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UNSTEADY ONE-DIMENSIONAL FLOWS WITH HEAT ADDITION OR ENTROPY GRADIENTS

BY

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SUMMARY

The present interest in aerodynamic propulsive devices such as the pulse jet and the ram jet has stimulated recent research in the field of combustion. One important aspect of the combustion problem which is considered herein is the unsteady gas-dynamical effects associated with the burning process.

Non-linear differential equations of the Riemann type are derived for the solution of problems involving the propogation of one-dimensional waves in flows in tubes of slowly varying cross section with heat addition or entropy variation. These equations can be solved graphically or numerically with the method of characteristics; the method is described in an appendix. The transient flows arising when heat is added to a section (as in a combustion chamber) of an initially isentropic flow in a tube have been calculated. The results of this calculation afford an insight into

the gas dynamic aspects of intermittent heat addition in a flowing gas, as well as to the apparently anomalous behavior at sonic velocity of steady gas flows with heat addition. The equations derived are well suited to the calculation of the non-linear pulse jet cycle with heat addition, once a suitable model of combustion has been selected.

INTRODUCTION

The present interest in aerodynamic propulsive devices such as the pulse jet and the ram jet has stimulated recent research in the field of combustion. One important aspect of the combustion problem which is considered herein is the unsteady gas dynamical effects associated with the burning process.

The propagation of plane waves due to combustion was theoretically investigated by MacDonald[1] and others with application to the pulse jet cycle. The Lagrangian form of the equations of motion were used; analytic solutions were obtained by linearizing through the use of the small perturbation method. A disadvantage of the linearization, however, is that waves of finite amplitude are essentially non-linear, and with linearization phenomena such as the distortion of the wave form and the formation of shock waves are precluded. In the present report, non-linear differential equations of the Riemann type are derived for the solution of problems involving the propagation of one-dimensional waves in flows in tubes of slowly varying cross-sectional area with heat addition or entropy gradients. These equations can be solved graphically or numerically with the method of characteristics; the method is described in an appendix. The transient flows arising when heat is added to a section (as in a combustion chamber) of an initially isentropic flow in a tube have been calculated. The results of this calculation afford an insight into the gas dynamic aspects of intermittent heat addition in a flowing gas as well as to the mechanism of the readjustment of the steady flow in a ram-jet when the quantity of heat added to the flow is changed.

The most complete analysis of the pulse-jet cycle up to the present time has been made by Schultz-Grunow.[2] His analysis, however, does not consider the effect of heat input, the combustion process being simulated merely by an isentropic pressure rise taking place in the combustion chamber, with all the resulting wave propagation processes considered also as isentropic. Although these simplifying assumptions lead to a quick method of calculating the effect of various parameters on the pulse jet cycle, the method obviously cannot give any insight into the effects of heat addition on the cycle nor can values of thrust be calculated. The equations derived herein make it possible to calculate the non-linear pulse jet cycle with a full consideration of heat addition, and it should be possible to obtain values of thrust from such calculations.

SYMBOLS

a	Velocity of sound, feet per second.
A	Cross section area of tube, square feet.
C_p	Specific heat at constant pressure, Btu/slug/^oF.
C_v	Specific heat at constant volume, Btu/slug/^oF.
L	Length of heating chamber, feet.
p	Static pressure, pounds per square foot.
P	Riemann variable, $P = u + \frac{2}{\gamma - 1} a$, feet per second.
Q	Riemann variable, $Q = u - \frac{2}{\gamma - 1} a$, feet per second.
Q^*	Quantity of heat added per unit mass, Btu/slug.
R	Gas constant, Btu/slug/^oF.
S	Entropy Btu/slug/^oF.
t	Time, seconds.
T	Absolute temperature, ^oR.
u	Particle velocity, feet per second.
x	Distance along tube, feet.
γ	Ratio of specific heats, C_p/C_v.
ρ	Mass density of fluid, slugs/ft^3.

DERIVATION OF CHARACTERISTIC EQUATIONS

The characteristic equations for the propagation of waves in flows with heat addition or entropy variations will now be derived. The flows will be assumed to take place in tubes of slowly varying cross-section and will therefore be assumed one-dimensional. It will further be assumed that the gas constant, R, and the specific heats C_p and C_V are constants.

The equations of motion are:

Dynamical equation

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0 \qquad (1)$$

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{1}{A} \frac{\partial (\rho u A)}{\partial x} = 0 \qquad (2)$$

Energy equation

$$\frac{dQ^*}{dt} = T \frac{dS}{dt} = C_V \frac{dT}{dt} - \frac{p}{\rho^2} \frac{d\rho}{dt} \qquad (3)$$

Equation of state

$$p = \rho R T \qquad (4)$$

From equations 3 and 4 the relation between the pressure and density can be found to be

$$p = \text{constant} \times \rho^{\gamma} e^{S/C_V} \qquad (5)$$

and by defining*

$$a = \sqrt{\frac{\gamma p}{\rho}}$$

equations 1 and 2 can be transformed to

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{2}{\gamma - 1} a \frac{\partial a}{\partial x} - \frac{a^2}{(\gamma - 1)Cp} \frac{\partial S}{\partial x} = 0 \quad (1a)$$

$$\frac{2}{\gamma - 1} \frac{\partial a}{\partial t} + \frac{2}{\gamma - 1} u \frac{\partial a}{\partial x} + a \frac{\partial u}{\partial x}$$

$$- \frac{\gamma}{\gamma - 1} \frac{a}{Cp} \frac{dS}{dt} + \frac{ua}{\Lambda} \frac{d\Lambda}{dx} = 0 \quad (2a)$$

where

$$\frac{dS}{dt} = \frac{\partial S}{\partial t} + u \frac{\partial S}{\partial x}$$

is the rate of change of entropy following a fluid particle. Addition and subtraction of the above equations gives:

$$\frac{\partial}{\partial t} \left(u \pm \frac{2a}{\gamma - 1}\right) + (u \pm a) \frac{\partial}{\partial x} \left(u \pm \frac{2}{\gamma - 1} a\right)$$

$$- \frac{a^2}{(\gamma - 1)C_p} \frac{\partial S}{\partial x} \mp \frac{\gamma}{\gamma - 1} \frac{a}{Cp} \frac{dS}{dt} \pm \frac{ua}{\Lambda} \frac{d\Lambda}{dx} = 0 \quad (3)$$

The above equations are essentially wave equations and indicate that disturbances are propogated downstream

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*The quantity " a" is equal to the value of the velocity of sound if the compression and expansion processes occurring in the sound wave are isentropic. If the passage of the sound wave in itself causes heat addition, so that the compressions and expansions of the sound wave are non-adiabatic, then " a" is not exactly the velocity of sound.

and upstream at the velocity "a" relative to the stream velocity (the upper and lower signs denote downstream and upstream wave motions respectively).

It will be noted that for isentropic waves in constant cross-section tubes, the equations reduce to that of Riemann;[4,5] because of heat addition and area change therefore, a single progressive wave will be continually transmitted and reflected as it passes down the tube, and of course its reflections will in turn be transmitted and reflected. For steady flow, the equations can be reduced to those of Chambré and Lin.[6]

Since in most cases analytic solution of equation 6 is extremely difficult, the numerical or graphical calculation procedures of the well known characteristic method must be used. Such calculations are carried out on the time-distance or $t - x$ plane. The equations of the characteristic lines are

$$\left(\frac{dx}{dt}\right)_1 = u + a$$

$$\left(\frac{dx}{dt}\right)_2 = u - a \quad .$$

If the variables P and Q are introduced (Riemann and others used the symbols "r" and "s") such that:*

$$P \equiv u + \frac{2}{\gamma - 1} a$$

$$Q \equiv u - \frac{2}{\gamma - 1} a$$

then the total change of these variables with time as one proceeds along characteristic lines is

$$\frac{\delta P}{dt} = \frac{\partial P}{\partial t} + \frac{\partial P}{\partial x} \left(\frac{dx}{dt}\right)_1$$

$$\frac{\delta Q}{dt} = \frac{\partial Q}{\partial t} + \frac{\partial Q}{\partial x} \left(\frac{dx}{dt}\right)_2$$

and from equation (6)

$$\frac{\delta P}{dt} = \frac{a^2}{(\gamma - 1)C_p} \frac{\partial S}{\partial x} + \frac{\gamma}{\gamma - 1} \frac{a}{C_p} \frac{dS}{dt} - \frac{ua}{A} \frac{dA}{dx} \qquad (7a)$$

$$\frac{\delta Q}{dt} = \frac{a^2}{(\gamma - 1)C_p} \frac{\partial S}{\partial x} - \frac{\gamma}{\gamma - 1} \frac{a}{C_p} \frac{dS}{dt} + \frac{ua}{A} \frac{dA}{dx} \qquad (7b)$$

Thus for a given tube the characteristic network may be constructed so long as the entropy variations are known. A method that may be used in constructing the network is described in the appendix. The method of characteristics is also described in the Shock Wave Manual[7] and by Sauer.[8]

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* $\frac{\delta}{dt}$ indicates the total derivative along a characteristic line.

APPLICATIONS

The equations derived in the preceding section have many interesting applications in the field of gas dynamics. Some possible applications include the calculation of the pulse-jet cycle, once a suitable model of combustion has been assumed, and studies of the stability of the flow pattern in the ram-jet. A study of the stability of the ram-jet operation might include the gas-dynamical effect of a wave disturbance upon the initial steady flow combustion pattern, or the effect of disturbances generated by "rough burning" (simulated by small variations of the quantity of heat input) on the motion of the diffuser shock wave in a supersonic ram-jet.

A problem that is treated in this report is the effect of addition of heat to an initially isentropic flow in a tube. The processes occurring in such a configuration are similar to those that occur during intermittent combustion in a flowing gas, as well as being similar to those that occur during steady flow combustion when the quantity of heat addition is suddenly changed.

The Addition of Heat to An Initially Isentropic Flow.

Of interest is the transient phenomena occurring when heat is suddenly added to an initially isentropic flow in a constant area tube of infinite length. Consider a tube in which the flow initially is at a Mach number of 0.80. Heat will be assumed to be added between stations A and B, at a rate such that

$$\frac{\frac{dQ^*}{dt}}{T} = \frac{dS}{dt} = \text{constant} = K$$

within the heating chamber. The value of $\frac{dS}{dt}$ was chosen as a constant to simplify the calculations.

The transients can now be calculated with the characteristic method utilizing equations (7a) and (7b). The entropy may be determined in the following manner: a plot of the actual particle paths can be constructed along with the characteristic calculation on an $x - t$ plane (the equation of a particle path lines is $dx/dt = u$). The entropy at any point is found by performing the following integration along the particle path

$$S - S_1 = \int_{t_1}^{t} \frac{\frac{dQ^*}{dt}}{T} \, dt$$

Once the entropy distribution is known, values of $\partial S/\partial t$ and $\partial S/\partial x$ at a given point can be estimated.

A great simplification in the present calculation can be made by the following observations. If the characteristic $x - t$ plane is divided up into regions bounded by the lines $x = A$ and $x = B$ (the entrance and exit of the heat chamber) and the particle path lines of the particles which are initially at $x = A$ and $x = B$ at the time $t = 0$ (see Figure 1), then for the prescribed heat addition $\frac{dQ^*}{dt}/T = K$ it can be ascertained that the entropy variations in the various regions are approximately

$$
\begin{array}{ll}
\mathrm{I} & \left\{ \begin{array}{l} \dfrac{\partial S}{\partial t} = 0 \\[2ex] \dfrac{\partial S}{\partial x} = 0 \end{array} \right. \\[6ex]
\mathrm{II} & \left\{ \begin{array}{l} \dfrac{\partial S}{\partial t} = K \\[2ex] \dfrac{\partial S}{\partial x} = 0 \end{array} \right. \\[6ex]
\mathrm{III} & \left\{ \begin{array}{l} \dfrac{\partial S}{\partial t} = 0 \\[2ex] \dfrac{\partial S}{\partial x} = \dfrac{K}{u} \end{array} \right. \\[6ex]
\mathrm{IV} & \left\{ \begin{array}{l} \dfrac{dS}{dt} = 0 \\[2ex] \dfrac{\partial S}{\partial x} = -\dfrac{K}{u} \end{array} \right.
\end{array}
\qquad (8)
$$

The above formulae were obtained by assuming that all the particle path lines in the $x - t$ plane deviate only slightly from straight lines all parallel to each other. As an example, consider the region numbered II. Since the heat is first added at $t = 0$, at any given constant value of t within region II, each particle has increased its entropy by the same amount under the assumptions made. Thus clearly $\frac{\partial s}{\partial x} = 0$. Then since

$$\frac{ds}{dt} = \frac{\partial s}{\partial t} + u \frac{\partial s}{\partial x} = K$$

it follows that

$$\frac{\partial s}{\partial t} = K .$$

A similar reasoning applied to the other regions will give the remaining equations.

These approximations to the entropy variations were used in calculation of the transient flow. Use of the approximation may also be regarded as equivalent to slightly varying the addition of heat during the transient phase so that the expressions (8) are satisfied.

The characteristic $x - t$ plane for this calculation is shown in Figure 2; the main results are illustrated in Figure 3, in which distributions of $\frac{u}{a_o}$ and $\frac{a}{a_o}$ are plotted against $\frac{x}{L}$ for several values of the time parameter

$$\frac{a_o t^*}{L} .$$

These graphs indicate that with the addition of heat compression waves are propagated both upstream and downstream of the heat chamber. It may be observed that the upstream moving compression wave is rapidly steepening into a shock wave. For the infinite tube the flow would always be unsteady because of the upstream and downstream moving waves. The transition to a steady flow in a tube of finite length will be discussed in a later paragraph.

The calculation carried out affords an insight into the processes occurring during intermittent combustion in an initial steady flow. It is evident that in combustion of this type the pressure is raised in the combustion chamber, this pressure increase causing the propagation in both directions of compression waves. The magnitude of the pressure rise in the combustion chamber is proportional to the rapidity of combustion; i.e. the rate of release of energy $\dot{Q}^*$. Thus, for large values of $\dot{Q}^*$ the thermodynamic combustion process approaches the constant-volume process (ρ = constant) obtained in the Otto-cycle;

whereas for small values of $\dot{Q}^*$ the burning process approaches the so-called constant pressure process obtained with steady-flow combustion as in the ram-jet and turbo-jet.

The Transition to the Steady Flow State.

As pointed out earlier in this paper, no steady state flow will ever occur in an infinitely long tube when heat is being added to an initially isentropic flow. Consider now that the tube is of finite length, such as a ram-jet moving at a flight Mach number of $M = 0.8$. (See Figure 4). When the heat is added to the flow, the compression waves which are propagated upstream and downstream will be reflected at the entry and exit of the tube and will continually reflect and refract until a new steady flow is established. The new steady flow will depend only on the ram stagnation pressure, the quantity of heat added by the burner and the exit pressure, (assuming frictionless flow) and can easily be calculated by the equations presented by Chambré and Lin[6] or Hicks.[9] Since the exit pressure is atmospheric, and since the steady addition of heat causes a pressure drop across the burner, it is evident that the pressure upstream of the burner is higher than that occurring in the completely adiabatic flow. Thus, the velocity ahead of the burner, and therefore, the mass flow through the system is reduced. Also it may be observed that, since the stagnation pressure of the flow is reduced in passing through the combustion chamber, the exit Mach number is less than that of the completely adiabatic flow. A plot of flow parameters for steady state flows with several values of the quantity of heat added is presented in Figure 4. It is evident that increasing the quantity of heat added will cause a readjustment of the flow with a further reduction of mass flow through the system.

Consider now a ram-jet propelled at supersonic speed with a supersonic diffuser at the inlet (Figure 5). In this configuration the mass flow is fixed once supersonic flow is established in the inlet of the diffuser, and a normal shock wave will be present in the diverging portion of the diffuser. If the quantity of heat added is increased, a new steady flow will be established with the shock moved to a more forward position.

The reason for this can easily be seen by considering the diverging part of the diffuser as analogous to the diverging part of a Laval nozzle.

Since the mass flow through the system is fixed, as long as sonic velocity exists at the throat of the exhaust nozzle, it follows that the Mach number at the burner exit must remain constant. Thus, increasing the quantity of heat added will reduce the Mach number M_A at the entry of the burner. Since the flow is adiabatic upstream of the burner, the mass flow per unit area depends only on the stagnation density behind the shock, the stagnation temperature which is constant, and the Mach number at the burner entry, i.e. $m = \rho_S \sqrt{T_S}\, f(M_A)$. Therefore, a reduction in M_A must be accompanied by an increase in ρ_S behind the shock, and the shock wave is weaker and occurs farther upstream. Additional increase in the quantity of heat added will finally move the shock to a more forward position until eventually it will reach the converging portion of the diffuser where it is unstable[5] and it will move out in front of the ram-jet tube as a detached shock. Now the internal flow is subsonic and the effect of further addition of heat will be the same as that of the subsonic jet.

The conclusions of the present study also give an insight into the apparently anomalous behavior at sonic velocity of a steady gas flow in a straight tube with a steady rate of heat addition.

From the equations of motion for steady flow it is concluded that the gas cannot absorb heat at sonic velocity; Chambré and Lin[6] conclude that a "sharp front" will result if heat is added to the gas at or beyond the point at which sonic velocity is attained. From the present study it appears that when a quantity of heat, greater than the "critical" amount that would bring the gas to sonic velocity, is added, compression waves travelling in both directions are generated initially and a new equilibrium flow is established.

APPENDIX

A Graphical Calculation Procedure

The method of characteristics is a graphical or numerical procedure for integrating partial differential equations of the hyperbolic type. It is assumed here that all quantities including u, a, and S are known at the points 1 and 2 in the $x - t$ plane and the values of these quantities are to be found at a third point designated 3. The rate of heat release is also assumed known throughout the $x - t$ plane, or

$$\dot{Q}^* = \dot{Q}^* \,(x, t)$$

To calculate the point 3, the characteristic differential equations (7a) and (7b) are written as difference equations and are solved by substitution in them of mean values of the quantities between 1 and 3 and 2 and 3, which are referred to as the quantities at I and II respectively. Inasmuch as the quantities at 3 are unknown as yet, the computation is of necessity an iterative procedure, the first approximation of which is as follows: (see Figure 6)

1. The characteristic lines are drawn through points 1 and 2 at angles

$$\alpha_1 = \cot^{-1}(u_1 + a_1)$$
$$\alpha_2 = \cot^{-1}(a_2 - u_2)$$

The intersection of these segments will be considered the first approximation to the point 3.

2. The values of $\frac{dS}{dt}$ and $\frac{\partial S}{\partial x}$ are to be found at the points I and II which bisect the characteristic segments 1-3 and 2-3 respectively. The value of $\frac{dS}{dt}$ may be found from

$$\frac{dS}{dt} = \frac{\frac{dQ^*}{dt}}{T} = \frac{(\gamma - 1)c_p \frac{dQ^*}{dt}}{a^2} .$$

Since the value of a at I and II is not yet known, the values at 1 and 2 may be used.

The value of $\frac{\partial S}{\partial x}$ may be estimated from the definition of a partial derivative, which for the point I is

$$\left(\frac{\partial S}{\partial x}\right)_I = \lim_{\Delta x \to 0} \frac{S(x_I + \frac{\Delta x}{2}, t_I) - S(x_I - \frac{\Delta x}{2}, t_I)}{\Delta x}$$

In estimating $\frac{\partial S}{\partial x}$ finite values of Δx must be used. The values of S used in the formula are determined by integrating along suitable particle path lines using the equation

$$S - S_o = \int_{t_o}^{t} \frac{\frac{dQ^*}{dt}}{T}\, dt$$

3. Equations (7a) and (7b) are utilized to determine P_3 and Q_3. They may be written as follows:

$$P_3 - P_1 = \left[\frac{a_I^2}{(\gamma-1)C_p}\left(\frac{\partial S}{\partial x}\right)_I + \frac{\gamma}{\gamma-1}\frac{a_I}{C_p}\left(\frac{dS}{dt}\right)_I - u_I a_I \frac{d \log A_I}{dx}\right](t_3 - t_1)$$

$$Q_3 - Q_2 = \left[\frac{a_{II}^2}{(\gamma-1)C_p}\left(\frac{\partial S}{\partial x}\right)_{II} - \frac{\gamma}{\gamma-1}\frac{a_{II}}{C_p}\left(\frac{dS}{dt}\right)_{II} + u_{II} a_{II} \frac{d \log A_{II}}{dx}\right](t_3 - t_2)$$

Where $u_I = \frac{u_1 + u_3}{2}$, $u_{II} = \frac{u_2 + u_3}{2}$, etc.

Since u_3 and a_3 are unknown as yet, in the first approximation the values of u and a at 1 and 2 are substituted for their values at I and II respectively. Values of u_3 and a_3 are then found from

$$u_3 = \frac{P_3 + Q_3}{2}$$

$$a_3 = \frac{\gamma - 1}{4}(P_3 - Q_3)\ .$$

The second approximation consists of constructing new characteristic segments using mean values of u and a between 1 and 3 and 2 and 3, finding a better approximation to the entropy derivatives, and recalculating P_3 and Q_3 using the mean values of u and a along the segments as well as the more accurate time change. The method usually converges very rapidly and for most applications the first approximation is sufficiently accurate.

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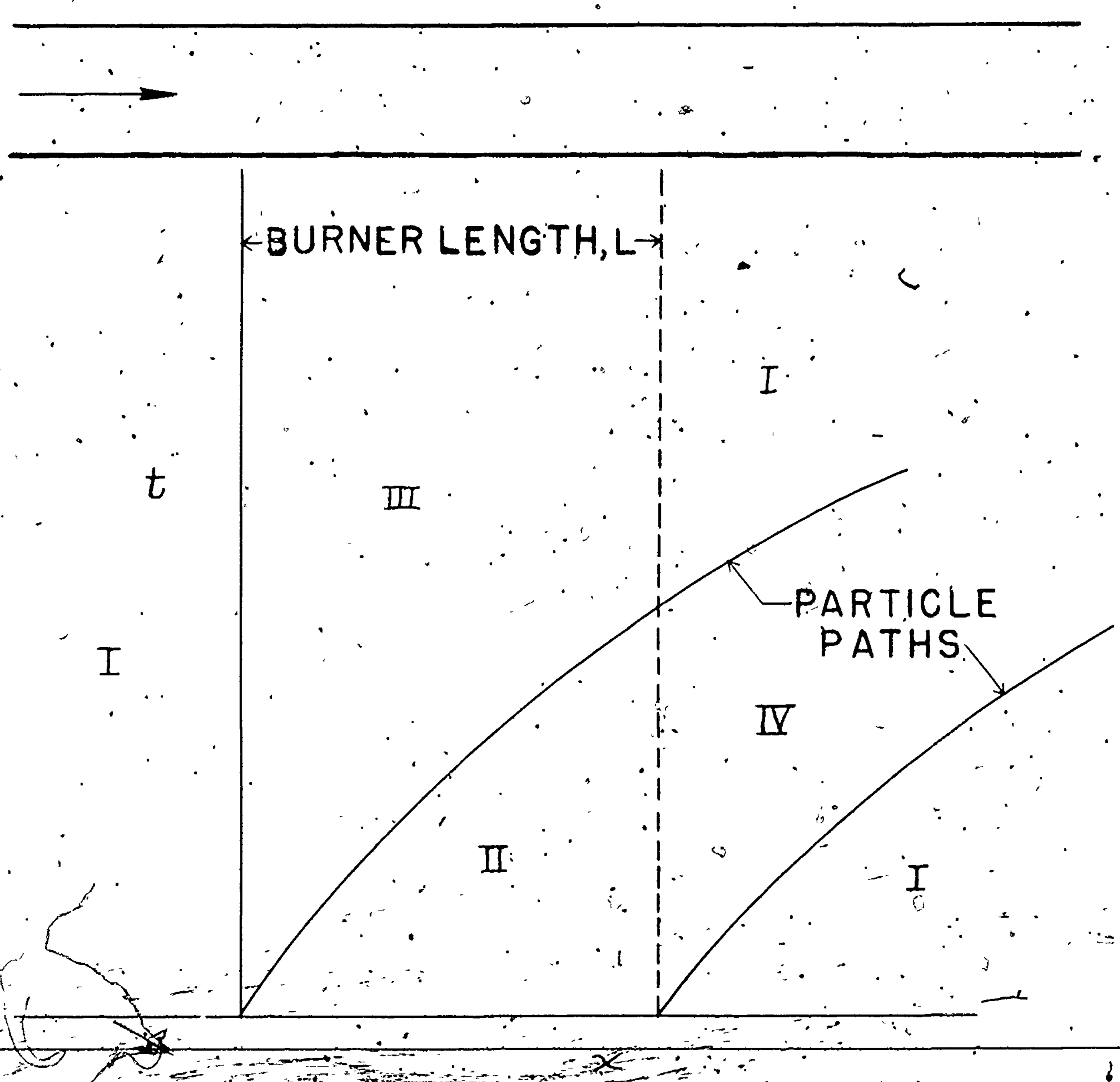

FIGURE I / REGIONS OF THE CHARACTERISTIC PLANE FOR WHICH APPROXIMATE ENTROPY DERIVATIVES ARE DETERMINED.

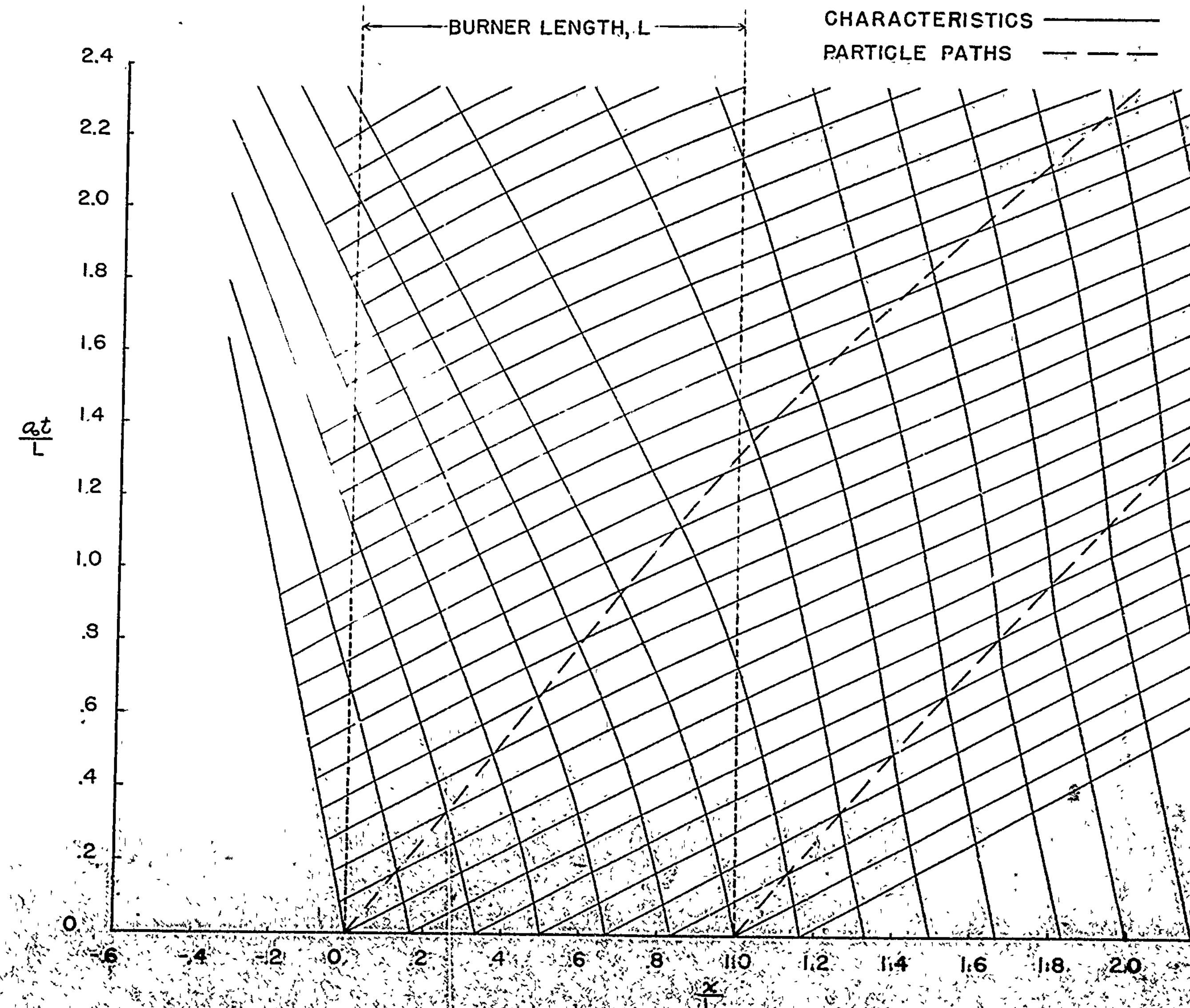

FIGURE 2. CHARACTERISTIC DIAGRAM FOR THE ADDITION OF HEAT IN A TUBE TO AN INITIALLY ISENTROPIC FLOW OF $M_o = 0.8$, $\frac{KL}{a_o C_p} = 0.36$

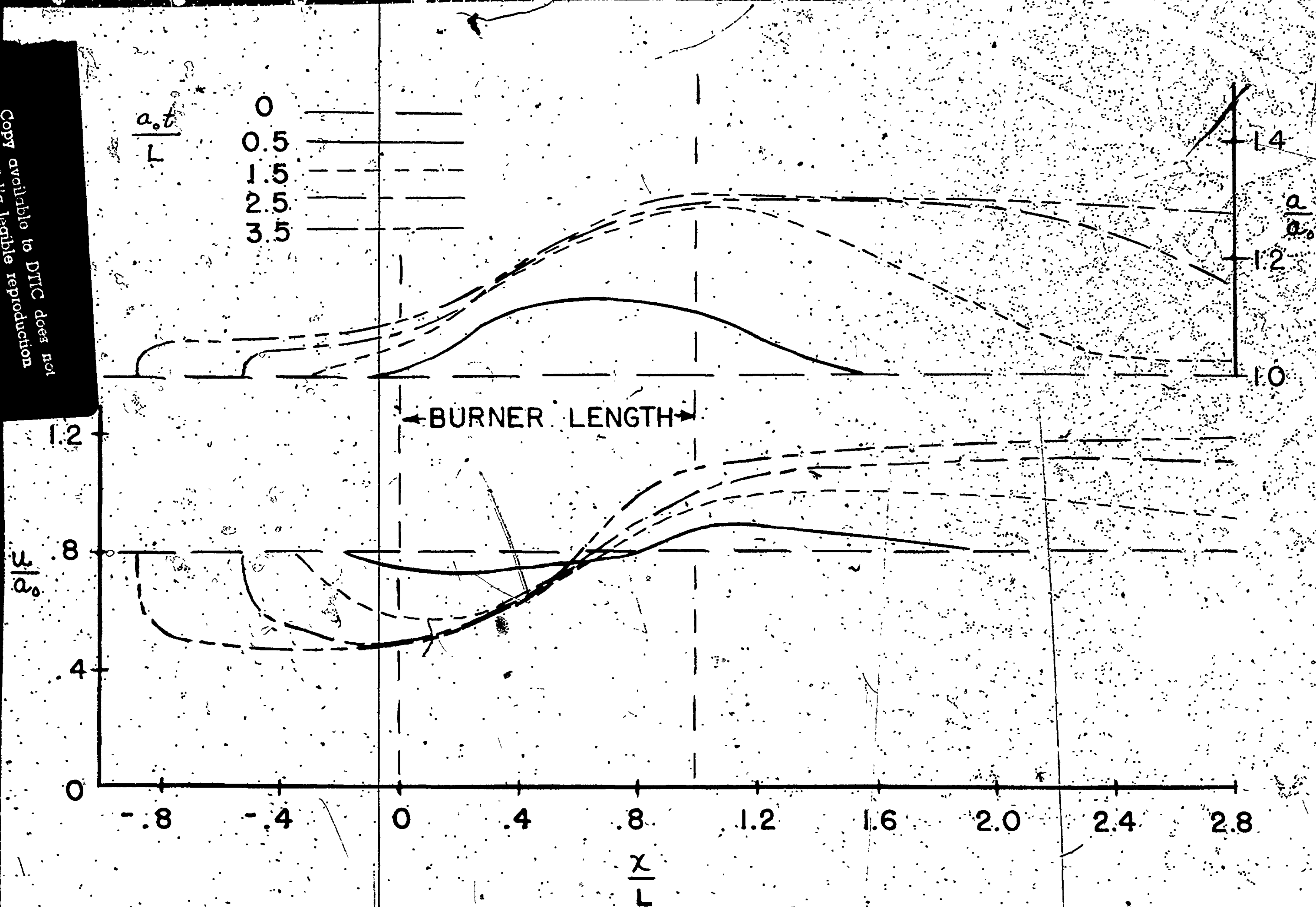

FIG. 3 DISTRIBUTION OF $\frac{u}{a_0}$ AND $\frac{a}{a_0}$ FOR SEVERAL VALUES OF THE TIME PARAMETER $\frac{a_0 t}{L}$.

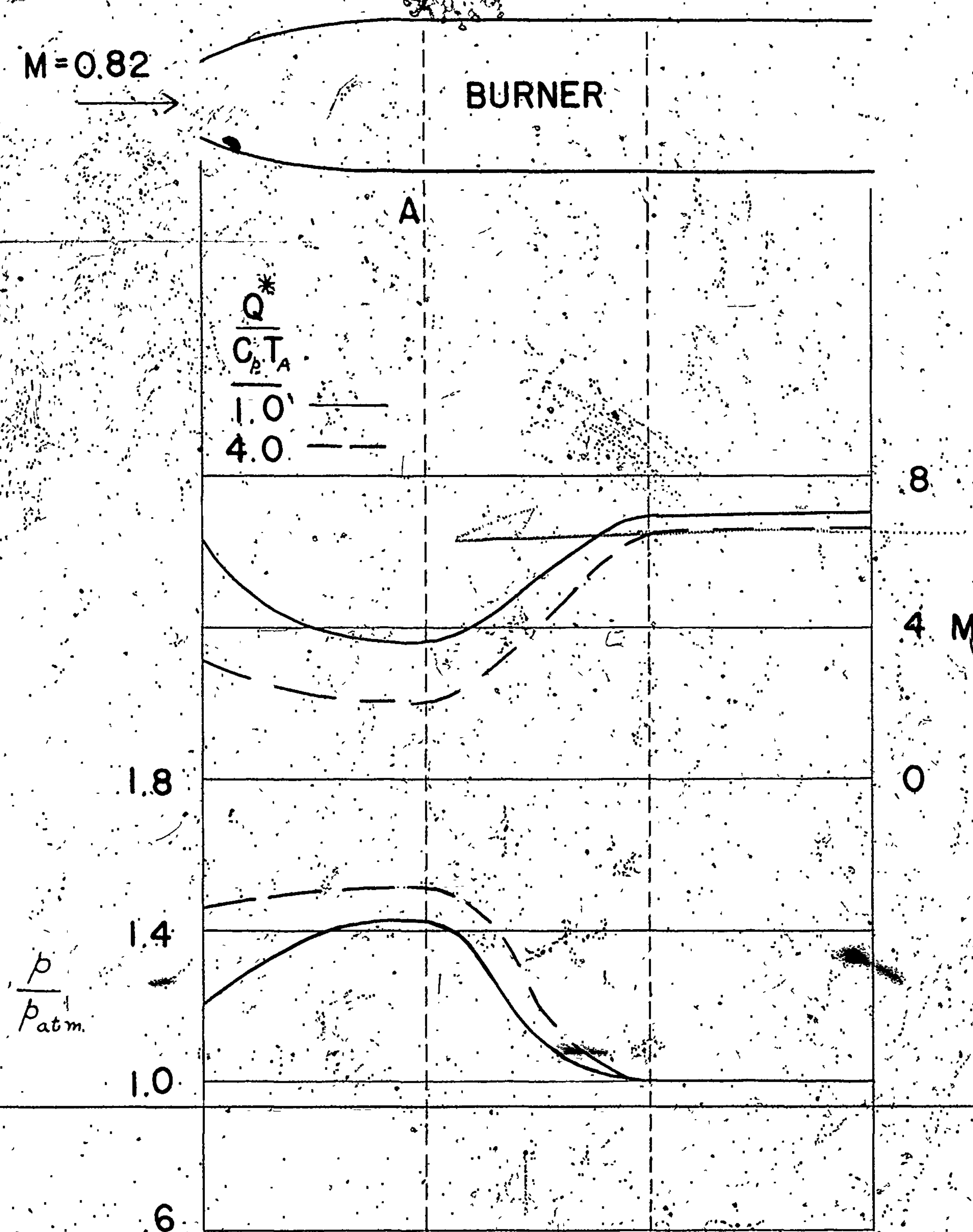

FIGURE 4 THE STEADY FLOW OBTAINED IN AN INITIALLY SUBSONIC FLOW FOR SEVERAL VALUES OF THE QUANTITY OF HEAT ADDED.

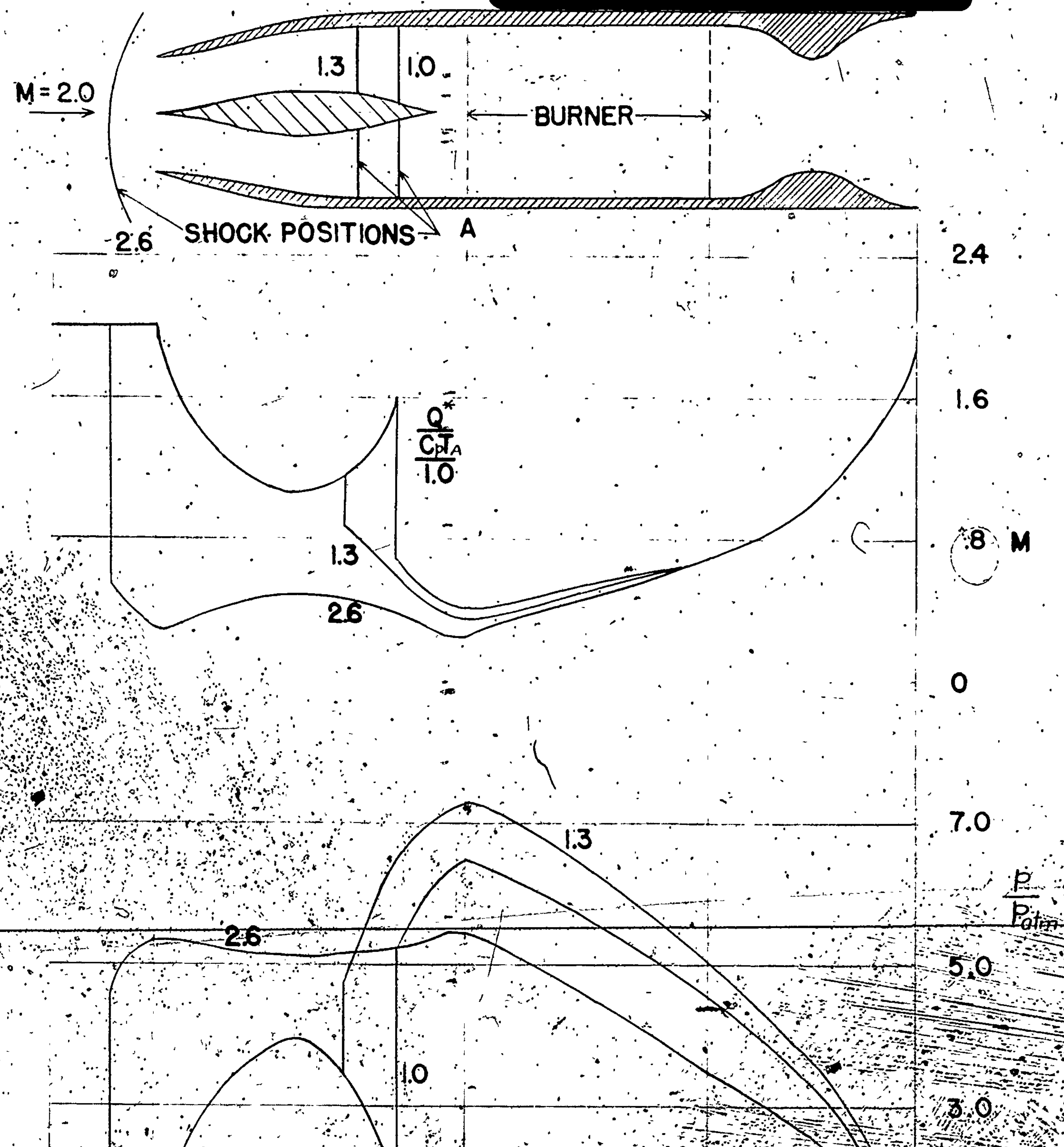

FIGURE 5 THE STEADY FLOW OBTAINED IN AN INITIALLY SUPERSONIC FLOW FOR SEVERAL VALUES OF QUANTITY OF HEAT ADDED.

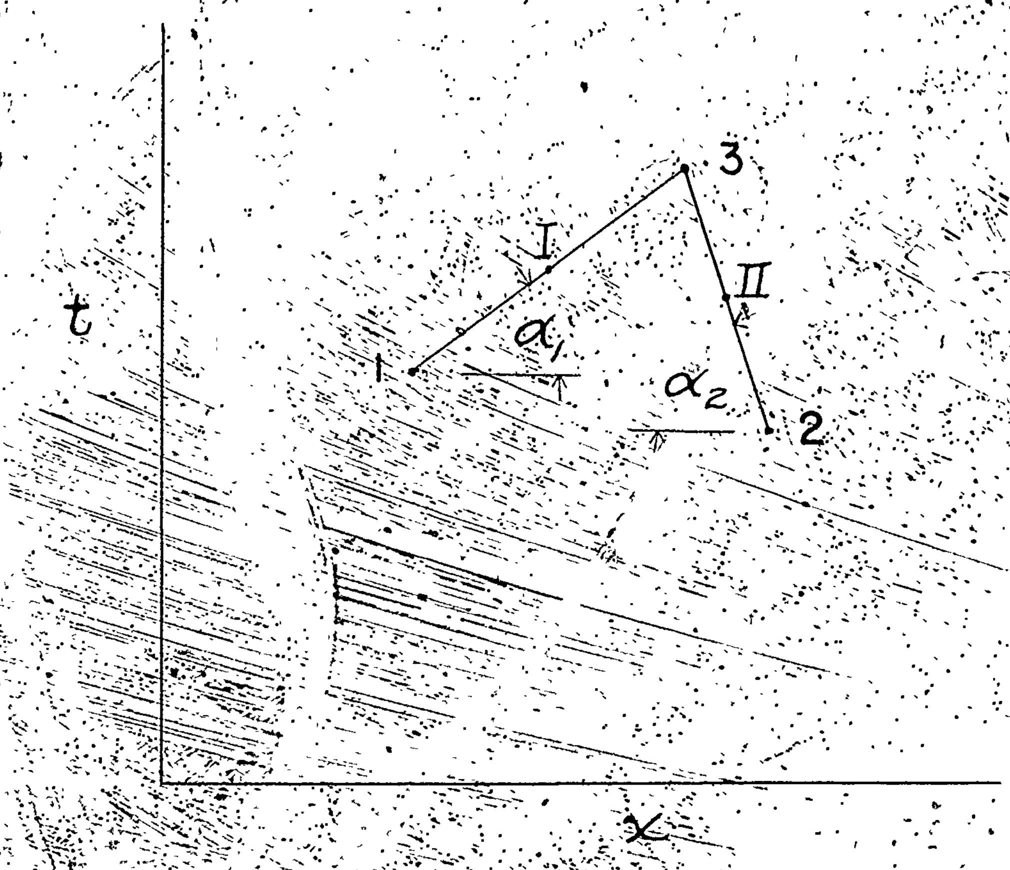

FIG. 6. GRAPHICAL METHOD OF CONSTRUCTING CHARACTERISTICS

Same as Ati 20867

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ABSTRACT

The combustion problem considered refers to unsteady gas-dynamical effects associated with the burning process. Characteristic equations for the propagation of waves in flows with heat addition or entropy variations are derived. These equations are applicable to the calculation of the pulse-jet cycle, once a suitable model of combustion has been selected, and to studies of the stability of the flow pattern in a ramjet. Transient flows arising when heat is added as in a combustion chamber of an initially isentropic flow in a tube have been calculated.

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Non-linear differential equations of the Rieman type are derived to solve problems involving propagation of one-dimensional waves in flows in tubes of slowly varying cross section with heat addition or entropy variation. Transient flows arising when heat is added to a section of an initially isentropic flow in a tube are calculated. The results afford an insight into gas dynamic aspects of intermittent heat addition in a flowing ags and into the apparently anomalous behavior at sonic velocity of steady gas flows with heat addition.

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DIVISION: Thermodynamics (1B)	SUBJECT HEADINGS: Combustion - Gas dynamics (23620); Flow, Nonadiabatic (40550); Engines, jet propulsion - Thermodynamics (33710)
SECTION: Combustion (2)	
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