NASA TECHNICAL MEMORANDUM

NASA TM X-3077

NASA TM X-3077

CASE FILE COPY

THERMODYNAMIC ANALYSIS OF AN AXIAL-FLOW LASER-POWERED THRUSTER

by Albert F. Kascak

Lewis Research Center

Cleveland, Ohio 44135

AMERICAN REVOLUTION BICENTENNIAL 1776-1976

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1974

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-3077		

4. Title and Subtitle	5. Report Date
THERMODYNAMIC ANALYSIS OF AN AXIAL-FLOW LASER-POWERED THRUSTER	JUNE 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Albert F. Kascak	E-7891
	10. Work Unit No.
9. Performing Organization Name and Address	502-04
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A one-dimensional model of a laser-powered thruster is analyzed. The model consists of two flow regions: a laser-heated region and a coaxial region outside the laser region. Different bulk velocities and temperatures are assigned for each region, and a common pressure is assigned for both regions. The one-dimensional inviscid flow equations are solved for each region with the same initial conditions. The results indicate that in order to prevent choked flow while increasing the enthalpy of the inlet gas by a factor of 10, the initial Mach number must be less than 0.14. For hydrogen gas seeded with 10 percent tungsten and entering the thruster tube at 10 atm and 300 K and a laser beam one-half the area of the tube, a tube length between 20 and 50 cm is required to vaporize the particles.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Laser-powered thruster	Unclassified - unlimited Category 33

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	20	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

THERMODYNAMIC ANALYSIS OF AN AXIAL-FLOW LASER-POWERED THRUSTER

by Albert F. Kascak

Lewis Research Center

SUMMARY

A preliminary analysis of an axial-flow laser-powered thruster is performed. An axial-flow laser-powered thruster is a device in which laser energy is beamed axially through an exhaust nozzle into a cylindrical chamber. The laser energy is absorbed by small solid particles suspended in the propellant gas. These particles then heat the gas by conduction. The propellant flows axially from the chamber inlet toward the exhaust nozzle.

The model analyzed assumes two inviscid flow regions: a region heated directly by the laser beam and a region between the chamber wall and the laser beam. The flow in each region is characterized by a bulk velocity and temperature, and there is a common pressure for both regions. The propellant is assumed to be a perfect gas with negligible solid particle thermodynamic properties and a constant optical absorption cross section. The one-dimensional inviscid flow equations are solved for each region with the same initial conditions.

The results show that, in general, the fluid in the laser-beam region heats up, expands, and causes a pressure gradient which accelerates the less dense laser-beam fluid more than the more dense coaxial fluid. Fluid is convected from the laser-beam region to the coaxial region. As the laser-beam fluid is heated, it begins to radiate heat to the fluid in the coaxial region, which in turn becomes heated and expands. This heating results in a pressure gradient which causes fluid to be transferred from the slower moving coaxial region to the faster moving laser-beam region and thus causes the fluid in the coaxial region to accelerate faster than the fluid in the laser-beam region.

It is concluded that for a given inlet Mach number there is a maximum laser intensity which will choke the flow. This maximum intensity increases as the inlet Mach number decreases. If the laser beam is the same size as the thruster tube, the inlet Mach number must be less than 0.14 to achieve a factor of 10 increase in the propellant gas enthalpy.

For a hydrogen gas seeded with 10 percent tungsten and entering the thruster tube at 10 atmospheres and 300 K and a laser beam that is one-half the area of the tube, a tube length between 20 and 50 centimeters is required to vaporize the tungsten particles.

INTRODUCTION

Several authors have considered the possibility of using high-power lasers as an energy source for rocket propulsion (e.g., ref. 1). Energy is converted into a laser beam at some convenient location. This energy is transmitted (by the beam) to a remote location. At the remote location, the energy is absorbed in a thruster, where it is used to heat a propellant. The heated propellant is expanded through a nozzle and produces thrust. A conceptual system is illustrated in figure 1. System performance of laser-powered thruster systems is described in references 1 and 2.

An axial-flow thruster of the type suggested in reference 1 is shown in figure 2. The laser energy is beamed axially through an exhaust nozzle into a cylindrical chamber. This energy is absorbed by small solid particles suspended in the propellant gas. These particles then heat the gas by conduction. The propellant flows axially from the chamber inlet toward the exhaust nozzle. Part of the propellant is heated by the laser beam and expands. The rest of the propellant does not "see" the laser beam and is heated by reradiation. This difference results in pressure gradients which cause flow profile redistributions. The coupling of the laser energy to the propellant and the subsequent flow redistribution are the subjects of this report. One of the major questions to be answered is How large must the chamber be to absorb the laser energy?

The approach taken is to assume two inviscid flow regions: the region heated by the laser beam and the region between the chamber wall and the laser beam. The flow is characterized by a bulk velocity and temperature in each region and a common pressure for both regions. The one-dimensional inviscid flow equations are solved for each region with the same initial conditions. The heat transfer between the two regions is assumed to be by thermal radiation.

SYMBOLS

A	area
a	absorption coefficient
C_1	constant defined in eq. (8b)
C_2	constant defined in eq. (8c)
C_3	constant defined in eq. (8d)
$\dot{H}$	convective energy
h	enthalpy

I laser-beam intensity

M Mach number

$\dot{\mathcal{M}}$ convective momentum

$\dot{m}$ convective mass

N constant defined in eq. (8e)

P pressure

Q heat generation rate

T temperature

u axial velocity

z axial distance

α constant defined in eq. (12c)

β constant defined in eq. (13c)

γ ratio of specific heat at constant pressure to specific heat at constant volume

δ constant defined in eq. (15b)

ϵ constant defined in eq. (15c)

η constant defined in eq. (15d)

ξ ratio of coaxial flow area to laser-beam area

ρ density

σ Steffan-Boltzmann constant

τ optical distance based on initial absorption coefficient

Subscripts:

B laser-beam region

C coaxial flow region

max quantity evaluated at condition of maximum laser-beam intensity

0 inlet region

Superscripts:

$-$ quantity nondimensionalized by initial value of quantity

$'$ derivative with respect to distance or optical distance

$*$ velocity or enthalpy associated with mass transferred into region for which equations are written

ANALYSIS

This analysis of an axial-flow laser-powered thruster assumed that the propellant is a mixture of solid particles and a perfect gas. The solid particles absorb the laser radiation and then conduct the heat to the surrounding gas. The heat-transfer coefficient between the particles and the gas is assumed to be so large that there is negligible temperature difference between the particles and the gas.

The model used in the analysis is shown in figure 2. The cylindrical chamber is divided into two regions. The first region (B) "sees" the laser beam. The second region (C) is coaxial to the first and does not "see" the laser beam. The propellant flows axially from the chamber inlet toward the exhaust nozzle. At the inlet (0), the flow is uniform in both regions and has the same properties.

The axial mass, momentum, and energy convection are defined, respectively, as

$$\dot{m} = \rho u A \tag{1a}$$

$$\dot{\mathcal{M}} = u\dot{m} \tag{1b}$$

$$\dot{H} = \left(h + \frac{1}{2} u^2\right)\dot{m} \tag{1c}$$

where ρ is the density, u is the axial velocity, A is the cross-sectional area, and h is the enthalpy in either region B or C. For inviscid one-dimensional flow, the axial momentum and energy equation are written, respectively, as

$$\dot{\mathcal{M}}' = -AP' + u^* \dot{m}' \tag{2a}$$

$$\dot{H}' = QA + \left(h^* + \frac{1}{2} u^{*2}\right)\dot{m}' \tag{2b}$$

where P is the pressure, $\dot{m}'$ is the mass transferred from one region into the region of interest, and Q is the heat generation rate. (The superscript * indicates the velocity or enthalpy that is transferred with the associated mass transfer, and the region of interest is the region for which the equations are written.)

The equation of state for a perfect gas can be written as

$$\frac{\rho}{\rho_0} = \frac{\dfrac{P}{P_0}}{\dfrac{T}{T_0}} = \frac{\dfrac{P}{P_0}}{\dfrac{h}{h_0}} \tag{3}$$

where solid particle thermodynamic properties have been neglected, and T is temperature. The absorption coefficient for a gas seeded with small solid particles is proportional to the mixture density:

$$\frac{a}{a_0} = \frac{\rho}{\rho_0} \tag{4}$$

where it is assumed that the mass fraction of seed is small compared to that of the gas, and the seed particle radius remains constant with temperature and pressure.

The heat source terms for the two regions are

$$Q_B = a_B\left[I_B - 4\sigma\left(T_B^4 - T_C^4\right)\right] \tag{5a}$$

$$Q_C = 4\sigma a_B \frac{A_B}{A_C}\left(T_B^4 - T_C^4\right) \tag{5b}$$

where the radiation term between the two regions is based on the transparent approximation, and all the heat radiated from region B is deposited in region C. (This formulation neglects conduction between the two regions.) The intensity of the laser beam I_B is given by the radiation absorption law:

$$I_B' = a_B I_B \tag{6}$$

The inlet to the chamber is a permeable wall. Flow enters the wall from a reservoir at a very low temperature ($T \sim 0$). As the flow passes through the wall, it must pick up the laser energy falling on the inside of the wall $A_B I_{B,0}$. Since the flow leaves the wall at a temperature T_0, the heat balance on the wall is

$$A_B I_{B,0} = (A_B + A_{C,0})\rho_0 u_0\left(h_0 + \frac{1}{2}u_0^2\right) \tag{7}$$

where A_B is a constant equal to the laser-beam cross-sectional area.

The laser intensity at the exit of the thrust chamber is given. In order to make the problem an initial value problem, the laser intensity at the inlet must be known. The required inlet intensity can be calculated from equation (7) and an inlet wall temperature limit. The initial value problem can then be integrated to the exit intensity. The length for this integration is thus the length of the thrust chamber.

The variables can be nondimensionalized by dividing the variable by its inlet value and denoting the nondimensional variable by a superscript bar. The axial distance is transformed to the nondimensional optical distance by

$$\tau = a_0 z \tag{8a}$$

The prime will now refer to the derivative with respect to the optical distance. From the perfect gas law and thermodynamics

$$\frac{P_0}{\rho_0 h_0} = \frac{\gamma - 1}{\gamma} \equiv C_1 \tag{8b}$$

where γ is the ratio of specific heats. The inlet Mach number M_0 is

$$M_0^2 = \frac{1}{\gamma - 1} \frac{u_0^2}{h_0} \equiv \frac{C_2}{\frac{1}{2}(\gamma - 1)} \tag{8c}$$

At the inlet the ratio of the radiated to convected heat transfer is

$$C_3 = \frac{\sigma T_0^4}{\rho_0 u_0 h_0} = \frac{\sqrt{\gamma - 1}\, N}{\gamma M_0} \tag{8d}$$

where N is the radiative to convective number, defined as

$$N \equiv \frac{\sigma T_0^4}{P_0 \sqrt{h_0}} \tag{8e}$$

Using the constants defined in equation (8) and the previously defined nondimensional variables gives for the momentum and energy equations

$$\dot{\overline{\mathscr{M}}}' = -\frac{C_1}{2C_2} \overline{AP}' + \overline{u}^* \dot{\overline{m}}' \tag{9a}$$

$$\dot{\overline{H}}' = \frac{Q\overline{A}}{(1 + C_2) a_0 \rho_0 u_0 h_0} + \frac{\left(\overline{h}^* + C_2 u^{*2}\right)\dot{\overline{m}}'}{1 + C_2} \tag{9b}$$

where

$$\frac{Q_B}{a_0 \rho_0 u_0 h_0} = \overline{a} \left[\left(1 + \frac{A_{C,0}}{A_B}\right) (1 + C_2)\overline{I}_B - 4C_3\left(\overline{T}_B^4 - \overline{T}_C^4\right)\right] \tag{9c}$$

and

$$\frac{Q_C}{a_0\rho_0 u_0 h_0} = 4\bar{a}C_3 \frac{A_B}{A_C}\left(\bar{T}_B^4 - \bar{T}_C^4\right) \tag{9d}$$

(Eq. (9c) used the initial condition, eq. (7).) With the nondimensional variables defined, the equation of state (eq. (3)) becomes

$$\bar{\rho} = \frac{\bar{P}}{\bar{T}} = \frac{\bar{P}}{\bar{h}} \tag{10a}$$

and from equation (3) the nondimensional absorption coefficient becomes equal to the nondimensional density:

$$\bar{a} = \bar{\rho} \tag{10b}$$

The radiation absorption law (eq. (6)) then becomes

$$\frac{\bar{I}'_B}{\bar{I}_B} = \bar{a}_B = \bar{\rho}_B = \frac{\bar{P}_B}{\bar{h}_B} \tag{11}$$

Using the definition of the nondimensional axial momentum convection results in

$$\dot{\bar{\mathcal{M}}} = \bar{u}\dot{\bar{m}} \tag{12a}$$

and equation (9a), the derivative of the nondimensional axial velocity, becomes

$$\frac{\bar{u}'}{\bar{u}} = -\frac{C_1}{2C_2}\frac{\bar{P}'}{\bar{\rho}\bar{u}^2} + \alpha\frac{\dot{\bar{m}}'}{\dot{\bar{m}}} \tag{12b}$$

where α is defined as

$$\alpha = \frac{\bar{u}^* - \bar{u}}{\bar{u}} \tag{12c}$$

Using the definition of the nondimensional axial energy convection gives

$$\dot{\bar{H}} = \frac{\left(\bar{h} + C_2\bar{u}^2\right)\dot{\bar{m}}}{1 + C_2} \tag{13a}$$

and equations (9b) and (12b); the derivative of the nondimensional enthalpy becomes

$$\frac{\bar{h}'}{\bar{h}} = \frac{1}{\bar{\rho}\bar{u}\bar{h}}\frac{Q}{a_0\rho_0 u_0 h_0} + C_1\frac{\bar{P}'}{\bar{\rho}\bar{h}} + \beta\frac{\dot{\bar{m}}'}{\dot{\bar{m}}} \tag{13b}$$

where β is defined as

$$\beta = \frac{\bar{h}^* - \bar{h} + C_2(u^* - u)^2}{\bar{h}} \tag{13c}$$

Using the definition of the nondimensional axial mass convection gives

$$\bar{\dot{m}} = \overline{\rho u A} \tag{14a}$$

and the equation of state (10a); the derivative of the nondimensional axial mass convection becomes

$$\frac{\bar{\dot{m}}'}{\bar{\dot{m}}} = \frac{\bar{u}'}{\bar{u}} + \frac{\bar{P}'}{\bar{P}} - \frac{\bar{h}'}{\bar{h}} + \frac{\bar{A}'}{\bar{A}} \tag{14b}$$

Substituting equations (12b) and (13b) into equation (14b) and rearranging yield

$$\delta \frac{\bar{\dot{m}}'}{\bar{\dot{m}}} = \epsilon \frac{\bar{P}'}{\bar{P}} + \eta \tag{15a}$$

where

$$\delta = 1 - \alpha + \beta \tag{15b}$$

$$\epsilon = 1 - C_1 - \frac{C_1}{2C_2} \frac{\bar{P}}{\bar{\rho}\bar{u}^2} \tag{15c}$$

$$\eta = \frac{\bar{A}'}{\bar{A}} - \frac{1}{\overline{\rho u h}} \frac{Q}{a_0 \rho_0 u_0 h_0} \tag{15d}$$

The mass leaving one region must be equal to the mass entering the other; therefore,

$$\bar{\dot{m}}_B' = -\bar{\dot{m}}_C' \tag{16}$$

It is assumed that the pressures in both regions are equal, that is, there are no radial pressure gradients:

$$P = P_B = P_C \tag{17}$$

Substituting equations (10a), (14a), and (15a) into equations (12b), (13b), and (16) yields

$$\frac{\bar{u}'}{\bar{u}} = \left(\frac{\alpha\epsilon}{\delta} - \frac{C_1}{2C_2}\,\frac{\bar{h}}{\bar{u}^2}\right)\frac{\bar{P}'}{\bar{P}} + \frac{\alpha\eta}{\delta} \tag{18a}$$

$$\frac{\bar{h}'}{\bar{h}} = \left(\frac{\beta\epsilon}{\delta} + C_1\right)\frac{\bar{P}'}{\bar{P}} + \frac{\beta\eta}{\delta} + \frac{\bar{A}'}{\bar{A}} - \eta \tag{18b}$$

$$\frac{\bar{P}'}{\bar{P}} = -\frac{\dfrac{\bar{u}_B\eta_B}{\bar{h}_B\delta_B} + \xi\,\dfrac{\bar{u}_C\eta_C}{\bar{h}_C\delta_C}}{\dfrac{\bar{u}_B\epsilon_B}{\bar{h}_B\delta_B} + \xi\,\dfrac{\bar{u}_C\epsilon_C}{\bar{h}_C\delta_C}} \tag{18c}$$

where equations (18a) and (18b) are applicable in both region B and region C. Substituting equations (10a) and (14a) into (15a) and evaluating it in region B yield

$$\bar{\dot{m}}_B' = \frac{\bar{P}\bar{u}_B\bar{A}_B}{\bar{h}_B\delta_B}\left(\epsilon_B\frac{\bar{P}'}{\bar{P}} + \eta_B\right) \tag{19}$$

If $\bar{\dot{m}}_B' < 0$, mass is being convected from region B to region C, and the associated velocity and enthalpy are

$$\bar{u}^* = \bar{u}_B \tag{20a}$$

$$\bar{h}^* = \bar{h}_B \tag{20b}$$

If $\bar{\dot{m}}_B' \geq 0$, mass is being convected from region C to region B, and the associated velocity and enthalpy are

$$\bar{u}^* = \bar{u}_C \tag{21a}$$

$$\bar{h}^* = \bar{h}_C \tag{21b}$$

Equations (11) and (18), when applied to both regions, form a complete set of six differential equations in six unknowns: $\bar{u}_B$, $\bar{u}_C$, $\bar{h}_B$, $\bar{h}_C$, $\bar{P}$, and $\bar{I}_B$. These equations can be solved by using a predictor-corrector numerical technique. Initially the variables are normalized to 1. Auxiliary equations used are (9), (10), (12), (13), (15), (19), and either (20) or (21). The gamma of the gas, the initial Mach number, the initial radiative to convective number, and the ratio of the wall area to the beam must be given.

A special case arises when the wall area is equal to the cross-sectional area of the beam. For this case there is no flow outside the beam, and the wall temperature is equal to the beam gas temperature:

$$\overline{\dot{m}}'_B = 0 \tag{22a}$$

$$\overline{A}_B = 1 \tag{22b}$$

$$\overline{T}_B = \overline{T}_C \tag{22c}$$

The mass convection in the beam is a constant:

$$\overline{\dot{m}}_B = 1 \tag{23a}$$

Therefore,

$$\overline{h}_B = \overline{u}_B \overline{P} \tag{23b}$$

The momentum equation (9a) can be integrated and when solved for the pressure becomes

$$\overline{P} = 1 - \frac{2C_2}{C_1} (\overline{u}_B - 1) \tag{24a}$$

Using equations (23b) and (24a) gives the enthalpy:

$$\overline{h}_B = \overline{u}_B \left[1 - \frac{2C_2}{C_1} (\overline{u}_B - 1) \right] \tag{24b}$$

The heat source term (9c) becomes

$$\frac{Q_B}{a_0 \rho_0 u_0 h_0} = (1 + C_2)\overline{aI}_B = (1 + C_2)\overline{I}'_B \tag{25a}$$

Substituting this into the energy equation and integrating yield

$$\overline{h}_B + C_2 \overline{u}_B^2 - (1 + C_2) = (1 + C_2)(\overline{I}_B - 1) \tag{25b}$$

Substituting equation (24b) into (25b) and solving for the intensity give

$$\bar{I}_B = \frac{\bar{u}_B}{C_1(1 + C_2)} \left[C_1 + 2C_2 + (C_1 - 2)C_2\bar{u}_B\right] \tag{26a}$$

Differentiating equation (26a) yields

$$\bar{I}'_B = \frac{\bar{u}'_B}{C_1(1 + C_2)} \left[C_1 + 2C_2 + 2(C_1 - 2)C_2\bar{u}_B\right] \tag{26b}$$

Substituting equations (23b) and (26) into equation (11) yields

$$d\tau = \frac{C_1 + 2C_2 + 2(C_1 - 2)C_2\bar{u}_B}{C_1 + 2C_2 + (C_1 - 2)C_2\bar{u}_B}\, d\bar{u}_B \tag{27a}$$

Integrating equation (27a) from the initial condition results in

$$\tau = 2(\bar{u}_B - 1) - \frac{C_1 + 2C_2}{(C_1 - 2)C_2} \ln \frac{C_1 + 2C_2 + (C_1 - 2)C_2\bar{u}_B}{C_1(1 + C_2)} \tag{27b}$$

The maximum laser intensity (choked flow) is obtained by letting the derivative of the laser-beam intensity (eq. (26b)) equal zero:

$$\bar{u}_{B,max} = \frac{C_1 + 2C_2}{2(2 - C_1)C_2} \tag{28}$$

With this value of the axial velocity known, the corresponding variables are obtained from equations (24), (26), and (27).

DISCUSSION

A model of a coaxial flow laser-powered thruster is shown in figure 2. The cylindrical chamber is divided into two coaxial regions. The first (inner) region is heated directly by the laser beam. The propellant flows axially from the chamber inlet toward the exhaust nozzle. At the inlet the flow is uniform in the two regions, both having the same temperature, pressure, and velocity. The fluid in the center is heated and expands and thus causes pressure gradients. These pressure gradients accelerate both the heated and the nonheated fluid. As the flow accelerates, energy and mass are transferred between the two regions. The laser is assumed to be beamed through the nozzle. It is further assumed that the beam intensity in the propellant decreases exponentially with the distance from the nozzle. The region of interest is shown in figure 2.

The first case studied is one in which the laser beam occupies the entire cylindrical volume. There is no coaxial flow. This condition is equivalent to heating a tube with nonfrictional flow. It has been analyzed in many texts on advanced fluid flow, such as reference 3. These analyses showed that there is a maximum amount of heat that can be deposited in the gas in the tube. This condition is expressed in equation (28), in which the laser-beam intensity is maximized. With this value of the axial velocity known, the corresponding variables are obtained from equations (24), (26), and (27) and are plotted in figure 3.

Figure 3 shows nondimensional axial velocity, enthalpy, laser intensity, pressure, and optical distance plotted against the initial Mach number for the condition of maximum laser-beam intensity. For this case the laser beam fills the thruster tube, and there is no coaxial flow. Values for a monatomic gas, such as dissociated hydrogen ($\gamma = 1.667$), are shown in figure 3(a); and values for a diatomic gas, such as undissociated hydrogen ($\gamma = 1.4$), are shown in figure 3(b).

Figure 3 shows that to increase the maximum laser-beam intensity, and thus the amount of energy deposited in the propellant gas, the initial Mach number must be decreased. If the propellant gas is heated to at least 10 times the initial enthalpy, the initial Mach number must be less than 0.14, and the minimum optical distance must be greater than 13.

An example of the detailed axial profiles which result in this maximum laser-beam intensity is shown in figure 4. This figure shows the Mach number and nondimensional axial velocity, enthalpy, laser intensity, and pressure plotted against optical distance (the initial absorption coefficient times the distance from the inlet). The initial Mach number is 0.01, and the laser fills the thruster tube (there is no coaxial flow). Figure 4(a) is for a monatomic gas, and figure 4(b) is for a diatomic gas. Over a large portion of the range of optical distance there is very little difference between a monatomic and a diatomic gas; this is the region where the Mach number is low. As the Mach number approaches 1, the flow begins to choke. The slopes of all the curves in figure 4 approach plus or minus infinity. As the Mach number increases above 1, the laser-beam intensity decreases. Since the laser-beam intensity must increase, this portion of the curve is not physically possible.

In any real system, the laser-beam cross-sectional area would be less than the cross-sectional area of the thruster tube. (Besides the obvious problems of misalinement and heat transfer to the tube wall, the previous discussion indicated a need for a convergent-divergent nozzle to make the flow supersonic. This nozzle shadows a portion of the cross-sectional area of the tube.) Figure 5 presents results for a case in which the cross-sectional area of the laser beam is one-half the cross-sectional area of the thruster tube. In this figure the calculated Mach number and nondimensional axial velocity, enthalpy, mass convection, and intensity in the laser-beam region; Mach number and nondimensional axial velocity, enthalpy, and mass convection in the coaxial region; and nondimensional pressure are plotted against optical distance from the inlet. At the inlet the initial pressure was 10 atmospheres, and the initial temperature was 300 K. Figures 5(a) and (c) represent undissociated hydrogen, and figures 5(b) and (d) represent dissociated hydrogen. Figures 5(a) and (b) present data for an initial Mach number of 0.01, and figures 5(c) and (d) for an initial Mach number of 0.005.

In general, the fluid in the laser-beam region heats up and expands. This expansion causes a pressure gradient which accelerates the fluid in the laser-beam region and to a lesser extent the fluid in the coaxial region. (The latter fluid is accelerated less because it is more dense.) Some of the fluid in the laser-beam region is convected into the coaxial region, and thus the enthalpy in the coaxial region is raised. As the enthalpy in the laser-beam region is raised, the region begins to radiate energy to the coaxial region. The coaxial region then heats up and expands. This expansion causes a pressure gradient which accelerates the fluid in the coaxial region and to a lesser extent the fluid in the laser region. (Some of the more slowly moving fluid in the coaxial region is convected back into the laser region and reduces acceleration in the laser region.)

If the solid seed particles in the propellant gas were tungsten, the particles would vaporize between 5000 and 6000 K. This behavior corresponds to an enthalpy increase of a factor of about 20. An enthalpy increase of a factor of 20 in the laser-beam region corresponds to an optical distance of about 14 for an initial Mach number of 0.01 and an optical distance of about 21 for an initial Mach number of 0.005. For a seed mass fraction of about 10 percent and a seed absorption cross section 10 000 square centimeters per gram, the corresponding thruster tube length is between 20 and 50 centimeters.

CONCLUSIONS

The following conclusions were drawn from a thermodynamic analysis of a two-region model of an axial-flow laser-powered thruster:

1. There is a maximum laser intensity which will choke the flow in the thruster tube.

2. If the inlet Mach number is reduced, the maximum laser intensity can be increased.

3. If the laser beam is the same size as the thruster tube, the inlet Mach number must be less than 0.14 to achieve a factor of 10 increase in the propellant gas enthalpy.

4. For hydrogen gas seeded with 10 percent tungsten and entering the thruster

tube at 10 atmospheres and 300 K and a laser beam that is one-half the area of the tube, a tube length between 20 and 50 centimeters is required to vaporize the tungsten particles.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 1, 1974,
502-04.

REFERENCES

1. Rom, Frank E.; and Putre, Henry A.: Laser Propulsion. NASA TM X-2510, 1972.
2. Ragsdale, Robert G.; and Putre, Henry A.: Some Thermodynamic Characteristics of a Laser Thermal-Rocket Engine. NASA TM X-2862, 1973.
3. Compressible Frictionless Flow in Pipes with Heat Transfer. In Advanced Fluid Dynamics and Fluid Machinery, R.C. Binder, Sec. 3-5, Prentice-Hall, Inc., 1951, pp. 77-82.

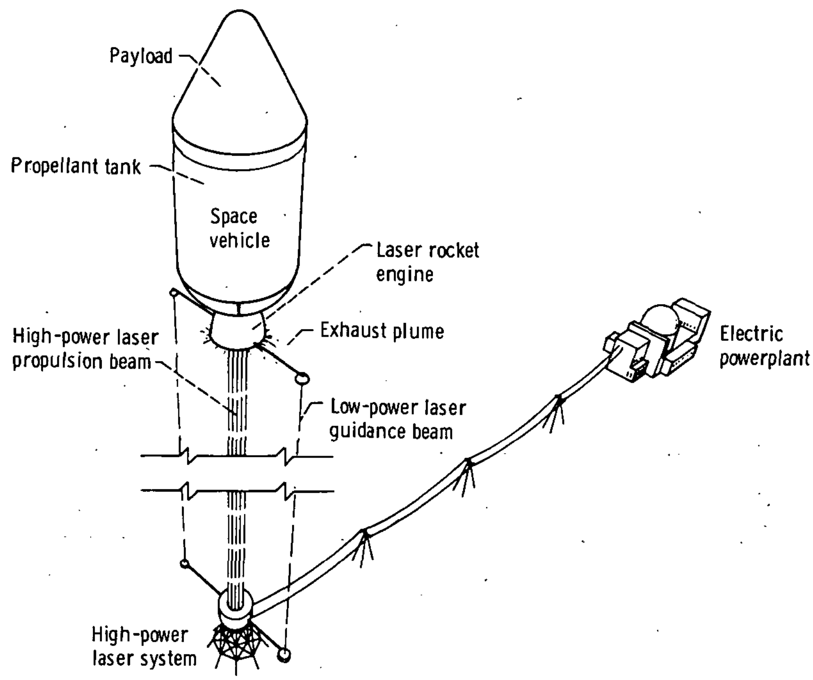


Figure 1. - Laser rocket system.

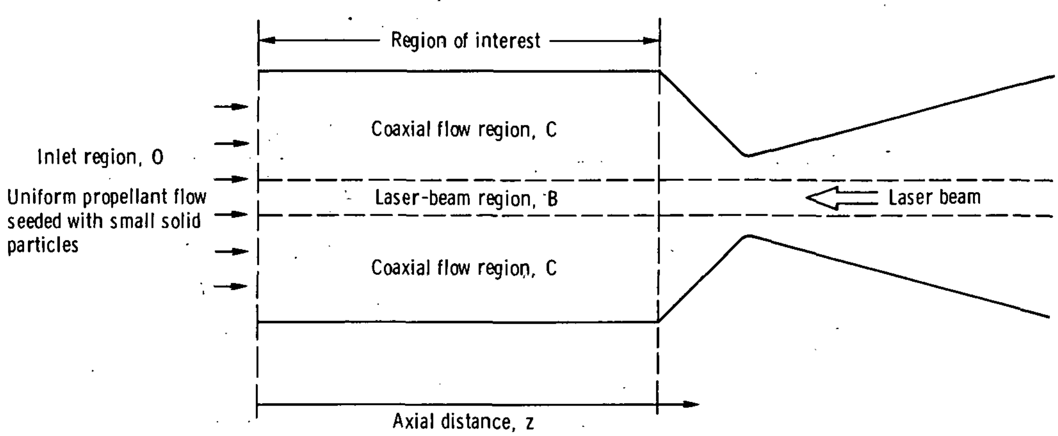
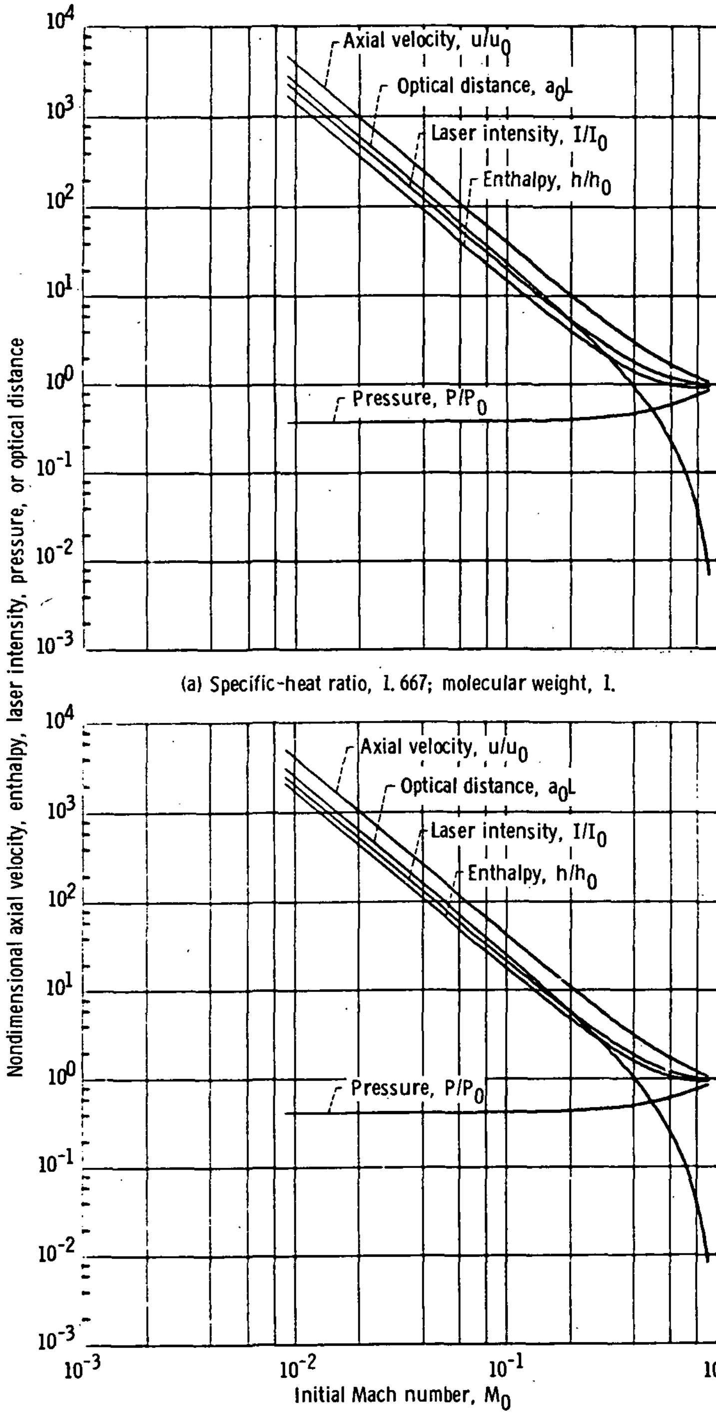
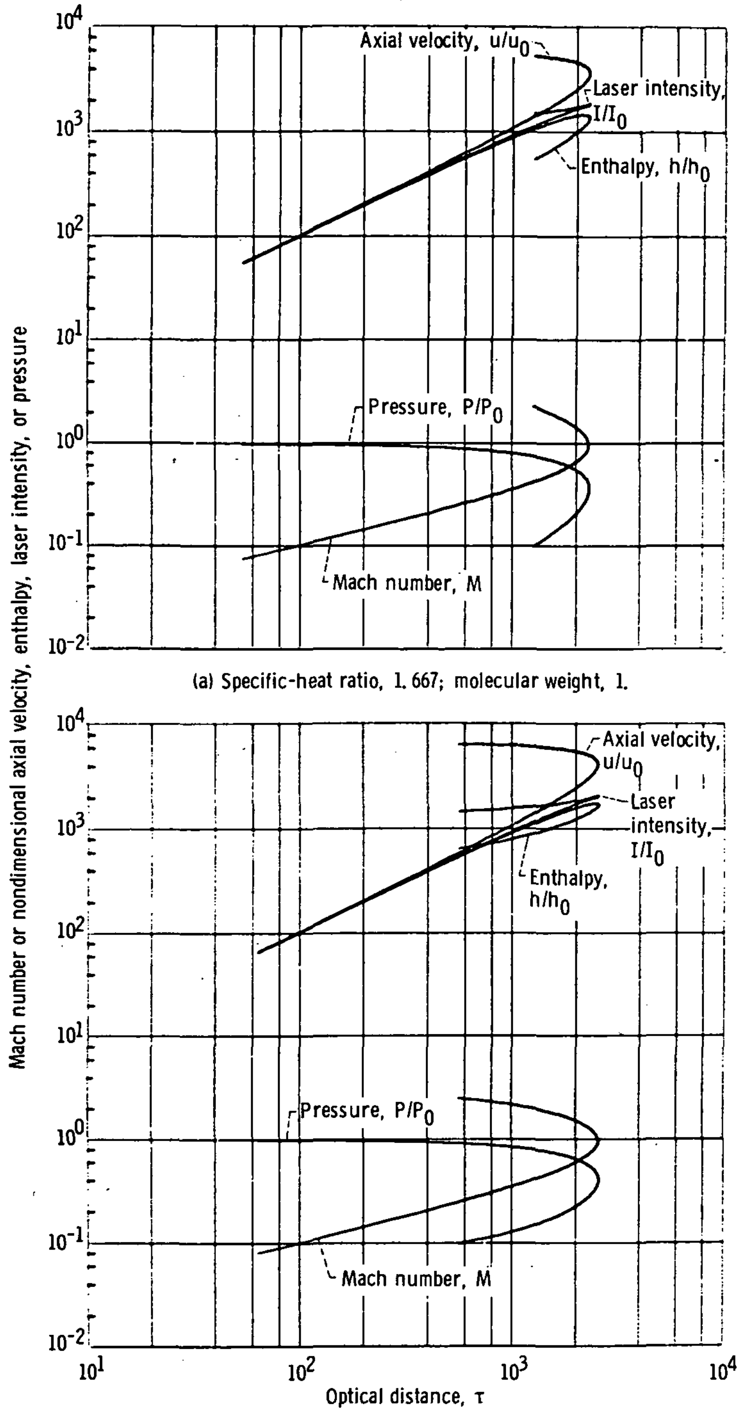


Figure 2. - Model of coaxial flow laser-powered thruster.



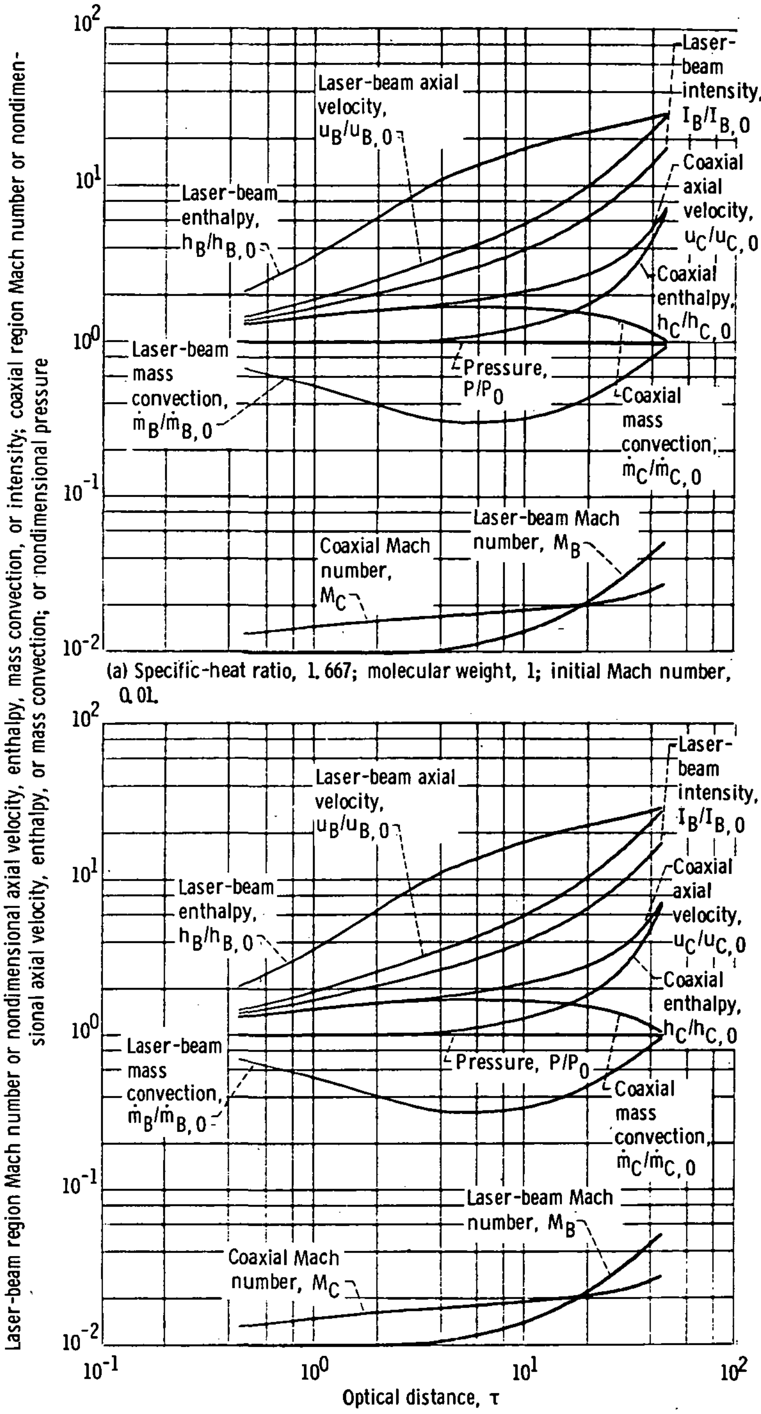
(b) Specific-heat ratio, 1.4; molecular weight, 2.

Figure 3. - Nondimensional axial velocity, enthalpy, laser intensity, pressure, and optical distance as functions of initial Mach number for condition of maximum laser intensity. Laser fills thruster tube (no coaxial flow).



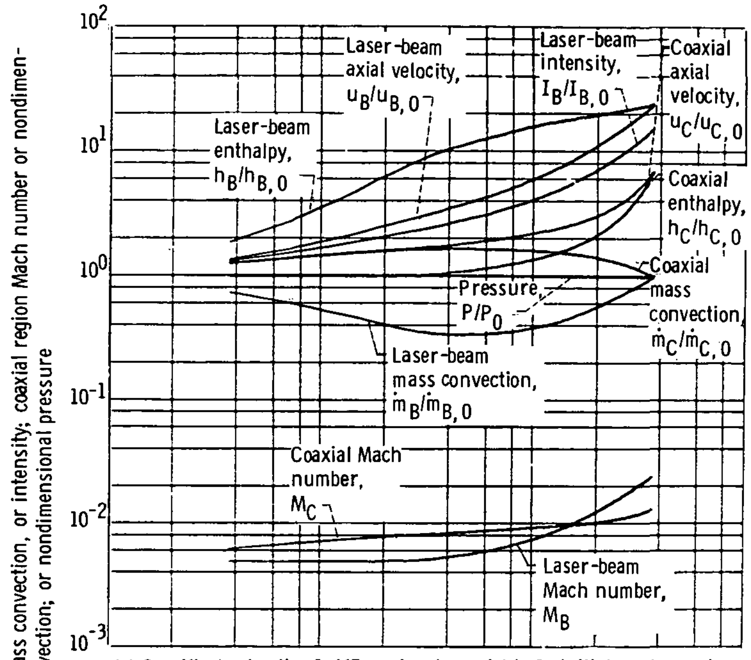
(b) Specific-heat ratio, 1.4; molecular weight, 2.

Figure 4. - Mach number and nondimensional axial velocity, enthalpy, laser intensity, and pressure as functions of optical distance for initial Mach number of 0.01. Laser fills thruster tube (no coaxial flow).

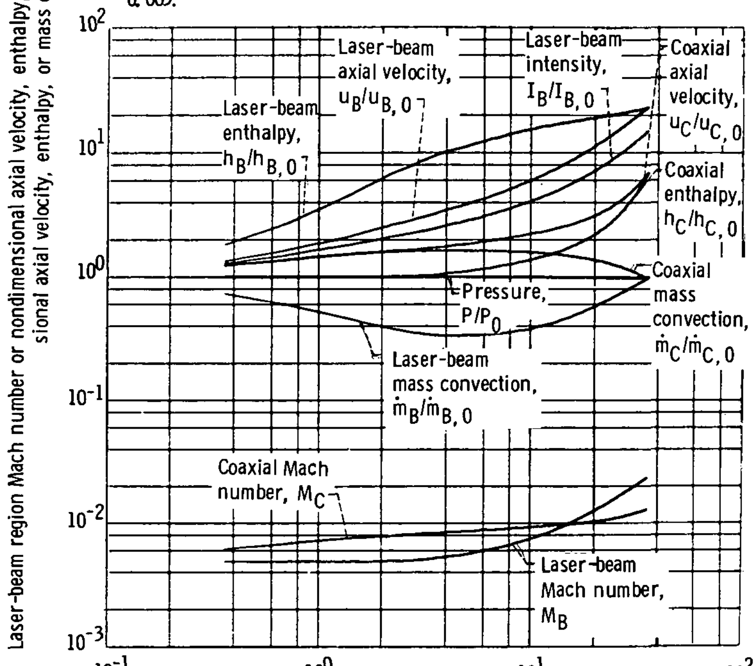


(b) Specific-heat ratio, 1.4; molecular weight, 2; initial Mach number, 0.01.

Figure 5. - Laser-beam region Mach number and nondimensional axial velocity, enthalpy, mass convection, and intensity; coaxial region Mach number and nondimensional axial velocity, enthalpy, and mass convection; and nondimensional pressure as functions of optical distance. Laser beam fills one-half of thruster tube; initial pressure, 10 atmospheres; initial temperature, 300 K.



(c) Specific-heat ratio, 1.667; molecular weight, 1; initial Mach number, 0.005.



(d) Specific-heat ratio, 1.4; molecular weight, 2; initial Mach number, 0.005.

Figure 5. - Concluded.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546