL ISEN4
      GO TO 2222
842   WRITE(2,843)
843   FORMAT(1X,'INPUT T,P,M')
      READ ,T,P,M
      DN=P/R/T
      GO TO 840
844   WRITE(2,845)
845   FORMAT(1X,'INPUT TO,P,DNO')
      READ ,TO,P,DNO
921   PO=DNO*R*TO
      M=SQRT(C1*((PO/P)**PW4-1))
      T=TO/(1+C2*M*M)
      CALL ISEN1
      GO TO 2222
846   WRITE(2,847)
847   FORMAT(1X,'INPUT TO,DNO,V')
      READ ,TO,DNO,V
      PO=DNO*R*TO
      GO TO 841
848   WRITE(2,849)
849   FORMAT(1X,'INPUT TO,DNO,M')
      READ ,TO,DNO,M
923   PO=DNO*R*TO
      DN=DNO/(1+C2*M*M)**PW2
      CALL ISEN3
      GO TO 2222
850   WRITE(2,851)
851   FORMAT(1X,'INPUT TO,P,DN')
      READ ,TO,P,DN
      T=P/(R*DN)
      M=SQRT(C1*((TO/T)-1))
      PO=P*(1+C2*M*M)**PW3
      CALL ISEN1
      GO TO 2222
852   WRITE(2,853)
853   FORMAT(1X,'INPUT TO,P,V')
      READ ,TO,P,V
      CALL ISENM1
```

```
854    PO=P*(1+C2*M*M)**PW3
       T=TO/(1+C2*M*M)
       CALL ISEN1
       GO TO 2222
855    WRITE(2,856)
856    FORMAT(1X,'INPUT TO,P,M')
       READ ,TO,P,M
2010   CONTINUE
       T=TO/(1+C2*M*M)
       GO TO 854
857    WRITE(2,858)
858    FORMAT(1X,'INPUT PO,T,DNO')
       READ ,PO,T,DNO
       TO=PO/R/DNO
       M=SQRT(C1*(TO/T-1))
859    P=PO/(1+C2*M*M)**PW3
       CALL ISEN1
       GO TO 2222
860    WRITE(2,861)
861    FORMAT(1X,'INPUT PO,T,DN')
       READ ,PO,T,DN
       P=R*DN*T
       M=SQRT(C1*((PO/P)**PW4-1))
862    TO=T*(1+C2*M*M)
       CALL ISEN1
       GO TO 2222
863    WRITE(2,864)
864    FORMAT(1X,'INPUT PO,T,V')
       READ ,PO,T,V
       M=V/SQRT(K*R*T)
865    TO=T*(1+C2*M*M)
       GO TO 859
866    WRITE(2,867)
867    FORMAT(1X,'INPUT PO,T,M')
       READ ,PO,T,M
       GO TO 865
868    WRITE(2,869)
869    FORMAT(1X,'INPUT TO,DN,V')
       READ ,TO,DN,V
       CALL ISENM1
       T=V*V/(K*R*M*M)
870    DNO=DN*(1+C2*M*M)**PW2
       CALL ISEN2
       GO TO 2222
871    WRITE(2,872)
872    FORMAT(1X,'INPUT TO,DN,M')
       READ ,TO,DN,M
       T=TO/(1+C2*M*M)
       GO TO 870
873    WRITE(2,874)
```

```
874     FORMAT(1X,'INPUT PO,DN,V')
        READ ,PO,DN,V
        M=V*(1+C2)**(0.5*PW3)*SQRT(DN/K/PO)
        DO 875 I=1,30
        MP=V*(1+C2*M*M)**(0.5*PW3)*SQRT(DN/K/PO)
        EP=ABS(1-MP/M)
        IF (EP.LT.0.00001) GO TO 876
        M=MP
875     CONTINUE
876     P=PO/(1+C2*M*M)**PW3
877     DNO=DN*(1+C2*M*M)**PW2
        CALL ISEN5
        GO TO 2222
878     WRITE(2,879)
879     FORMAT(1X,'INPUT PO,DN,M')
        READ ,PO,DN,M
        GO TO 876
880     WRITE(2,881)
881     FORMAT(1X,'INPUT PO,DNO,V')
        READ ,PO,DNO,V
        TO=PO/R/DNO
        CALL ISENM1
        P=PO/(1+C2*M*M)**PW3
        DN=DNO/(1+C2*M*M)**PW2
        CALL ISEN3
        GO TO 2222
882     WRITE(2,883)
883     FORMAT(1X,'INPUT PO,DNO,M')
        READ ,PO,DNO,M
        P=PO/(1+C2*M*M)**PW3
884     DN=DNO/(1+C2*M*M)**PW2
        CALL ISEN5
        GO TO 2222
885     WRITE(2,886)
886     FORMAT(1X,'INPUT T,DN,V')
        READ ,T,DN,V
        M=V/SQRT(K*R*T)
        TO=T*(1+C2*M*M)
        GO TO 870
887     WRITE(2,888)
888     FORMAT(1X,'INPUT T,DN,M')
        READ ,T,DN,M
        TO=T*(1+C2*M*M)
        GO TO 870
889     WRITE(2,890)
890     FORMAT(1X,'INPUT T,DNO,V')
        READ ,T,DNO,V
        M=V/SQRT(K*R*T)
891     TO=V*V*(1+C2*M*M)/(K*R*M*M)
        DN=DNO/(1+C2*M*M)**PW2
```

```
      CALL ISEN2
      GO TO 2222
892   WRITE(2,893)
893   FORMAT(1X,'INPUT PO,T,M')
      READ ,T,PO,M
      GO TO 891
894   WRITE(2,895)
895   FORMAT(1X,'INPUT P,DN,V')
      READ ,P,DN,V
      T=P/R/DN
      M=V/SQRT(K*R*T)
      DNO=DN*(1+C2*M*M)**PW2
      CALL ISEN4
      GO TO 2222
896   WRITE(2,897)
897   FORMAT(1X,'INPUT P,DN,M')
      READ ,P,DN,M
      PO=P*(1+C2*M*M)**PW3
      GO TO 972
898   WRITE(2,899)
899   FORMAT(1X,'INPUT P,DNO,V')
      READ ,P,DNO,V
      M=SQRT(DNO*V*V/(K*P*(1+C2)**PW2))
      DO 900 I=1,30
      MP=SQRT(DNO*V*V/(K*P*(1+C2*M*M)**PW2))
      EP=ABS(1-MP/M)
      IF (EP.EQ.0.00001) GO TO 901
      M=MP
900   CONTINUE
901   T=V*V/(M*M*R*K)
      TO=T*(1+C2*M*M)
902   PO=P*(1+C2*M*M)**PW3
      CALL ISEN1
      GO TO 2222
903   WRITE(2,904)
904   FORMAT(1X,'INPUT P,DNO,M')
      READ ,P,DNO,M
      PO=P*(1+C2*M*M)**PW3
      GO TO 884
905   WRITE(2,906)
906   FORMAT(1X,'INPUT P,M,V')
      READ ,P,M,V
      T=V*V/(M*M*R*K)
      TO=T*(1+C2*M*M)
      GO TO 854
907   WRITE(2,908)
908   FORMAT(1X,'INPUT PO,M,V')
      READ ,PO,M,V
      T=V*V/(M*M*R*K)
      TO=T*(1+C2*M*M)
```

```
      P=PO/(1+C2*M*M)**PW3
      CALL ISEN1
      GO TO 2222
913   WRITE(2,909)
909   FORMAT(1X,'INPUT DN,M,V')
      READ ,DN,M,V
      T=V*V/(M*M*R*K)
      TO=T*(1+C2*M*M)
      GO TO 870
910   WRITE(2,911)
911   FORMAT(1X,'INPUT DNO,M,V')
      READ ,DNO,M,V
      T=V*V/(M*M*R*K)
      GO TO 891
C     ------------------------------------------------------
C      PROGRAM FOR CONVERGING NOZZLE AND
C          CONVERGING-DIVERGING NOZZLE
C     ------------------------------------------------------
2001  KK=0
      WRITE (2,2003)
2003  FORMAT(1X,'INPUT TO,PO,PB(BACK PRESSURE)')
      READ ,TO,PO,PB
      IF (PO.EQ.PB) WRITE (2,2002)
2002  FORMAT(//,4X,'###  FLUID IS REMAIN STATIONARY  ###',//)
2007  FORMAT(//,3X,'##  UNCHOKED CONDITION  (SUBSONIC FLOW)  #
     #')
2008  FORMAT(//,3X,'##   CRITICAL CONDITION  (SONIC FLOW)   ##
     ')
2009  FORMAT(//,3X,'##  CHOKED CONDITION  ##')
      IF (PO.EQ.PB) GO TO 9997
      IF (PO.LT.PB) GO TO 9996
      IF (J1.EQ.3) GO TO 2020
      M=1
      CALL ISEN6
      WRITE (2,2006)
2006  FORMAT(//,3X,'##  PROPERTIES AT THE EXIT PLANE  ##',//)
      IF (PB.EQ.P) WRITE (2,2008)
      IF (PB.LT.P) WRITE (2,2009)
      IF (PB.LE.P) GO TO 2222
      P=PB
      GO TO 2004
2005  CONTINUE
      IF ((M.GT.0.9995).AND.(M.LT.1.0005)) M=1
      IF (M.NE.1) GO TO 2040
      CALL ISEN6
      WRITE (2,2008)
      P=PB
      GO TO 2222
2040  WRITE (2,2007)
      GO TO 2222
2020  WRITE(2,2021)
2021  FORMAT(//,1X,'INPUT AREA RATIO BETWEEN EXIT & THROAT (AE
     /AT)',//)
```

```
      READ ,ARIO
      AR=ARIO
C    ------------------------------------------------------------
C     TO FIND MACH NUMBERS,ME2 & ME4 AT THE EXIT PLANE
C    ------------------------------------------------------------
      ME2=((C4+C3)**PW5)/AR
      DO 2030 I=1,30
      MP=((C4+ME2*ME2*C3)**PW5)/AR
      EP=ABS(1-MP/ME2)
      IF (EP.LT.0.00001) GO TO 2031
      ME2=MP
2030  CONTINUE
2031  ME4=SQRT((AR**(1/PW5)-C4)*(K+1)/(K-1))
      DO 2032 I=1,30
      MP=SQRT(((ME4*AR)**(1/PW5)-C4)*(K+1)/(K-1))
      EP=ABS(1-MP/ME4)
      IF (EP.LT.0.00001) GO TO 2033
      ME4=MP
2032  CONTINUE
2033  CONTINUE
      IF (ME2.GT.1) ME4=ME2
      IF (ME4.LT.1) ME2=ME4
      M=ME2
C    ------------------------------
C     TO DETERMINE PE2,PE3,PE4
C    ------------------------------
      CALL ISEN6
      PE2=P
      ME3=ME4
      M=ME4
      CALL ISEN6
      PE4=P
      ME5=SQRT((ME3*ME3+C1)/(2*PW3*ME3*ME3-1))
      PE3=PE4*((2*K*ME3*ME3)/(K+1)-C3)
      IF ((PE3.GT.PB).AND.(PB.GT.PE4)) WRITE (2,2035)
      IF (PB.LT.PE4) WRITE (2,2035)
      IF (PB.GT.PE2) WRITE(2,2007)
      IF (PB.EQ.PE4) WRITE (2,2027)
      IF (PB.EQ.PE3) WRITE (2,2036)
      IF (PB.LT.PE4) WRITE (2,2045)
2045  FORMAT(8X,'#####    UNDEREXPANDED    #####',//)
      IF ((PE3.GT.PB).AND.(PB.GT.PE4)) WRITE (2,2048)
2035  FORMAT(//,3X,'##  SHOCK WAVE OCCURED OUTSIDE THE NOZZLE
      ##',//)
2048  FORMAT(8X,'#####    OVEREXPANDED    #####',//)
2036  FORMAT(3X,'##  SHOCK AT EXIT PLANE  ##',//)
2023  FORMAT(1X,'##  THE CRITICAL PROPERTIES AT THE THROAT ARE
      :',//)
2024  FORMAT (1X,'##  THE PROPERTIES AT THE THROAT ARE :  ##',
     //)
2027  FORMAT(//,3X,'##   DESIGN CONDITION    ##',//)
2037  FORMAT(//,3X'##  SHOCK INSIDE  ##')
      IF (PB.LT.PE3) PB=PE4
```

```
      P=PB
      GO TO 2004
2042  CONTINUE
      IF (PB.NE.PE3) GO TO 2047
      WRITE (2,2036)
      WRITE (2,2043)
2043  FORMAT(//,3X,'## PROPERTIES BEFORE THE NORMAL SHOCK WAV
     E ##',//)
      WRITE (2,7) MF,TO,PO,T,P,DN,DNO,M,V
      M=SQRT((M*M+C1)/(K*C1*M*M-1))
      PO=PO/((C3+C4/M/M)**K*(K*C4*M*M-C3))**PW2
      P=P1*C4*K*M*M-C3
      DUM=(K+1)*M*M/(2+(K-1)*M*M)
      V=V/DUM
      DN=DNB1*DUM
      T=T*(K*C4*M*M-C3)*(C3+C4/M/M)
      WRITE (2,2044)
2044  FORMAT(//,3X,'## PROPERTIES AFTER THE NORMAL SHOCK WAVE
     ##',//)
      GO TO 2222
2047  IF ((PE2.GT.PB).AND.(PB.GT.PE3)) GO TO 2049
      WRITE (2,7) MF,TO,PO,T,P,DN,DNO,M,V
      IF (PB.LE.PE2) WRITE (2,2023)
      IF (PB.LE.PE2) M=1
      IF (PB.LE.PE2) CALL ISEN6
      IF (PB.LE.PE2) GO TO 2222
      WRITE (2,2024)
      MF=MF*AR
      CALL ISEN7
      GO TO 2222
2049  WRITE (2,2037)
      PP=PO
      ARR=ARIO
      ARL=1.0
      DO 2050 I=1,30
      M=1
      PO=PP
      CALL ISEN6
      AR=(ARR+ARL)/2
      M=SQRT((AR**(1/PW5)-C4)*(K+1)/(K-1))
      DO 2056 I1=1,30
      MP=SQRT(((M*AR)**(1/PW5)-C4)*(K+1)/(K-1))
      EP=ABS(1-MP/M)
      IF (EP.LT.0.00001) GO TO 2057
      M=MP
2056  CONTINUE
2057  CONTINUE
      CALL ISEN6
      MB1=M
      DNOB1=DNO
      TOB1=TO
```

```
      MFB1=MF
      PP=PO
      P1=P
      VB1=V
      DNB1=DN
      TB1=T
      IF (M.LT.1) GO TO 2070
      M=SQRT((M*M+C1)/(K*C1*M*M-1))
      PO=PP/((C3+C4/MB1/MB1)**K*(K*C4*MB1*MB1-C3))**PW2
      P=P1*C4*K*MB1*MB1-C3
      DUM=(K+1)*MB1*MB1/(2+(K-1)*MB1*MB1)
      V=VB1/DUM
      DN=DNB1*DUM
      T=TB1*(K*C4*MB1*MB1-C3)*(C3+C4/MB1/MB1)
      PO2=PO
      MB2=M
      MFB2=MF
      P2=P
      VB2=V
      DNB2=DN
      TB2=T
      MF=MF*AR/ARIO
      CALL ISEN7
      EP=ABS(1-P/PB)
      IF (EP.LT.0.001) GO TO 2051
2070  IF (P.GT.PB) ARL=AR
      IF (P.LT.PB) ARR=AR
      M=1
      PO=PP
2050  CONTINUE
      P=PB
2051  WRITE(2,2071) AR
2071  FORMAT(//,3X,'NORMAL SHOCK WAVE OCCURS AT AREA RATIO =',
      F6.3,//)
      WRITE (2,2043)
      WRITE (2,7)MFB1,TO,PP,TB1,P1,DNB1,DNO,MB1,VB1
      WRITE (2,2044)
      WRITE (2,7) MFB2,TO,PO2,TB2,P2,DNB2,DNO,MB2,VB2
      WRITE (2,2006)
      P=PB
      WRITE(2,7) MF,TO,PO,T,P,DN,DNO,M,V
      WRITE (2,2023)
      M=1
      PO=PP
      CALL ISEN6
2222  CONTINUE
      IF (KK.EQ.1) WRITE(2,1200)
      IF (KK.GE.2) WRITE(2,1201) KK
1200  FORMAT(//,3X,'THE RESULTS FOR INITIAL SECTION ## STATION
      1 ##',//)
1201  FORMAT(//,3X,'RESULTS FOR OTHER SECTION. ##STATION',I2,'
      ##')
```

```
      WRITE(2,7) MF,TO,PO,T,P,DN,DNO,M,V
7     FORMAT(//,6X,'MASS FLUX =',F12.3,//,
     $6X,'STAGNATION TEMPERATURE =',F12.3,//,
     $6X,'STAGNATION PRESSURE=',F12.3,//,
     $6X,'STATIC TEMPERATURE=',F12.3,//,
     $6X,'STATIC PRESSURE=',F12.3,//
     $6X,'STATIC DENSITY=',F12.3,//,
     $6X,'STAGNATION DENSITY=',F12.3,//,
     $6X,'MACH NUMBER=',F12.3,//,
     $6X,'LOCAL FLUID VELOCITY=',F12.3,//)
      IF ((J1.EQ.2).OR.(J1.EQ.3)) GO TO 9997
      GO TO 998
1111  WRITE(2,1112)
1112  FORMAT(/,2X,'NOT ENOUGH INFORMATION TO GET ALL THE PROPE
     RTIES')
      GO TO 9997
998   WRITE(2,999)
999   FORMAT(//,2X,'CONTINUE ?  YES-- ENTER 1  :  NO-- ENTER 0
      ')
      READ ,J
      IF (J.EQ.0) GO TO 9997
C     ------------------------------------------------
C     GIVEN ONE PROPERTY FROM ANY CROSS-SECTION TO
C       COMPUTE THE OTHER UNKNOWN PROPERTIES
C     ------------------------------------------------
      WRITE (2,1919)
1919  FORMAT(//,2X,'FIND PROPERTIES AT OTHER SECTION',//)
      KK=KK+1
      WRITE(2,51)
51    FORMAT(1X,'THE GIVEN PROPERTY IS',//,
     $6X,'1 - T2',6X,'4 - M2',//
     $6X,'2 - P2',6X,'5 - V2',//
     $6X,'3 - DN2',5X,'6 - AR(A1/A2)',//)
      READ ,J2
      IF (J2.EQ.1) GO TO 1203
      IF (J2.EQ.2) GO TO 1205
      IF (J2.EQ.3) GO TO 1207
      IF (J2.EQ.4) GO TO 1209
      IF (J2.EQ.5) GO TO 1225
      IF (J2.EQ.6) GO TO 1212
1203  WRITE (2,53)
53    FORMAT(1X,'INPUT T2')
      READ ,T
      GO TO 920
1205  WRITE (2,1206)
1206  FORMAT(1X,'INPUT P2')
      READ ,P
      GO TO 921
1207  WRITE (2,57)
57    FORMAT(1X,'INPUT DN2')
      READ ,DN
      GO TO 922
```

```
1209  WRITE (2,1210)
1210  FORMAT(1X,'INPUT M2')
      READ ,M
      GO TO 923
1225  WRITE(2,61)
61    FORMAT(1X,'INPUT V2')
      READ ,V
      GO TO 841
1212  WRITE(2,1213)
1213  FORMAT(1X,'INPUT AR(A1/A2)')
      READ ,AR
      MF=MF*AR
      CALL ISEN7
      GO TO 2222
9996  WRITE (2,9995)
9995  FORMAT (//,3X,'WRONG INFORMATION, CHECK THE INPUT DATA A
      GAIN.')
9997  CONTINUE
      STOP
      END
C-----------------------------------------
C      SUBROUTINE  PROGRAMS
C------------------------------------------
      SUBROUTINE ISENT1
      COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
      REAL*4 MF,M,K,MP
      V=M*SQRT(K*R*T)
      DN=MF/V
      DNO=DN*(1+C2*M*M)**PW2
      RETURN
      END
      SUBROUTINE ISENT2
      COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
      REAL*4 MF,M,K,MP
      P=DN*R*T
      PO=P*(1+C2*M*M)**PW3
      DNO=DN*(1+C2*M*M)**PW2
      RETURN
      END
      SUBROUTINE ISENM1
      COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
      REAL*4 MF,M,K,MP
      M=V*SQRT((1+C2)/(K*R*TO))
      DO 830 I=1,30
      MP=V*SQRT((1+C2*M*M)/(K*R*TO))
      EP=ABS(1-MP/M)
      IF (EP.LT.0.00001) GO TO 912
      M=MP
830   CONTINUE
912   CONTINUE
      RETURN
```

```
END
SUBROUTINE ISEN1
COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
REAL*4 M,K,MF
DN=P/(R*T)
DNO=PO/(R*TO)
V=M*SQRT(K*R*T)
MF=DN*V
RETURN
END
SUBROUTINE ISEN2
COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
REAL*4 M,K,MF
P=DN*R*T
PO=DNO*R*TO
V=M*SQRT(K*R*T)
MF=DN*V
RETURN
END
SUBROUTINE ISEN3
COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
REAL*4 M,K,MF
T=TO/(1+C2*M*M)
P=DN*R*T
V=M*SQRT(K*R*T)
MF=DN*V
RETURN
END
SUBROUTINE ISEN4
COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
REAL*4 M,K,MF
TO=T*(1+C2*M*M)
PO=DNO*R*TO
V=M*SQRT(K*R*T)
MF=DN*V
RETURN
END
SUBROUTINE ISEN5
COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
REAL*4 M,K,MF
T=P/(R*DN)
TO=PO/(R*DNO)
V=M*SQRT(K*R*T)
MF=DN*V
RETURN
END
SUBROUTINE ISEN6
COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
REAL*4 MF,M,K,MP
DNO=PO/R/TO
```

```
      DN=DNO/(1+C2*M*M)**PW2
      CALL ISEN3
      RETURN
      END
      SUBROUTINE ISEN7
      COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
      REAL*4 MF,M,K,MP
      DUMMY=PO*SQRT(K/R/TO)
      M=MF*(1+C2)**PW5/DUMMY
      DO 111 I=1,30
      MP=MF*(1+C2*M*M)**PW5/DUMMY
      EP=ABS(1-MP/M)
      IF(EP.LT.0.00001) GO TO 1000
      M=MP
111   CONTINUE
1000  T=TO/(1+C2*M*M)
      CALL ISENT1
      P=PO/(1+C2*M*M)**PW3
      RETURN
      END
      SUBROUTINE ISEN8
      COMMON V,DN,DNO,K,R,M,MF,TO,T,P,PO,C2,PW2,PW3,PW5
      REAL*4 MF,M,K,MP
      T=TO/(1+C2*M*M)
63    V=M*SQRT(K*R*T)
      DN=MF/V
      CALL ISENT2
      RETURN
      END
```

APPENDIX B

Sample of Example

Problem : Air flows through a frictionless adiabatic converging-diverging nozzle. The air stagnation temperature and pressure are 500K and 7.0×10^5 N/ M^2 respectively. The diverging portion of the nozzle has an area ratio between the exit plane and the throat (A_e / A_t) of 11.91. The back pressure at the exit plane is controlled to be at 2.2623×10^5 N/M^2. Analyse the flow characteristic and calculate all the properties of the flow. Assume K = 1.40 and R = 287.04 J/KG-K.

Results obtained from computer: (All in SI UNIT)

```
**FASTFOR (CONVERSATIONAL, VER 9)**

TO DEFINE THE SYMBOLS USED :

      MF = MASS FLUX
      R  = SPEC.HEAT CONST.
      K  = SPEC.GAS RATIO.
      M  = MACH NO.
      T  = STATIC TEMPERATURE
      P  = STATIC PRESSURE
      DN = STATIC DENSITY
      V  = LOCAL FLUID VELOCITY
      TO = STAGNATION TEMPERATURE
      PO = STAGNATION PRESSURE
      DNO= STAGNATION DENSITY
```

```
   SELECT PROGRAM :

         1 - GIVEN THREE PROPERTIES OF A FLOW IN A DUCT,
                  FIND THE OTHER PROPERTIES OF THE FLOW

         2 - CONVERGING NOZZLE FLOW FROM RESERVOIR

         3 - CONVERGING-DIVERGING NOZZLE

 *3

   ENTER K,R
*1.4,287.04


   SPECIFIC HEAT RATIO=       1.4000

   SPECIFIC GAS CONSTANT=     287.0400


 INPUT TO,PO,PB(BACK PRESSURE)
*500,700000,226230


 INPUT AREA RATIO BETWEEN EXIT & THROAT (AE/AT)

*11.91

   ##  SHOCK INSIDE  ##

   NORMAL SHOCK WAVE OCCURS AT AREA RATIO = 4.239



   ##  PROPERTIES BEFORE THE NORMAL SHOCK WAVE  ##



      MASS FLUX =      298.482

      STAGNATION TEMPERATURE =      500.000

      STAGNATION PRESSURE=  700000.000

      STATIC TEMPERATURE=      178.491

      STATIC PRESSURE=   19026.570

      STATIC DENSITY=       0.371

      STAGNATION DENSITY=       1.600
```

MACH NUMBER= 3.001

LOCAL FLUID VELOCITY= 803.741

** PROPERTIES AFTER THE NORMAL SHOCK WAVE **

MASS FLUX = 298.482

STAGNATION TEMPERATURE = 500.000

STAGNATION PRESSURE= 229633.900

STATIC TEMPERATURE= 478.400

STATIC PRESSURE= 199918.500

STATIC DENSITY= 1.433

STAGNATION DENSITY= 1.600

MACH NUMBER= 0.475

LOCAL FLUID VELOCITY= 208.325

** PROPERTIES AT THE EXIT PLANE **

MASS FLUX = 106.233

STAGNATION TEMPERATURE = 500.000

STAGNATION PRESSURE= 229633.900

STATIC TEMPERATURE= 497.756

STATIC PRESSURE= 226230.000

STATIC DENSITY= 1.582

STAGNATION DENSITY= 1.600

MACH NUMBER= 0.150

LOCAL FLUID VELOCITY= 67.146

** THE CRITICAL PROPERTIES AT THE THROAT ARE :

```
MASS FLUX =     1265.208

STAGNATION TEMPERATURE =      500.000

STAGNATION PRESSURE=  700000.000

STATIC TEMPERATURE=      416.667

STATIC PRESSURE=  369797.000

STATIC DENSITY=        3.092

STAGNATION DENSITY=        4.877

MACH NUMBER=       1.000

LOCAL FLUID VELOCITY=      409.194
```

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