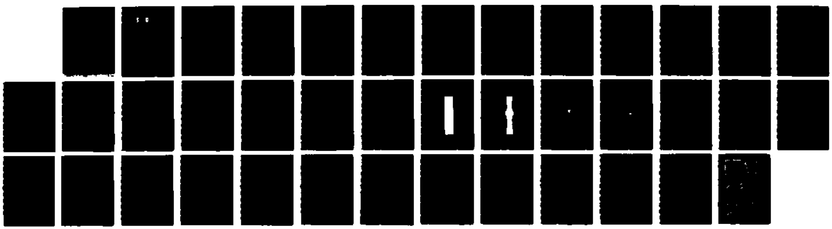
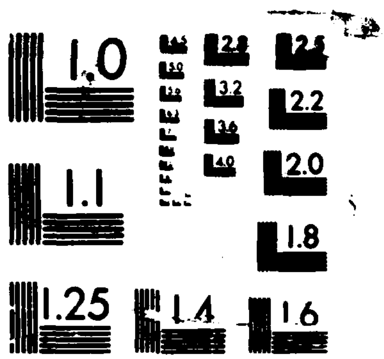
AD-A181 951 COUPLING BETWEEN RADIATION AND GAS DYNAMICS(U) 1/1
PENNSYLVANIA STATE UNIV UNIVERSITY PARK DEPT OF
MECHANICAL ENGINEERING C L MERKLE 31 MAR 87
UNCLASSIFIED AFOSR-TR-87-0844 AFOSR-84-0048 F/G 20/13 NL





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[REPORT DOC]UMENTATION PAGE

DTIC ELECTE JUL 0 7 1987 S D D

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release Distribution is Unlimited

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: NA

4. PERFORMING ORGANIZATION REPORT NUMBER(S): None

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 87-0844

6a. NAME OF PERFORMING ORGANIZATION: Pennsylvania State University

6b. OFFICE SYMBOL (If applicable):

7a. NAME OF MONITORING ORGANIZATION: AFOSR

6c. ADDRESS (City, State and ZIP Code): Mechanical Engineering Department, University Park, PA 16802

7b. ADDRESS (City, State and ZIP Code): Bldg 410, Bolling AFB DC 20332-6448

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Office of Scientific Research

8b. OFFICE SYMBOL (If applicable): NA

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR-84-0048

8c. ADDRESS (City, State and ZIP Code): Bldg 410, Bolling AFB, Washington, D.C. 20332

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2308	A1	

11. TITLE (Include Security Classification): Coupling Between Radiation and Gas Dynamics

12. PERSONAL AUTHOR(S): Charles L. Merkle

13a. TYPE OF REPORT: Annual

13b. TIME COVERED: FROM 01Dec85 TO 01Feb87

14. DATE OF REPORT (Yr., Mo., Day): 1987, March 31

15. PAGE COUNT: 34

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Laser-Gasdynamic Interaction, Beamed Energy, Microwave Heating of Gases, Advanced Propulsion

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Direct heat addition of flowing gases by radiation absorption is considered. In the IR regime, the coupling between a laser beam ad a flowing gas is being modeled numerically. Implicit time-iterative procedures originally developed for transonic flows are being adapted to the low Mach number, low Reynolds number regimes of interest. Two-dimensional solutions show that absorption plasmas can exist over a wide range of flow speeds and that buoyancy can be a dominant factor when the forced convection velocity is small. In the microwave regime, an experimental investigation of various absorption modes is underway. An overview of the experimental design and initial experimental results is presented. Numerical predictions of the resonant cavity and propagating plasma modes of microwave absorption are also discussed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

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22c. OFFICE SYMBOL: AFOSR/NA

AFOSR-TR- 87-0844

Annual Report

on

COUPLING BETWEEN RADIATION AND GAS DYNAMICS

Submitted to:

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March 1987

TABLE OF CONTENTS

ABSTRACT

Direct heat addition of flowing gases by radiation absorption is considered. In the IR regime the coupling between a laser beam and a flowing gas is being modeled numerically. Implicit time-iterative procedures originally developed for transonic flows are being adapted to the low Mach number, low Reynolds number regimes of interest. Two-dimensional solutions show that absorption plasmas can exist over a wide range of flow speeds and that buoyancy is a dominant factor in the forced convection flowfields. In the microwave regime, an experimental investigation of various absorption modes is underway. An overview of the experimental design and initial experimental results is presented. Numerical predictions of the resonant cavity and propagating plasma modes of microwave absorption are also discussed.

I. STATUS OF RESEARCH EFFORT

The advanced computational algorithms that have been developed for transonic, external aerodynamics in the past decade are being adapted for low speed flows with strong heat addition. The specific area of focus has been on the computation of laser gas-dynamic interactions, but the techniques are equally applicable to solar energy absorption in flowing gases, arcjets and other advanced propulsion concepts as well as to the more traditional combustion problems that occur in propulsion environments. The family of techniques being addressed is time dependent procedures. These are attractive because they apply to either viscous or inviscid flows and require a minimum amount of artificial viscosity. In addition, time dependent procedures are applicable to either steady or unsteady flows, making them candidates for studying both the steady flow characteristics of propulsion environments as well as the stability characteristics of these flowfields.

The extension of time dependent algorithms from external transonic flows to internal propulsion environments requires advances in several directions. First, the methods must be modified to handle very low Mach number flows (which are nonetheless compressible because of the energy deposition) as opposed to the transonic flows for which they were developed. Second, they must be extended from high Reynolds number applications to low Reynolds number conditions for at least some of the energy deposition problems of interest. The laser absorption problem in particular is a phenomenon that takes place at low Reynolds numbers. Very effective extensions to low Mach number have been accomplished as discussed below. Work on developing an effective low Reynolds number algorithm is still in progress. Finally, the consideration of strong heat addition at low speeds implies that the effects of buoyancy must be addressed, and substantial progress has been made along this line also.

The equations of motion for a flowing gas with heat addition (by absorption of radiation, I^2R heating, or combustion) can be expressed in vector form as,

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = H + \frac{\partial E_v}{\partial x} + \frac{\partial F_v}{\partial y} \tag{1}$$

Here, Q, E, F, H, E_v and F_v are vectors. The primary dependent variables are contained in Q while the remaining five vectors are (in general) nonlinear functions of Q. These vectors are defined as,

$$Q = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix} \quad E = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (e+p)u \end{pmatrix} \quad F = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ (e+p)v \end{pmatrix} \quad H = \begin{pmatrix} 0 \\ \rho g \\ 0 \\ q \end{pmatrix}$$

and,

$$E_v = R_{xx} \frac{\partial Q_v}{\partial x} + R_{xy} \frac{\partial Q_v}{\partial y}$$

$$F_v = R_{yx} \frac{\partial Q_v}{\partial x} + R_{yy} \frac{\partial Q_v}{\partial y}$$

where $Q_v = (\rho,\ u,\ v,\ T)^T$, and R_{xx}, R_{xy}, R_{yx}, and R_{yy} are matrices containing only the viscosity and the thermal conductivity. For computational purposes, the equations are transformed to generalized nonorthogonal coordinates. Convergence to a steady state corresponds to following Eqn. 1 through a transient from some arbitrary initial condition to a final steady condition. We begin by discussing the inviscid terms on the left-hand side and then add the viscous terms on the right-hand side.

It is well known that the convergence range of typical time dependent methods becomes slower as the flow Mach number is reduced. The reason is because the eigenvalues of the system become increasingly stiff as Mach number is reduced. We have developed two methods for circumventing this problem. In the first, the time derivatives are multiplied by some matrix Γ which is chosen in such a way that the eigenvalues remain well conditioned at low Mach numbers. This matrix preconditioning procedure corresponds to modifying the physical time derivatives so that the preconditioned derivatives provide faster convergence. Our first attempts at preconditioning allowed rapid convergence down to a Mach number of 0.01, but became ineffective below that. In addition, extension to real gases with variable properties showed that the preconditioning was not effective when specific heats varied strongly. Later refinements of the preconditioning allowed us to maintain rapid convergence to much lower Mach numbers but eventually round-off errors were encountered in the pressure computations. These round-off errors effectively prevent the use of the procedure at Mach numbers below about 10^{-4}. Testing of the refined preconditioning scheme for real gas equations of state has not yet been done, but it is possible that preconditioning will now be effective for real gases. These results have been summarized in Ref. 9.

The second method for accomplishing low Mach number computations has been to use a perturbation expansion of the equations of motion to obtain a low Mach number system. In this low Mach number system, artificial acoustic modes were introduced that provided a well-conditioned eigenvalue system at any Mach number. This system also included a rescaling of the pressure and, thus far, all inviscid applications have shown it to be very effective. We have obtained successful convergence to Mach numbers as low as 10^{-6} which exceeds the low speed range of the laser propulsion problem of interest. The low Mach number expansion procedure is described in Refs. 9 and 10.

At these very low speeds, buoyancy becomes a significant parameter. Buoyancy introduces a source term into the momentum equations and source terms (as opposed to sink terms) are always destabilizing in a numerical solution. The effects of the source term on convergence can be mitigated by an alternative preconditioning that effectively makes the equations become stiff again, but results have shown that adequate convergence can be maintained to Mach numbers as low as 10^{-4} in argon with heating representative of that in laser propulsion environments. Additional potential methods for counteracting the effect of buoyancy have been developed, but not implemented yet.

The viscous terms also have a different effect on convergence at low Reynolds numbers than they do at high Reynolds numbers. Implicit schemes traditionally use approximate methods for solving the large sparse matrices that are generated. These approximate methods introduce errors of order Δt^2 that become large and dominate convergence when large time steps are involved. In the case of the Euler equations, these error terms represent products of inviscid derivatives in the x-direction with inviscid derivatives in the y-direction. The resulting approximate algorithm is unconditionally stable. Similarly, when only the viscous terms are present the error terms are composed of viscous derivatives in x times viscous derivatives in y. Again, the approximate algorithm for the viscous equations remains unconditionally stable. Because both the viscous and inviscid problems are stable, it is logical to expect that combined viscous-inviscid problems would also remain stable, but stability analyses and numerical experiments demonstrate this is not the case. Approximate factorization of the combined viscous-inviscid problem also generates cross-derivativ error terms such as inviscid derivatives in x times viscous derivatives in y. These additional error terms are destabilizing and cause the algorithm to be unstable in the Reynolds number range of interest. Several methods for circumventing this difficulty have been tested though none has yet been found that is completely successful.

The primary direction being pursued is the use of an alternative formulation of the energy equation. When the diffusive terms were added to the form of the energy equation that was used for inviscid flow, it became,

$$\frac{\partial p_1}{\partial t} + \gamma p_o\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = \frac{\partial}{\partial x}\,\lambda\frac{\partial T}{\partial x} + \frac{\partial}{\partial y}\,\lambda\frac{\partial T}{\partial y} \qquad (2)$$

Here, p_1 is the perturbation pressure and the time derivative represents an artificial derivative that is used for convergence purposes. The quantity, p_o, is the nominal or mean pressure in the flowfield. Both theoretical (stability results) and experimental (computer solutions) analyses of this form showed that it was unstable for viscous flows. To avoid this instability, the energy equation was modified by combining it with the continuity equation and changing the time derivative to one containing the temperature to give,

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\,\rho uT + \frac{\partial}{\partial y}\,\rho vT = \frac{\partial}{\partial x}\,\lambda\frac{\partial T}{\partial x} + \frac{\partial}{\partial y}\,\lambda\frac{\partial T}{\partial y} \qquad (3)$$

This has slightly better convergence than does Eqn. 2, but it still remains unstable at Reynolds numbers of about 100. (Note that when $\lambda = 0$, both Eqns. 2 and 3 perform very well in inviscid flows.)

In full vector form, the perturbation equations corresponding to Eqn. 3 can again be written in the vector form of Eqn. 1 except that now the various terms become:

$$Q = \begin{pmatrix} p_1 \\ u \\ v \\ T \end{pmatrix} \quad E = \begin{pmatrix} \rho u \\ \rho u^2 + p_1 \\ \rho uv \\ \rho uT \end{pmatrix} \quad F = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ \rho vT \end{pmatrix} \quad E_v = R_{xx} \frac{\partial Q}{\partial x} + R_{xy} \frac{\partial Q}{\partial y}$$

$$F_v = R_{yx} \frac{\partial Q}{\partial x} + R_{yy} \frac{\partial Q}{\partial y} \tag{4}$$

where R_{xx}, R_{xy}, R_{yx}, and R_{yy} are the same as before.

In addition to using standard approximate factorization, a diagonally dominant ADI procedure has also been considered. This procedure is slightly more stable than the standard ADI procedure, but still encounters instability in ranges of interest.

Finally, the approximation of taking ρu and ρv as known quantities and solving the temperature equation (Eqn. 3) independently and in combination with the radiation equation has been attempted. This procedure works reasonably well and provides solutions for the laser absorption problem. To couple this equation with the laser equation, we express the laser equation as,

$$\frac{\partial \mathcal{J}}{\partial t} + \frac{\partial}{\partial s} \mathcal{J} e = - ck\mathcal{J} \tag{5}$$

where $\mathcal{J} = \ell n\, I_\ell A$ represents the natural logarithm of the power in each ray of the laser beam, c represents a (fictitious) speed of light, and k represents the absorptivity of the medium. When Eqn. 5 and 3 are coupled and solved simultaneously, they give a matrix like that shown in Fig. 1. When the absorptivity is independent of temperature and pressure, the two equations are uncoupled and the solution can be found by solving a tridiagonal matrix followed by a lower triangular matrix. When k depends on the properties, the two equations are coupled and generate a lower triangular plus tridiagonal matrix of the type shown in Fig. 1. Solution of this coupled system provides convergence that is as rapid with laser heating as it is when a specified heat addition rate is used. That is to say, when the energy and radiation equations are solved in coupled fashion, the laser heat addition does not slow convergence. When the coupling between these two equations is brought in iteratively, laser absorption causes the convergence to slow down dramatically eventually leading to divergence. These results show that coupling between the laser and energy equations is a desirable aspect of any numerical solution. Some representative solutions of these two equations are described in the next paragraph. Algorithms based on iterating between the energy/radiation equation system and the continuity/momentum equation system have thus far proved unfruitful.

Some results for the coupled energy and laser radiation equations are given in Figs. 2-9. Figures 2 and 3 show representatives of two families of grids that have been used. Both are for hollow beam laser radiation and the geometric shape of the converging beam can be seen by the rays used to represent it. The fluid dynamic grid has been treated as equally spaced as shown on Fig. 2, or highly stretched as given in Fig. 3. In general, calculations on the stretched grid proved most effective.

Figures 4, 5 and 6 show the results of varying inflow velocity for a laser power of 720 W. Figure 4 is for 1.0 m/s, Fig. 5 for 0.15 m/s, and Fig. 6 for 0.01 m/s. Figure 7 shows a close-up view of temperature profiles near the focal point for the case shown on Fig. 6. At 1.0 m/s

(Fig. 4), the absorption zone is pushed back almost to the focal region of the laser beam. As the velocity is reduced, the absorption zone remains almost constant. For the entire range of velocities, the peak temperature is nearly constant, varying from 17,800 K at the high speed to 16,850 K at the low speed.

The effect of changing laser power at an inflow velocity of 0.01 m/s is shown on Fig. 6 (720 W), Fig. 8 (900 W), and Fig. 9 (1000 W). For this range of parameters, changing the laser power has little effect on the shape of the absorption region, and the peak temperature again remains relatively constant although it does decrease slightly as power is increased.

II. A CUMULATIVE CHRONOLOGICAL LIST OF WRITTEN PUBLICATIONS

1. Merkle, C. L. and Gulati, A., "The Absorption of Electromagnetic Radiation in an Advanced Propulsion System", J. Spacecrafts and Rockets, Vol. 21, No. 1, Jan.-Feb. 1984, pp. 101-107.

2. Merkle, C. L., "The Potential for Using Laser Radiation to Supply Energy for Propulsion", Orbit Raising and Maneuvering Propulsion: Research Status and Needs, AIAA Progress in Astronautics and Aeronautics Series, L. H. Caveny, Ed., AIAA, New York, 1984, pp. 48-72.

3. Merkle, C. L., "The Use of Electromagnetic Radiation as an Energy Source for Propulsion", Proceedings of Workshop on Advanced Propulsion Concepts Using Time Varying Electromagnetic Fields, Michigan State University Press, 1984.

4. Merkle, C. L., "Prediction of the Flowfield in Laser Propulsion Devices", AIAA Paper 83-1445, AIAA 18th Thermophysics Conference, Montreal, Canada, May 1983. AIAA Journal, Vol. 22, No. 8, Aug. 1984, pp. 1101-1107.

5. Merkle, C. L., Gulati, A., Choi, Y.-H.. The Effect of Strong Heat Addition on the Convergence of Implicit Schemes, AIAA Paper 83-1914, AIAA 6th Computational Fluid Dynamics Conference Proceedings, Danvers, MA, July 1983, pp. 212-221. AIAA Journal, Vol. 23, No. 6, June 1985, pp. 847-855.

6. Merkle, C. L., Molvik, G. A. and Choi, D., "A Two-Dimensional Analysis of Laser Heat Addition in Converging Nozzles", AIAA Journal, Vol. 23, No. 7, July 1985, pp. 1053-1060.

7. Merkle, C. L., "Stability of Absorption Phenomena in Laser-Thermal Propulsion Gasdynamic Interaction", AIAA Paper 84-1571, AIAA 17th Fluid Dynamics, Plasmadynamics & Lasers Conference, Snowmass, CO, June 1984.

8. Merkle, C. L., Molvik, G. A. and Shaw, Eric J.-H., "Numerical Solution of Strong Radiation Gasdynamic Interactions", AIAA Paper 85-1554, AIAA 18th Fluid Dynamics, Plasmadynamics & Lasers Conference, Cincinnati, Ohio, July 16-18, 1985. Accepted for publication, J. Propulsion and Power.

9. Merkle, C. L. and Choi, Y.-H., "A Method For Computing Compressible Flows at Very Low Mach Numbers", AIAA Paper 86-0351, AIAA 24th Aerospace Sciences Meeting, Reno, NV, Jan. 1986. To appear in AIAA Journal, May 1987.

10. Merkle, C. L. and Choi, Y.-H., "Computation of Low Mach Number Flows With Buoyancy", Proceedings of the 10th International Conference on Numerical Methods in Fluid Dynamics, Beijing, China, June 23-27, 1986, pp. 169-173.

11. Merkle, C. L. and Hosangadi, A., "Computation of Low Speed Viscous Flows with Heat Addition", Sixth IMACS International Symposium on Computer Methods for Partial Differential Equations, Lehigh University, June 23-26, 1987, Bethlehem, PA.

III. PROFESSIONAL PERSONNEL ASSOCIATED WITH RESEARCH EFFORT

Professional Staff -

Charles L. Merkle, Principal Investigator, Professor, Mechanical Engineering

Graduate Students -

Michael J. Stanek, Graduate Assistant, February 1981-August 1982. M.S. Thesis title, "Analytical Studies of the Absorption Mechanisms of Equilibrium Hydrogen." Present position: Captain, US Air Force, AFWAL/POTC, WPAFB, OH.

Anil Gulati, Graduate Assistant, September 1981-August 1983. M.S. Thesis title, "The Absorption of Electromagnetic Radiation in an Advanced Propulsion System." Present position: Research Scientist, GE Corporate Research and Development Center, Schenectady, NY.

Gregory A. Molvik, Graduate Assistant, September 1982-January 1985. M.S. Thesis title, "A Two-Dimensional Analysis of Laser Heat Addition in Converging Nozzles". Present address: CFD Group, NASA/Ames, Moffett Field, CA.

Peter Tsai, Graduate Assistant, September 1983-August 1985. M.S. Thesis title, "Stability Characteristics of Laser-Supported Plasmas". Present position: Ph.D. Candidate Penn State University.

Yun-Ho Choi, Ph.D. Candidate, January 1985 to present. Anticipated Ph.D. Thesis title, "Computation of Low Mach Number Flowfields with Strong Heat Addition".

Eric Shaw, Graduate Assistant, September 1984 to May 1986. M.S. Thesis title, "Laser Absorption in Flowing Gas". Present position, Ph.D. Candidate, Pennsylvania State University.

Ashvin Hosangadi, Ph.D. Candidate, September 1985-present.

IV. INTERACTIONS/SPOKEN PRESENTATIONS

"Analysis of Laser-Supported Combustion Waves in Flowing Media", AFOSR/AFRPL Rocket Propulsion Research Meeting, Lancaster, CA, March 26, 1981.

"The Potential for Using Laser Radiation as an Energy Source for Propulsion", Orbit Raising Propulsion Workshop, Orlando, FL, January 16, 1982.

"The Use of Electromagnetic Radiation as an Energy Source for Propulsion", Symposium on Advanced Propulsion Concepts Using Time-Varying Electromagnetic Fields, East Lansing, MI, February 4, 1982.

"Analysis of Laser-Supported Plasmas in Flowing Media", AFOSR/AFRPL Rocket Propulsion Research Meeting, Lancaster, CA, March 3, 1982.

"The Absorption of Electromagnetic Radiation in an Advanced Propulsion System", AIAA Electric Propulsion Meeting, New Orleans, LA, November 19, 1982.

"Prediction of the Flowfield in Laser Propulsion Devices", AIAA 18th Thermophysics Conference, Montreal, Canada, May 1983.

"The Effect of Strong Heat Addition on the Convergence of Implicit Schemes", AIAA 6th CFD Conference, Danvers, MA, June 1983.

"A Two-Dimensional Analysis of Laser Heat Addition in Converging Nozzles", AIAA Aerospace Sciences Meeting, Reno, NV, January 1984.

"High Power Nd-Glass Laser Instrument for Advanced Propulsion and Diagnostics", AFOSR/AFRPL Rocket Propulsion Research Meeting, Lancaster, CA, March 12-15, 1984.

"Stability of Absorption Phenomena in Laser-Thermal Propulsion Gasdynamic Interaction", AIAA 17th Fluid Dynamics, Plasmadynamics & Lasers Conference, Snowmass, CO, June 25-27, 1984.

"Analytical Modeling of Strong Radiation Gasdynamic Interaction", AFOSR/AFRPL Chemical Rocket Research Meeting, Lancaster, CA, March 20, 1985.

"Numerical Solution of Strong Radiation Gasdynamic Interactions", AIAA 18th Fluid Dynamics, Plasmadynamics & Lasers Meeting, Cincinnati, OH, July 16-18, 1985.

"An Implicit Time-Dependent Scheme for Low Speed Flow with Buoyancy", 22nd Annual Meeting Society of Engineering Science, Inc., University Park, PA, Oct. 7-9, 1985.

"Computation of Compressible Flows at Very Low Mach Numbers", AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 6-9, 1986.

"Interaction Between Radiation and Gas Dynamics", invited lecture, Chemical Engineering Department Seminar Series, Michigan State University, East Lansing, MI, February 10, 1986.

"Computation of Low Mach Number Flows With Buoyancy", presented at the 10th International Conference on Numerical Methods in Fluid Dynamics, Beijing, China, June 23-27, 1986.

"Numerical Solution of Strong Radiation Gas Dynamic Interactions", AFOSR/AFRPL Chemical Rocket Research Meeting, Lancaster, CA, September 1986.

"Computation of Low Speed Viscous Flows with Heat Addition", to be presented at the Sixth IMACS International Symposium on Computer Methods for Partial Differential Equations, Lehigh University, June 23-26, 1987, Bethlehem, PA.

V. INTERACTIONS/ADVISORY FUNCTIONS

Member of Workshop Panel, "Concepts and Experiments", NASA/Michigan State Symposium on Advanced Propulsion Concepts Using Time-Varying Electromagnetic Fields, February 1982.

"Aerospace Propulsion at Penn State", presentation to General Robert T. Marsh, USAF, The Pennsylvania State University, University Park, PA, May 5, 1982.

"Modeling of Flowfields that Interact with Radiation Fields", AFRPL/UDRI Solar Plasma Propulsion Workshop, Bergamo Center, Dayton, OH, Jan. 21-22, 1986.

VI. NEW DISCOVERIES

See Publication List.

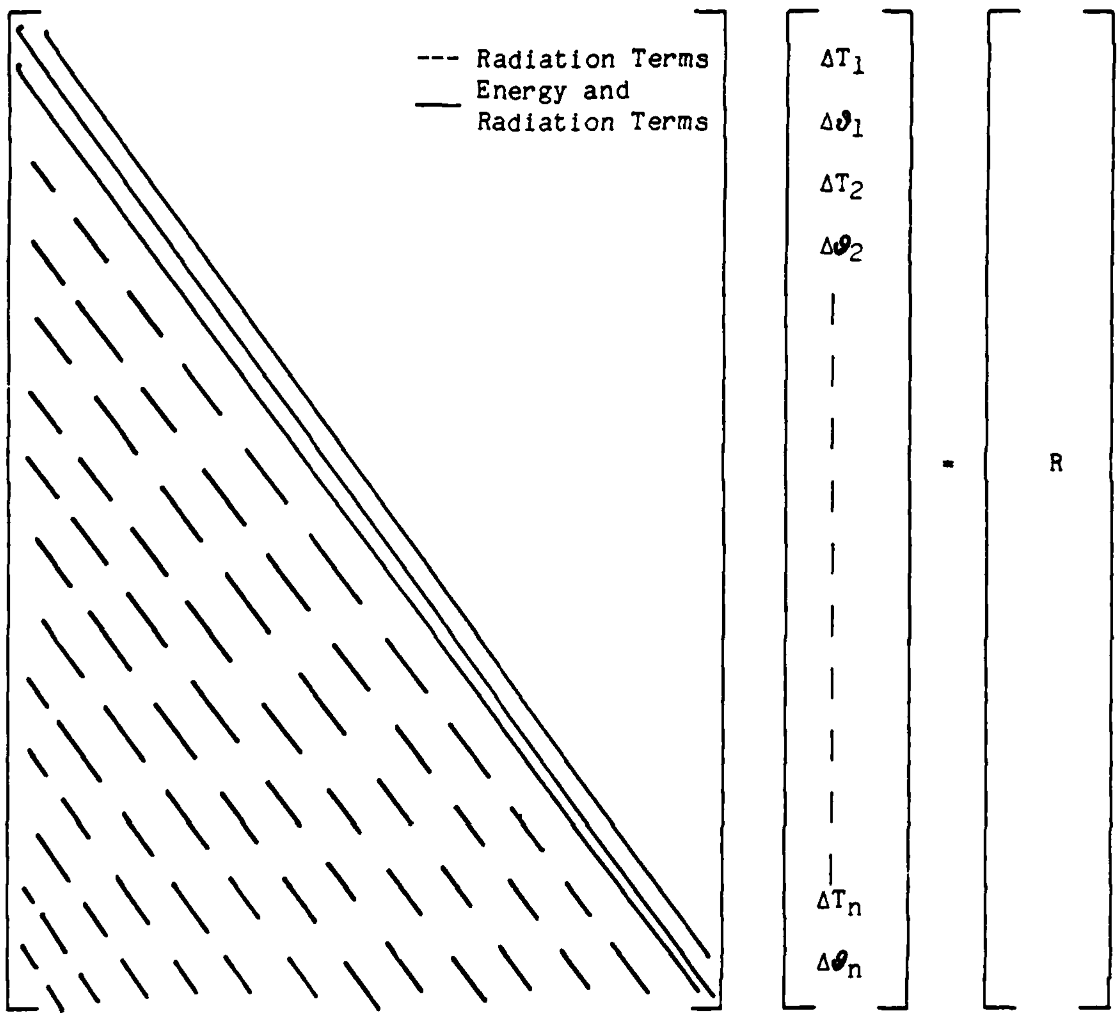

Fig. 1 Tridiagonal-plus-lower matrix character generated when laser equation is coupled with fluid dynamics

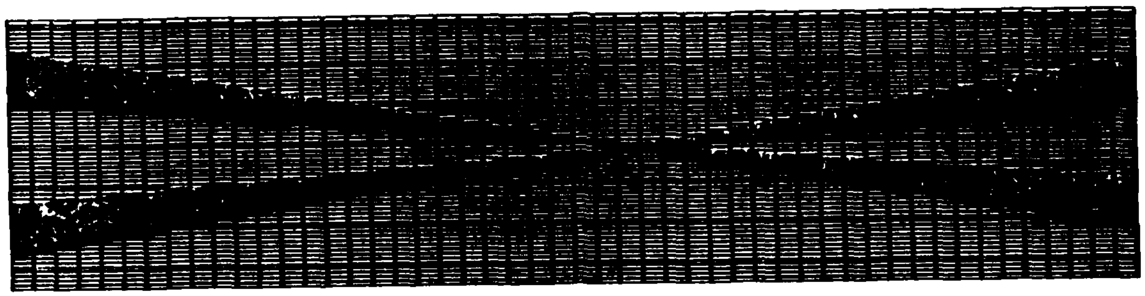

Fig. 2 Geometry and laser beam configuration for laser absorption calculation. Equally spaced grid used for fluid dynamics.

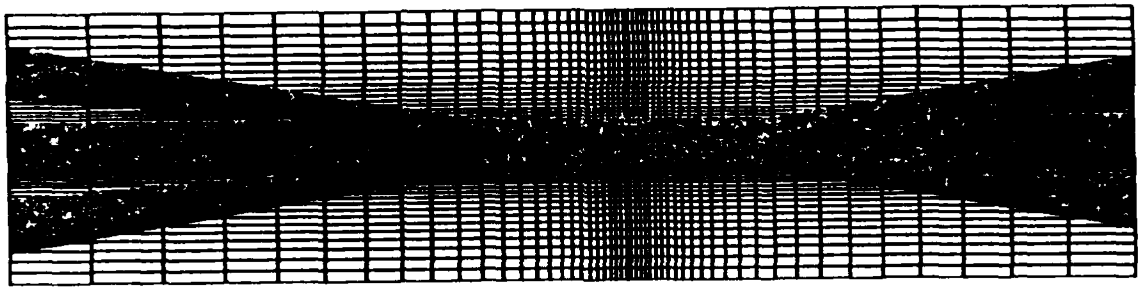

Fig. 3 Geometry and laser beam configuration for laser absorption calculation. Stretched grid used for fluid dynamics.

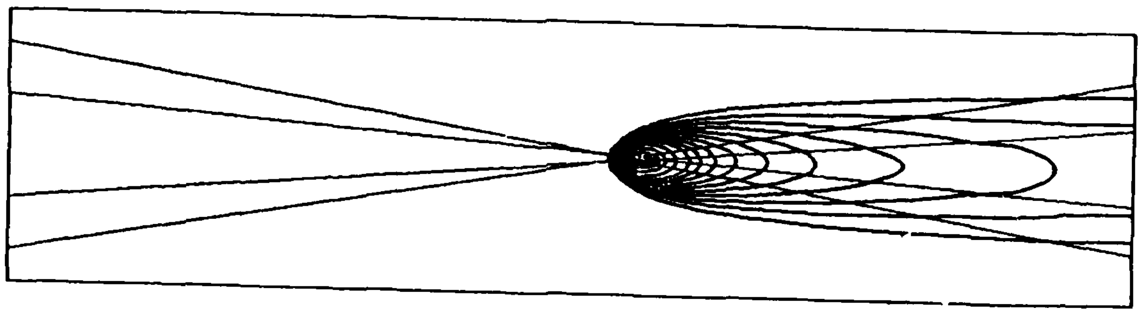

Fig. 4 Temperature contours for laser power of 720 W and an inlet velocity of 1.0 m/s. T_{MAX} = 17,809 K; ΔT = 1000 K.

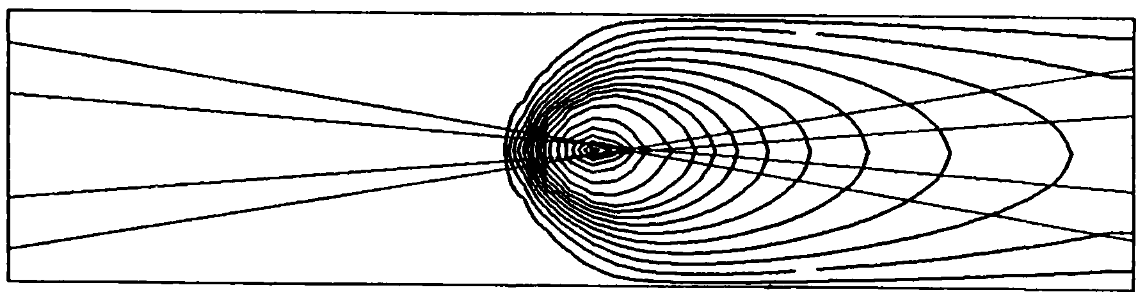

Fig. 5 Temperature contours for laser power of 720 W and inlet velocity of 0.15 m/s. T_{MAX} = 17,526 K; ΔT = 1000 K.

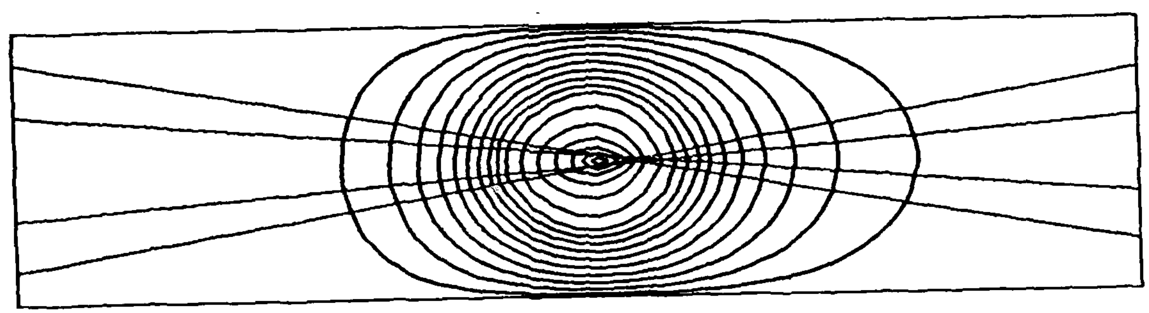

Fig. 6 Temperature contours for laser power of 720 W and inlet velocity of 0.01 m/s. T_{MAX} = 16,863 K; ΔT = 1000 K.

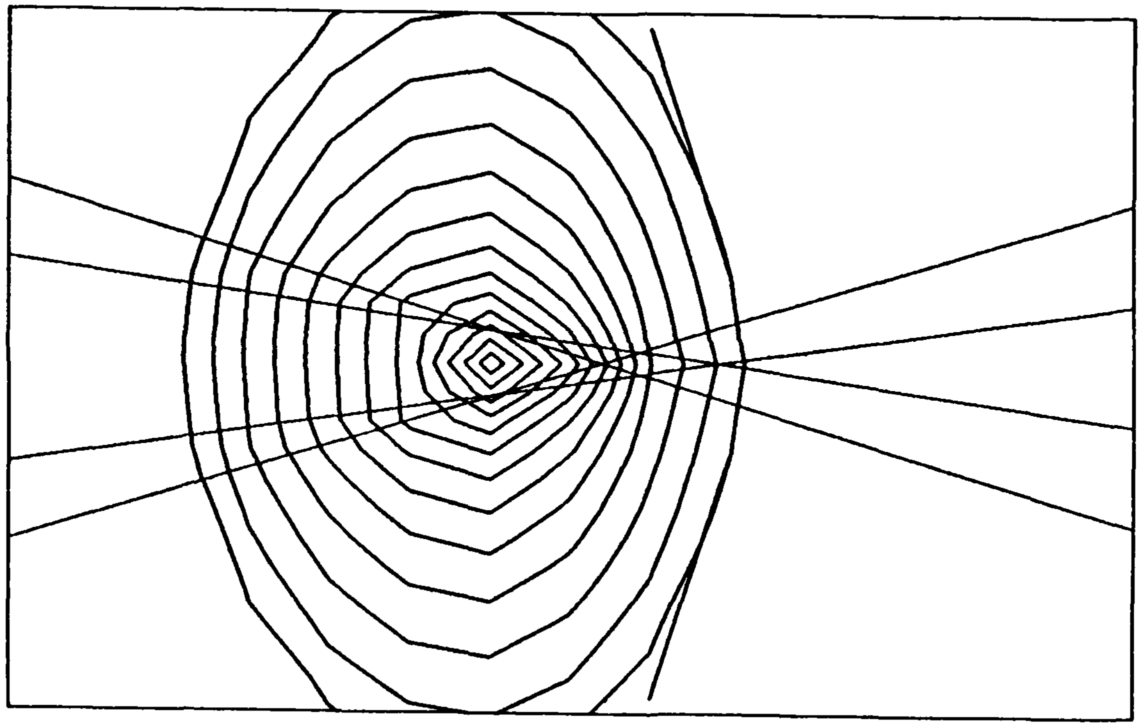

Fig. 7 Close-up view of temperature contours near focal point for case shown in Fig. 6. $\Delta T = 500$ K.

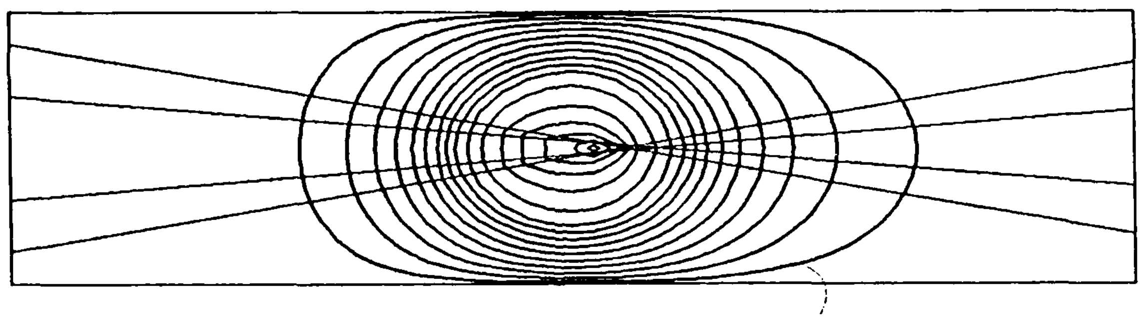

Fig. 8 Temperature contours for laser power of 900 W and inlet velocity of 0.01 m/s. T_{MAX} = 16,593 K; ΔT = 1000 K.

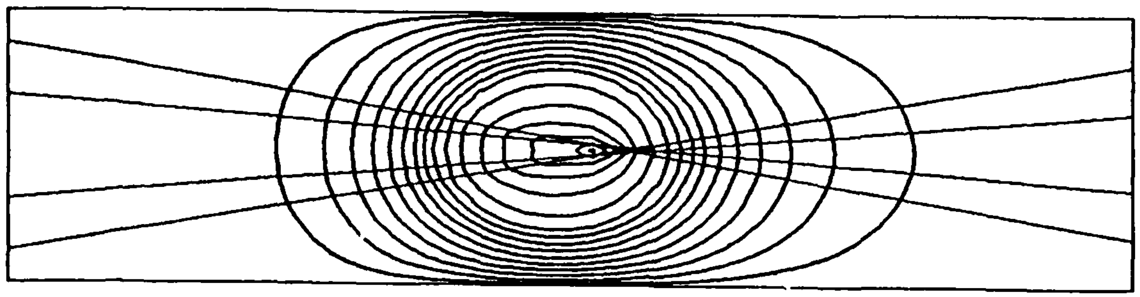

Fig. 9 Temperature contours for laser power of 1000 W and inlet velocity of 0.01 m/s. T_{MAX} = 16,246 K; ΔT = 1000 K.

A. Statement of Work

1. Determine experimentally the conditions under which plasmas can be initiated and sustained in the three energy addition modes (TM_{01}, TE_{01}, and planar). Initial testing will be with nitrogen and helium. Nitrogen will be used to simulate the molecular nature of hydrogen while helium will simulate atomic hydrogen. Final testing will be with hydrogen. Parameters to be examined include gas composition, pressures and flow rates and microwave power. Quantify system heat losses.
2. Measure spectroscopically electron and ion temperatures and densities in microwave generated plasmas in the three energy addition modes. Due to high gas pressures, local thermodynamic equilibrium (LTE) will be initially assumed although nonequilibrium effects will be examined. The principal measurement will be ion temperature as this translates to thrust. The effects of various hot and cold gas mixing schemes on final temperature will be studied.

B. Status of Research Effort

Microwave equipment capable of generating up to 3 kW CW power at a frequency of 2.45 GHz has been assembled and checked out. A microwave resonant cavity wherein both filamentary and toroidal plasmas can be produced was custom manufactured under the direction of Dr. Jes Asmussen of Michigan State University and has been interfaced with the microwave generator. Additional experimental equipment required to generate planar propagating plasmas has also been procured. A 0.5 meter Spex scanning monochrometer with a photomultiplier tube light sensor has been interfaced with an IBM PC to allow the microcomputer to both control the scanning of the monochrometer and the recording of the light intensity signal. Quartz gas containment vessels to be placed inside the resonant cavity capable of withstanding up to 3 atmospheres of internal pressure have been purchased and the associated plumbing to flow gases over a range of flow rates through the quartz vessels has been assembled. The production of filamentary microwave heated plasmas in nitrogen gas has been initiated. Figure 1 shown the three microwave absorption modes being examined in this program. Parameters to be determined are which combinations of gas composition, pressure and flow rate will permit a plasma to be sustained in the resonant cavity for a given microwave power input and standing wave mode.

A numerical model of the one-dimensional planar propagating microwave plasma in hydrogen gas had previously been successfully formulated. This model solves the system of governing equations consisting of the

SCIENTIFIC APPROACH

ABSORPTION MODES

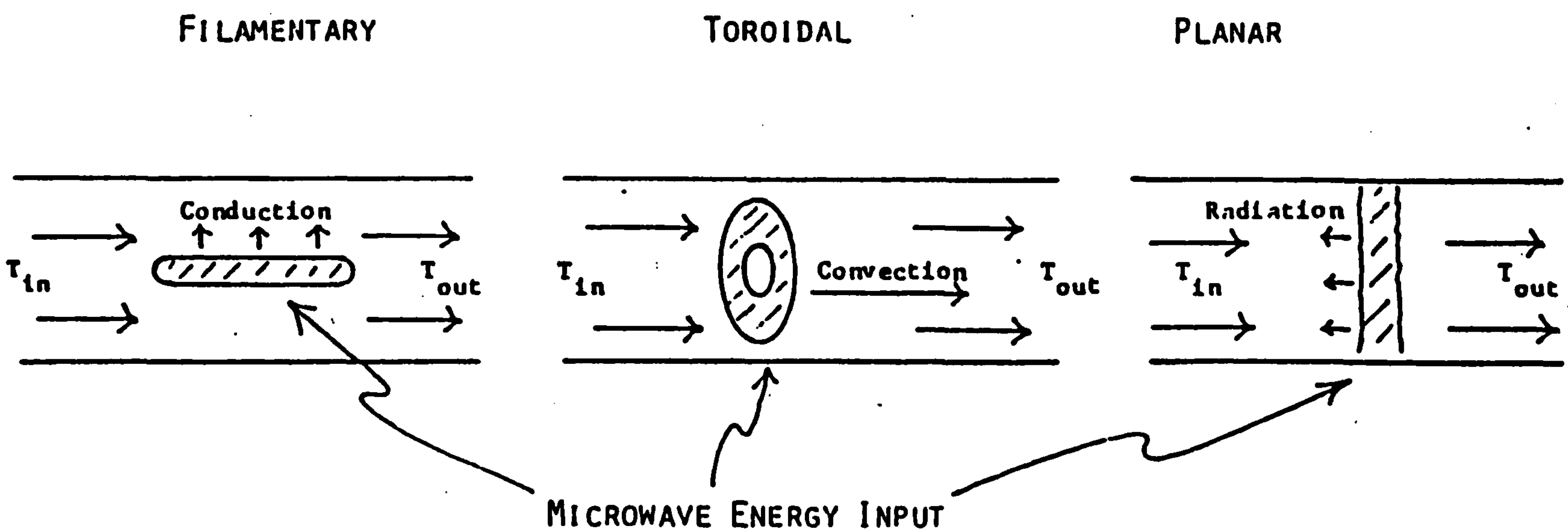

FIGURE 1

one-dimensional steady energy equation

$$\rho u \, C_p \frac{dT}{dx} = \frac{d}{dx} \lambda \frac{dT}{dx} + \frac{\sigma}{2} \left|E^2\right| \tag{1}$$

where ρ is the gas density, u is the gas velocity, C_p is the specific heat, T is the gas temperature, λ is the thermal conductivity, σ is the electrical conductivity and E is the electric field vector; and Maxwell's equation describing the propagation of the microwave energy

$$\frac{d^2E}{dx^2} = \sigma\mu \frac{\partial E}{\partial t} + \varepsilon\mu \frac{\partial^2 E}{\partial t^2} \tag{2}$$

where ε is the permitivity and μ is the permeability. The specific heat, thermal conductivity and electrical conductivity are functions of temperature. The electromagnetic energy is absorbed by the plasma as the temperature rises with some microwave energy being reflected or transmitted. Due to thermal conduction to the cold gas ahead of it, the plasma propagates toward the microwave energy source at a velocity determined by the energy balance between the absorbed microwave power and the heated gas which is convected away downstream. The two governing equations were numerically integrated using a fifth/sixth order variable step Runge-Kutta scheme. An iterative method was used to determine the propagation velocity eigenvalue, ρu, similar to the method used by Kemp and Root to solve for the propagation velocity of the laser heated plasma.

Since then, more accurate data for the electrical conductivity of hydrogen gas at elevated temperatures obtained by Yos has been incorporated into the model along with the temperature dependent properties of helium gas. Figure 2 plots the propagation velocity as a function of incident power for hydrogen and helium at one atmosphere pressure showing increased

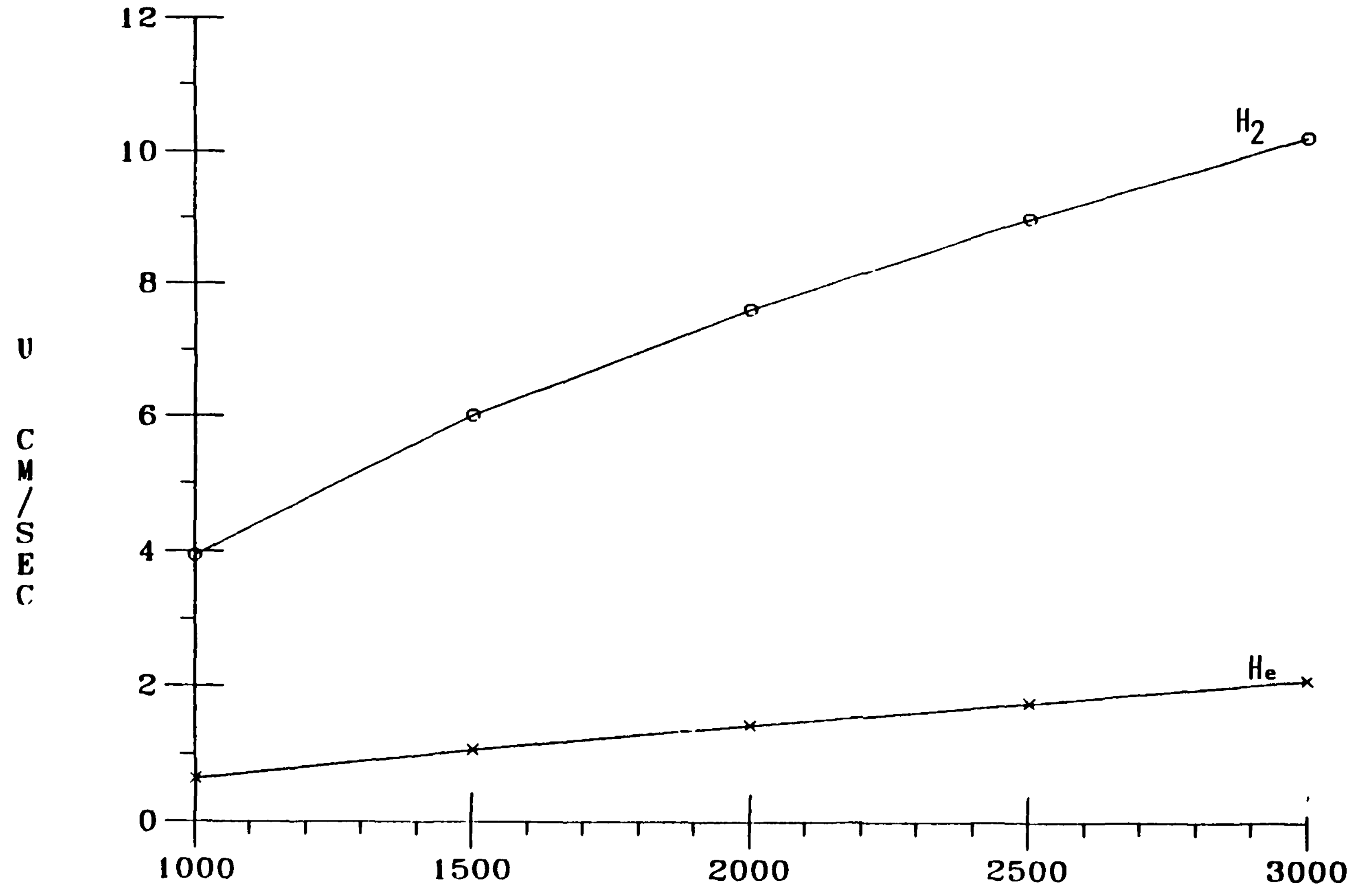

Fig. 2 Microwave heated plasma propagation velocity as a function of input microwave power for hydrogen and helium gas at one atmosphere showing increased propagation velocity with power.

plasma propagation velocity with increased microwave power. It can also be seen that for the same microwave power level the plasma propagates in hydrogen about four times faster than in helium. Figure 3 plots the maximum gas temperature as a function of incident power and shows a small increase in maximum gas temperature as the microwave power is increased. Figure 4 plots the percent power absorbed by the propagating plasma as a function of incident power. It was found that hydrogen absorbs approximately four times more power than helium and that for both gases all of the incident power was either reflected or absorbed with no power being transmitted through the plasma. The results of the numerical model will be compared to experimentally measured values as they become available. Calculations are planned for nitrogen gas and for all three gases at a pressure of ten atmospheres. Solutions for these gases are desired since initial experimental tests will use both nitrogen and helium. Other planned modifications include the inclusion of radiation losses by the hot gas and the examination of two-dimensional effects. Two-dimensional effects are important because microwave radiation transmitted through a waveguide is not spatially uniform in a direction normal to the propagation direction. Thus previous experimental investigations observed columnar-shaped plasmas instead of the planar-shaped.

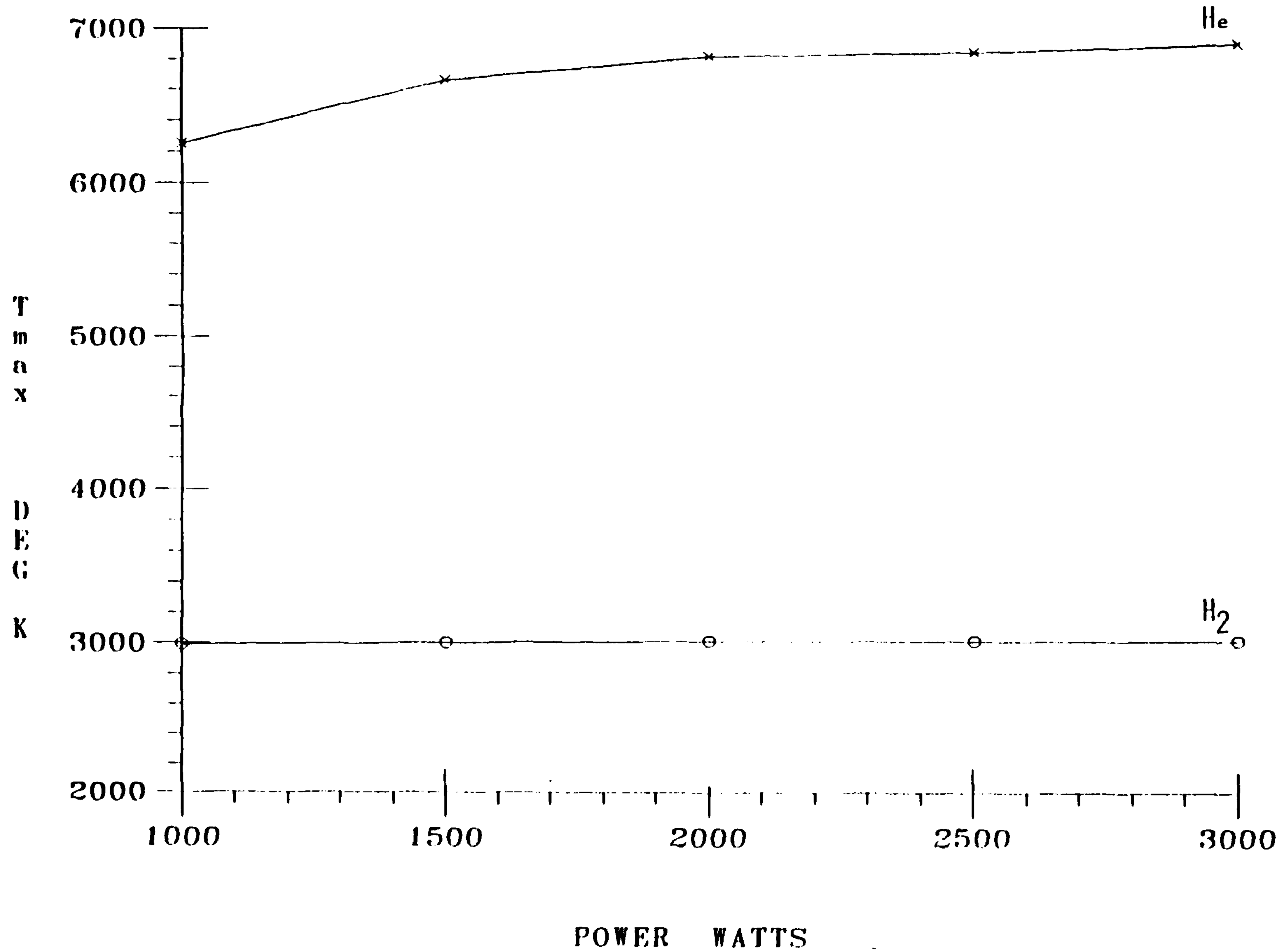

Fig. 3 Maximum plasma temperature as a function of input microwave power for propagating plasmas in hydrogen and helium gas at one atmosphere.

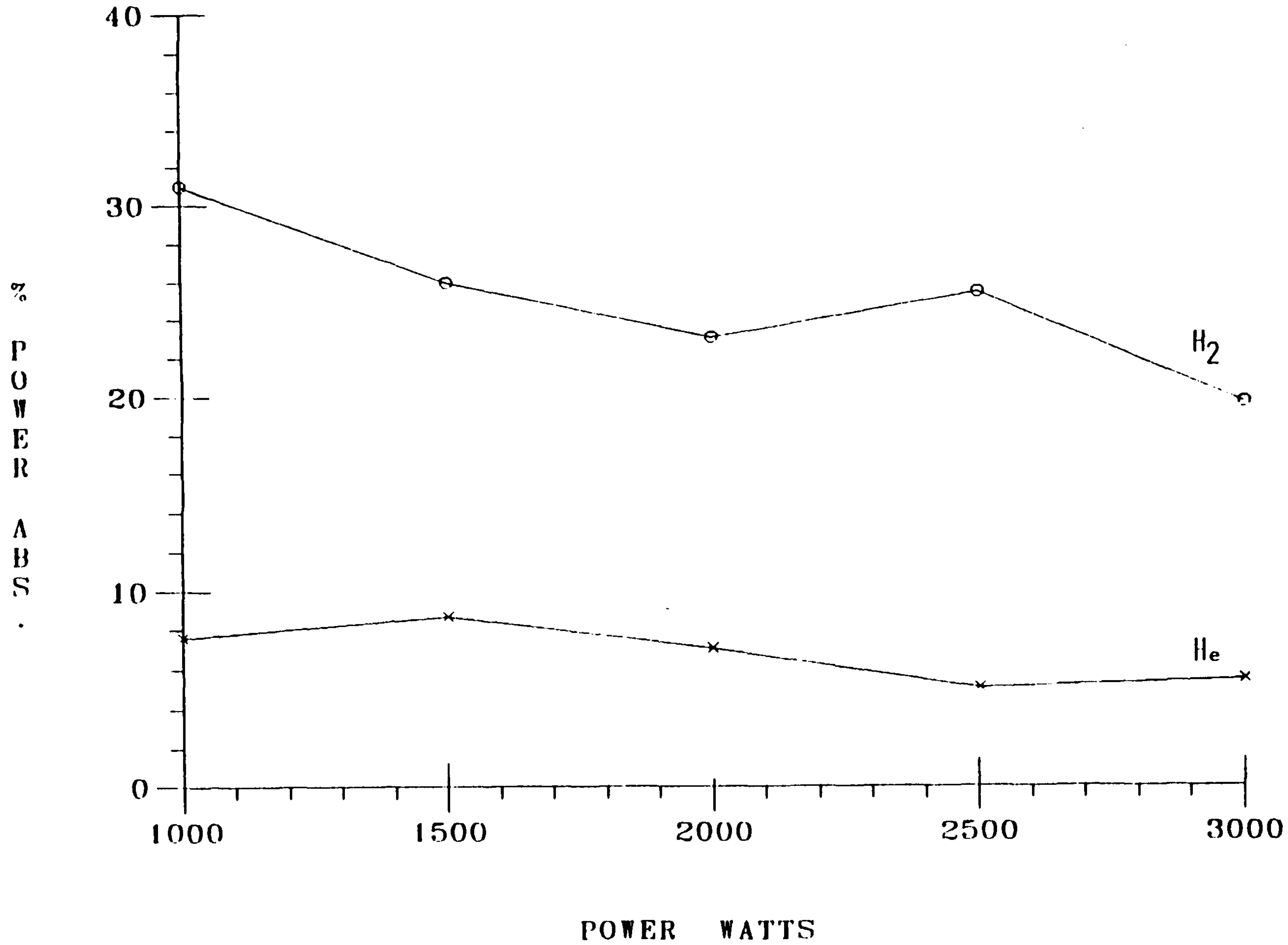

Fig. 4 Percent power absorbed by a propagating plasma as a function of input microwave power for hydrogen and helium gas at one atmosphere pressure showing hydrogen absorbing four times more power than helium.

C. Cumulative Chronological List of Written Publications in Technical Journals

1. Knecht, J. P. and Micci, M. M., "Analysis of a Microwave-Heated Planar Propagating Hydrogen Plasma." Submitted for publication in AIAA Journal.

2. Durbin, M. R. and Micci, M. M., "Analysis of Propagating Microwave Heated Plasmas in Hydrogen, Helium and Nitrogen," AIAA Paper 87-1013. To be submitted for publication in AIAA Journal.

D. Professional Personnel Associated with Research Effort

Professional Staff

Michael M. Micci, Assistant Professor, Aerospace Engineering

Graduate Students

James P. Knecht, Graduate Assistant, January 1985-May 1986. M. S. Thesis title, "Numerical Analysis of a Microwave-Heated Planar Propagating Hydrogen Plasma." Present position: MIT Lincoln Labs, Lexington, MA.

William Maul, Graduate Assistant, June 1985-present. Anticipated M. S. Thesis title, "Investigation of Resonant Cavity Microwave-Heated Plasmas."

Michael R. Durbin, Graduate Assistant, July 1986-present. Anticipated Ph.D. Thesis title, "Analytical and Experimental Study of Propagating Microwave-Heated Plasmas."

E. Interactions

(1) Spoken papers

Coupling Between Gas Dynamics and Microwave Energy Absorption. Presented at the AFOSR/AFRPL Rocket Propulsion Research Meeting, March 21, 1985, Lancaster, CA.

Prospects for Microwave Heated Propulsion. Presented at Aerojet Tech Systems, Sacramento, CA, Oct. 8, 1985.

Prospects for Microwave Heated Propulsion. Presented to Project Forecast II, November 19, 1985, Arlington, VA.

Coupling Between Gas Dynamics and Microwave Energy Absorption. Presented at the AFOSR/AFRPL Rocket Propulsion Research Meeting, September 11, 1986.

Microwave Electrothermal Propulsion. Presented at the Air Force Office of Scientific Research, Bolling AFB, DC, September 18, 1986.

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