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Heat addition in flowing gases by electromagnetic wave absorption is being considered for propulsive purposes. The research includes both microwave and solar radiation. In the microwave studies, an experimental investigation of helium and nitrogen discharges has shown that free-floating plasmas can be established in either medium for a range of input powers and gas flow rates, although helium gives the broader range of stable limits. The discharges are being set up in a 10.2 cm quartz sphere. For pressure ranges from 0.5 to 5.0 atm and input powers to 3 kW, maximum coupling efficiencies are measured to be between 40 and 65% with higher efficiencies for cases with larger flow rates. Spectroscopic techniques are being introduced to provide detailed local measurements of conditions inside the discharge. In companion analytical efforts, computational techniques are being used to model the experimental flowfields to provide improved understanding of the absorption process and to enable us to extend the experimental findings to broader conditions. In the solar radiation (over)

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Abstract (Cont'd)

studies, the feasibility of direct absorption of solar energy in flowing conditions is studied. Similar computational studies are also being used to study the absorption of solar radiation in hydrogen with alkali seedants. Results show peak gas temperatures of about 3500-4000 K can be reached with reasonable solar concentration ratios. Variations in the gas flow rate provide some control over the re-radiation losses, but regenerative cooled systems would appear capable of providing specific impulses of 500-1000 seconds in rockets of a few hundred Newtons thrust.

FINAL REPORT

on

COUPLING BETWEEN RADIATION AND GAS DYNAMICS

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May 1989

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Final Report

on

COUPLING BETWEEN GAS DYNAMICS AND MICROWAVE ENERGY ABSORPTION

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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 thermodynamics 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.

Summary of Results

Free-floating spherical plasmas have been generated in stationary and flowing nitrogen and helium gas contained inside a 10.2 cm diameter spherical quartz vessel located within a cylindrical resonant cavity operated in the TM_{012} mode at a frequency of approximately 2.45 GHz[1]. The plasmas are approximately two inches in diameter and are centered within the quartz sphere. Power coupled to the plasma was measured as a function of gas composition, flow rate and pressure and microwave power input to the cavity only for those conditions which resulted in the plasma being stabilized in the center of the quartz sphere away from adjacent walls.

The coupling efficiencies of helium and nitrogen plasmas were measured with no gas flow and an input power of 400 W. Similar measurements were made for a helium plasma with a gas flow rate of 1.056×10^{-4} kg/s and 400 W input power. Figure 1 shows the coupling efficiency versus pressure curves for the three cases considered. The coupling efficiency is defined to be the percentage of input microwave power actually absorbed in the gas. The most striking feature is the much greater range of operation of the helium discharges. The nitrogen discharge is limited to low pressure operation (less than 30 kPA (absolute)), whereas the helium discharges operate at well above 250 kPa (absolute). The helium discharges generally exhibit higher coupling efficiencies, with peak values of 51% (no flow) and 63% (with gas flow). In comparison, the nitrogen discharge exhibits a peak coupling efficiency of 40%.

For a given plasma in the resonant cavity, there is a maximum operating pressure, above which the plasma is extinguished. Tests were performed to investigate this stability boundary as a function of input power. The first tests examined nitrogen and helium plasmas with no gas flow, with later tests examining a helium plasma with various gas flow rates. As is shown in Figure 2, the maximum operating pressure for a given input power is significantly greater for helium discharges than for nitrogen discharges.

It was possible to sustain a nitrogen discharge up to a pressure of only 40 kPa (absolute) with an input power of 450 W, whereas helium discharges displayed much higher maximum pressures for cases both with and without flow present.

The helium discharges for various flow rates all have similar stability boundaries, which are approximately linear at first, then reaching a maximum possible operating pressure. For the no-flow case, the maximum pressure is 284 kPa (absolute) at an input power of 400 W. This input power is a maximum for the discharge with no flow, as it was found that further increase in the input power resulted in an excursion of the discharge to the surface of the quartz sphere.

The introduction of a gas flow did not affect the stability boundary dramatically, but did raise the maximum operating pressure of the discharge. For a mass flow rate 1.5 x 10^{-5} kg/s, the maximum operating pressur was 318 kPa (absolute), at an input power of 433 W. The tests were discontinued at an input power of 505 W, as higher input powers resulted in the plasma positioned close to the quartz surface. For an increased mass flow of 1.056 x 10^{-4} kg/s, the maximum operating pressure was 330 kPa (absolute) at an input power of 400 W, with a similar profile as before.

A numerical model of the one-dimensional planar propagating microwave plasma in hydrogen, helium and nitrogen gas has been successfully formulated.[2,3,4] This model numerically integrates the system of governing equations consisting of the one-dimensional steady energy equation and Maxwell's equation describing the propagation of the microwave energy. Due to thermal conduction of 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[5] to solve for the propagation velocity of a laser heated plasma. The propagation velocity, maximum temperature and percent power absorbed were calculated as functions of the input microwave power. The propagation velocity was found to rise with increased microwave power but the maximum gas temperature is constant for hydrogen and nitrogen because significant dissociation is occurring in this temperature range and is absorbing the additional absorbed power. The maximum gas temperature for helium, which is not dissociating, was found to rise with increasing input power. It was found that all of the input power was either reflected or absorbed with no power being transmitted through the plasma and that the present power absorbed for hydrogen decreases with increased input power while the percent power absorbed for helium and nitrogen remained fairly constant as a function of input microwave power. Radiative heat loss from the plasma was subsequently added to the model but was found to have no effect on the numerical results.[4]

The results of the experiment are shown in Fig. 3[4] which gives the measured plasma velocities for helium and nitrogen at 1 atm together with the numerical predictions. For helium a reasonable agreement between numerical and experimental data could only be found towards lower power levels, however, an enormous deviation can be observed for power levels above 1550 W. It is believed that in this power range a change in the propagation mode takes place towards resonant radiation. Nitrogen doesn't show this kind of behavior and agrees reasonably well with the numerical model. The percentage absorbed power values for helium at 1 atm range from the mid 60 to the low 70 percent and for nitrogen from the low to mid 60 percent. These values were much higher than those predicted by the model.

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1. Knecht, J. P. and Micci, M. M., "Analysis of a Microwave-Heated Planar Propagating Hydrogen Plasma," AIAA Journal, Vol. 26, No. 2, Feb. 1988, pp. 188-194.

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Juergen Mueller, Graduate Assistant, August 1987-present. Anticipated Ph.D. Thesis title, "Analytical and Experimental Study of Propagating Microwave-Heated Plasmas."

Philip Balaam, Graduate Assistant, August 1987-present. Anticipated Ph.D. Thesis title, "Investigation of Resonant Cavity Microwave-Heated Plasmas."

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, Lancaster, CA.

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

Analysis of Propagating Microwave Heated Plasmas in Hydrogen, Helium and Nitrogen. Presented at the 19th AIAA/DGLR/JSASS International Electric Propulsion Conference, May 12, 1987, Colorado Springs, CO.

Coupling Between Gas Dynamics and Microwave Energy Absorption. Presented at the AFOSR/ONR Combustion and Rocket Propulsion Contractors Meeting, June 26, 1987, State College, PA.

Microwave Electrothermal Propulsion. Presented at Purdue University, July 13, 1987, W. Lafayette, IN.

Microwave Electrothermal Propulsion. Presented at The Ohio State University, September 8, 1987, Columbus, OH.

Coupling Between Gas Dynamics and Microwave Energy Absorption. Presented at the AFOSR/ONR Contractors Meeting, June 13-17, 1988, Pasadena, CA.

Characteristics of Free-Floating Nitrogen and Helium Plasmas Generated in a Microwave Resonant Cavity (with P. Balaam and W. Maul). Presented at the DGLR/AIAA/JSASS 20th International Electric Propulsion Conference, Garmisch-Partenkirchen, W. Germany, October 3-6, 1988.

Numerical and Experimental Investigations of a Propagating Microwave-Heated Plasma (with J. Mueller). Presented at the DGLR/AIAA/JSASS 20th International Electric Propulsion Conference, Garmisch-Partenkirchen, W. Germany, October 3-6, 1988.

Microwave-Heated Plasmas for Use in Space Propulsion. Presented to the Department of Nuclear Engineering, The Pennsylvania State University, Nov. 8, 1988, University Park, PA.

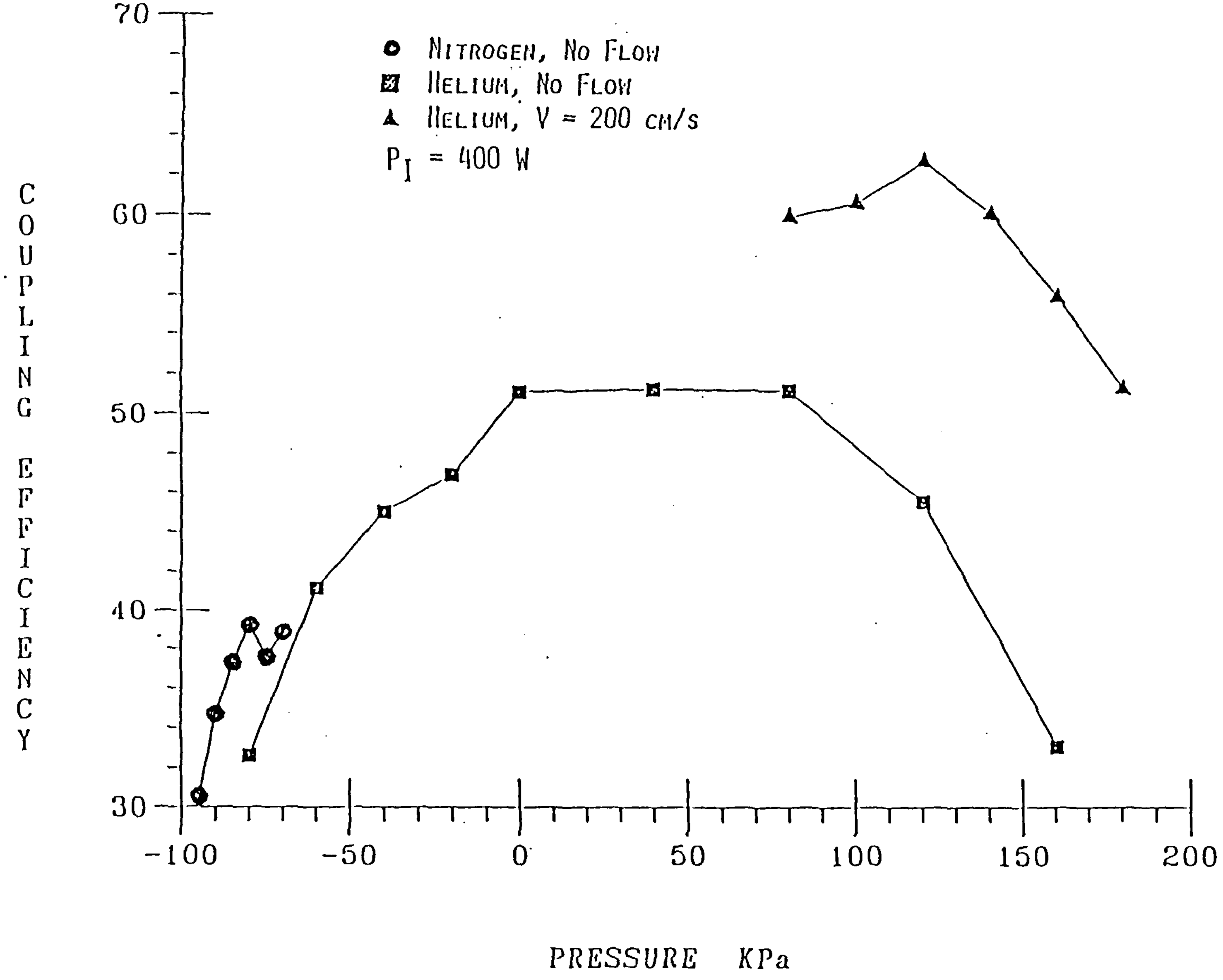

Fig. 1 Microwave coupli-g efficiency as a function of gas pressure for nonflowing nitroge- and helium and helium with a mass flow rate of 0.1 gm/s.

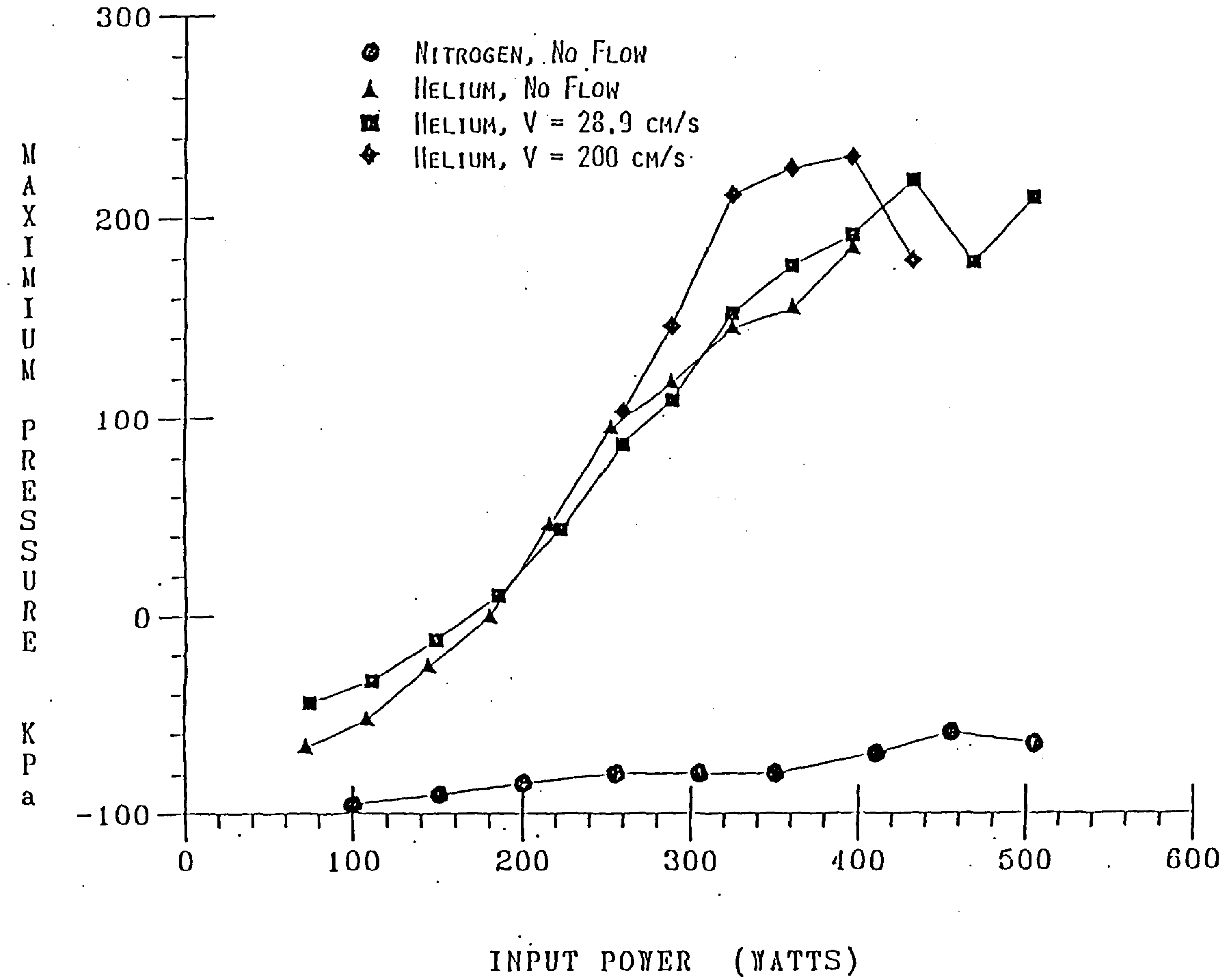

Fig. 2 Maximum sustainable gas pressure for a resonant cavity microwave-heated plasma as a function of input power for nonflowing nitrogen and helium and flowing helium.

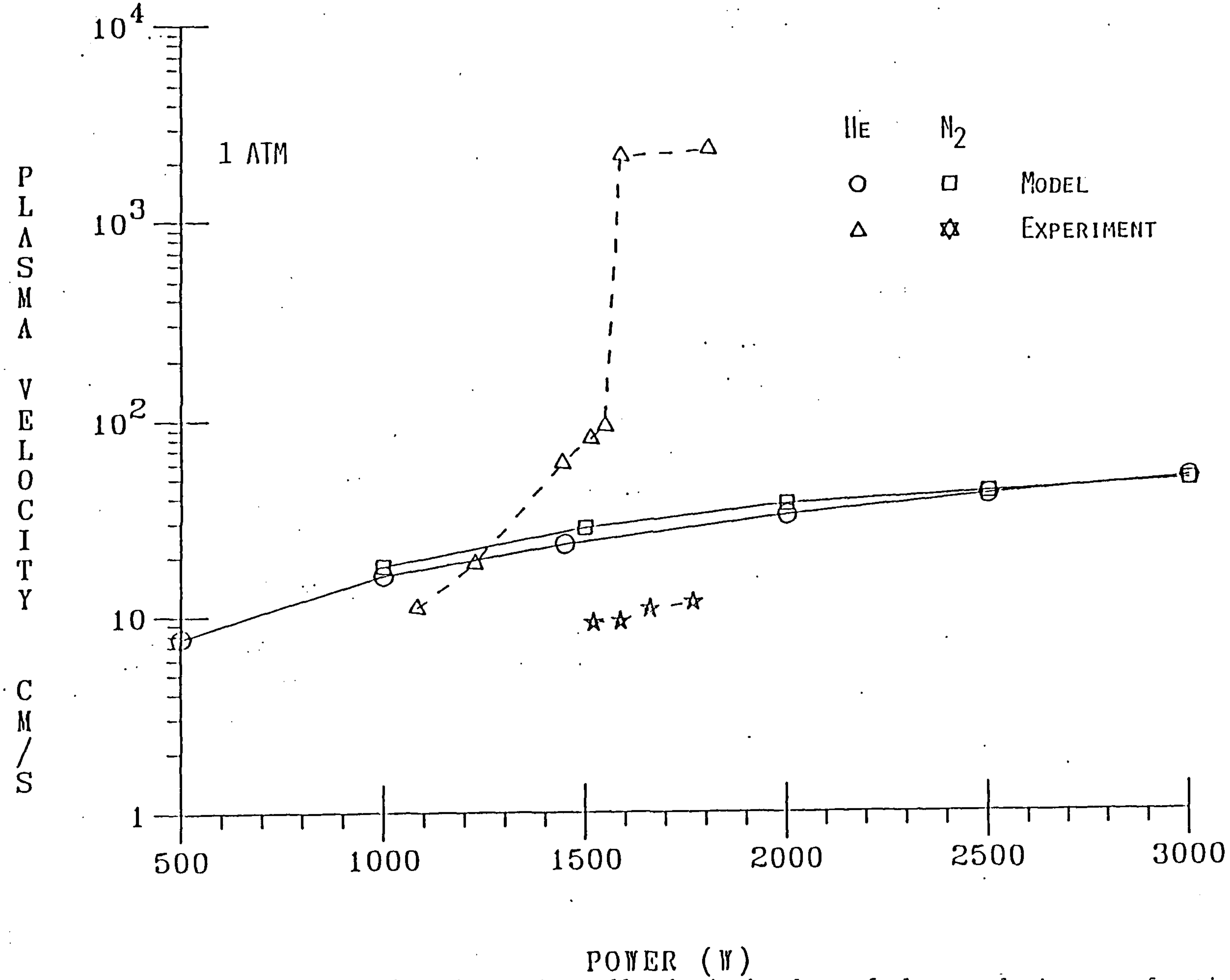

Fig. 3 Numerically and experimentally obtained values of plasma velocity as a function of incident power for helium and nitrogen at atmospheric pressure.

Final Report

on

ANALYTICAL MODELING OF STRONG RADIATION GAS-DYNAMIC INTERACTION

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I. STATUS OF RESEARCH EFFORT

Our research emphasis during the past year has been focussed on two radiation-gasdynamic problems, namely solar thermal propulsion and microwave thermal propulsion. Primary emphasis was on the solar concept with attention being shifted toward the microwave concept near the end of the contracted effort. The purposes in both areas was to assess the scientific feasibility of the particular propulsion concept on the basis of detailed analytical models. With respect to the solar problem, the key issue is to identify whether or not fluids can be obtained that will absorb the solar radiation directly. An assessment of this feasibility is summarized herein and presented in more detail in published articles. The primary issue with microwave propulsion is to determine whether or not the location and size of the heated plasma region can be controlled adequately to prevent arcing to the wall. The analytical portion of this study is just getting underway and is being performed in conjunction with the experimental program described in the earlier part of this report.

A. Feasibility of Solar Propulsion

Solar thermal heating appears to be a viable and realizable propulsion concept if the solar energy can be coupled directly to the working fluid. This is referred to as "direct" solar propulsion. An alternative is to use the solar energy to heat a working surface of the engine and then to heat the working fluid indirectly by using it to cool this surface[1-3]. This "indirect" solar thermal concept is clearly inferior to the direct concept. In the indirect concept, the maximum temperature within the cycle occurs on a material surface. The peak temperature of the working fluid is limited to temperatures that are less than this material temperature. In the direct solar thermal concept, the maximum temperature occurs in the fluid and standard techniques can be used for cooling adjacent surfaces to keep them at lower temperatures. This implies that higher working temperatures can be used resulting in improved thermodynamic efficiencies. In particular, higher temperatures in propulsion systems correspond to higher specific impulses. The maximum temperature in direct solar thermal propulsion thus becomes limited by the thermodynamic characteristics of the solar radiation, whereas in the indirect case it is limited by material considerations. As indicated above, the major question concerning the feasibility of solar thermal propulsion is whether or not the solar energy can be deposited directly in the working fluid. It is toward this issue that the present research is directed.

The first issue concerning the feasibility of absorbing solar energy in a gaseous working fluid is to select the fluid itself. For this purpose we have considered[4,5] hydrogen as the primary working fluid with seedant additives of three alkali metal vapors, Na, K and Cs. The particular composition we have selected is a mixture of 85% H_2, 5% Na, 5% K and 5% Cs by volume. Hydrogen provides low molecular weight (and high specific impulse) while the three alkali metals provide absorption capabilities in complementary parts of the solar spectrum. Absorption in alkali metals is comprised[5] of electronic transitions in dimers at the lower temperatures (below about 2500 K) and of photoionization at higher temperatures (2000 to 3000 K). The characteristic resonance doublet of alkali metals also contributes to absorption. Inverse bremsstrahlung generally does not become significant until above solar temperatures.

The net absorption coefficient for the 5% mixture of Na, K, and Cs in hydrogen is given in Fig. 1 for wavelengths corresponding to solar radiation. The multiple absorption paths in alkali metals and the different wavelength dependencies of the three alkali elements leads to a very complicated absorptivity-temperature-wavelength dependency as Fig. 1 shows. In particular, the absorptivity increases with temperature at some wavelengths, but decreases with temperature at others. This latter effect arises because of dimer absorption and reflects the fact that the number density of dimers decreases with temperature because of dissociation. For computations, the absorptivity curve of Fig. 1 was divided into wavelength bands in each of which the absorptivity was taken as constant. The number of bands used was typically from six to ten.

Calculations of heat absorption in a flowing gas were computed numerically using contemporary numerical methods[4,5]. The computations use a focussed solar beam with spot size chosen to correspond to a concentration ratio of 20,000 to one. Such concentration ratios correspond to a reasonable upper limit on the concentration factors that can be achieved in practice. Some representative results for flow in a straight duct and for flow in a converging duct that parallels the convergence of the focussed solar radiation are given in Figs. 2-5. Figures 2 and 3 show temperature contours in the straight and converging sections, respectively, for an inlet velocity corresponding to a Mach number of 4×10^{-4} (about 0.75 m/s). For this case, the dimer bands lead to rapid absorption and steep temperature gradients near the upstream window. For the straight duct case, about 75% of the incoming radiation is absorbed, but a large portion of this is re-radiated to the walls so the net fraction absorbed is only about 25%. Much of this re-radiation to the walls is, however, recovered by using the walls as a regenerative heat exchanger. The non-absorbed radiation also goes to heat the walls so it too can be used for regenerative purposes. All in all, the radiative flux on the walls is much less than in the corresponding direct solar heated case [1,2,6] and the peak fluid temperature is substantially higher. Some fraction of the re-radiated energy, however, escapes out the solar window so that the net efficiency is estimated at about 75%.

The converging geometry results in Fig. 3 show a slightly higher peak temperature of 3700 K but the energy balances are more or less similar to those for the straight duct case in Fig. 2.

The power coupled directly to the plasma depends on the incoming flow velocity. To test this sensitivity, we computed a case for a speed that was twice that for the results shown in Figs. 2 and 3. The results for this higher case ($M = 8 \times 10^{-4}$, u = 1.5 m/s) are given in Fig. 4. The higher speed decreases the peak temperature slightly (to about 3500 K) but increases the net energy absorbed to about 30%. This gives an idea of the type of control that is available by changing the fluid velocity.

As a final effect, we show in Fig. 5 the effect of using a solar concentration of 10,000 to one rather than the 20,000 to one case shown above. The reduced concentration ratio decreases the peak temperature from 3500 to 3000 K. The net energy absorbed is also slightly lower than for the higher concentration ratio case.

The overall conclusion of the direct absorption modeling is that solar energy can be absorbed directly in a flowing gas by using dimer seedants in a primary hydrogen flow. The resulting system gives much lower material temperatures and substantially higher gas temperatures than for the direct absorption case. The dimensions of the absorber are, however, quite large for the thrust sizes considered. Solar rockets with thrust capabilities of a few hundred Newtons and specific impulses of 500 to 1000 sec appear feasible. More detailed parametric studies are necessary in conjunction with experimental verification to quantify these general conclusions and to optimize the cycle.

B. Analytical Modeling of Microwave Plasmas

A detailed study of microwave plasmas has also begun using a method similar to that developed for the solar problem. This analytical study is to augment the companion experiment of Micci described in the first part of this report. The equations governing the interaction between a microwave field and a flowing gas are the compressible Navier-Stokes equations for the fluids and the Maxwell equations for the electromagnetic field. We are presently considering the solution of these equations in axisymmetric geometries. The equations are formulated in generalized body-fitted coordinates that allow arbitrary geometries and necessary grid stretching. Time-marching methods are used to solve the equations.

The configurations of interest center around the floating plasmas described in the first part of the flow. To date, we have obtained solutions with specified heat addition in the sphere cylinder combination used for the experiments and coupled plasma-gasdynamic solutions in cylindrical ducts (see Figs. 6 and 7). To date, these computations omit re-radiation losses, but do take into account temperature dependent viscosity and thermal conductivity. Effects of gravity have also been included (with a downward gas flow to mimic the experiments), but the results presented herein omit this effect. Figure 7 shows temperature contours, streamlines and the specified heat addition contours for a Reynolds number of 400 and a heat flux of 400 watts.

Figure 7 shows the outline of the microwave cavity through which the fluid flows in a smaller quartz tube. The tube is here taken as cylindrical. The original undisturbed standing waves in the cavity for the axisymmetric case are given in Fig. 8. The corresponding microwave contours in the presence of a conducting medium are given in Figs. 7 and 9 for two different flow conditions. Clearly, the presence of a conducting gas and of energy addition completely alters the microwave pattern. Temperature contours in these two figures show that peak temperatures of 9600 and 9900 K are reached for heat addition rates of 2.8 and 3.7 kW. A summary of four cases computed to date is given on Table 1.

Current emphasis is on computing coupled flowfields in the exact geometry of the experimental apparatus using the same and opposite gravitational orientation. Specific problems being addressed include methods for measuring the reflected power from the cavity and methods for modeling the line radiation loss from the plasma.

TABLE 1

PHYSICAL CONDITIONS FOR MICROWAVE-GASDYNAMIC CALCULATIONS

	CASE 1	CASE 2	CASE 3	CASE 4
Re #	90	450	180	18
$\dot{m}$ kg/s	3×10^{-4}	15×10^{-4}	6.5×10^{-4}	6.5×10^{-5}
Inlet velocity m/s	3.9	3.9	0.6	0.06
Heat added, kW	2.8	3.7	1.7	0.27
Maximum Temperature	9590	9890	9690	8670
Total Pressure N/m^2	0.2×10^5	1.0×10^5	3.0×10^5	3.0×10^5

T_{in} = 1000 K; gas: helium; flow geometry: 0.1 m diameter, 0.2 m long; cavity geometry: 0.18 m diameter, 0.17 m long

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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 position: 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: Research Scientist, Sverdrup, Inc., NASA/Lewis, Cleveland, OH.

Yun-Ho Choi, Ph.D. Candidate, January 1985-April 1989. Ph.D. Thesis title, "Computation of Low Mach Number Flowfields with Strong Heat Addition". Present position: Research Scientist, Sverdrup, Inc., NASA/Lewis Research Center, Cleveland, OH.

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.

Sankaran Venkateswaran, Ph.D. Candidate, September 1985-present, "Absorption of Solar Energy in Hydrogen Alkali Metal Vapor Mixtures".

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.

"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", presented at the Sixth IMACS International Symposium on Computer Methods for Partial Differential Equations, Lehigh University, June 23-26, 1987, Bethlehem, PA.

"Coupling Between Concentrated Solar Radiation and Gasdynamics", AFOSR/AFRPL Chemical Rocket Research Meeting, State College, PA, June, 1987.

"Solar Radiation Gasdynamic Interactions", AFOSR/AFRPL Chemical Rocket Research Meeting, Pasadena, CA, June 1988.

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.

Chairman, U.S. Committee to Assess Japanese Technology Status in Rocket and Advanced Airbreathing Propulsion, sponsored by NSF, March 1989-February 1990.

VI. NEW DISCOVERIES

See Publication List.

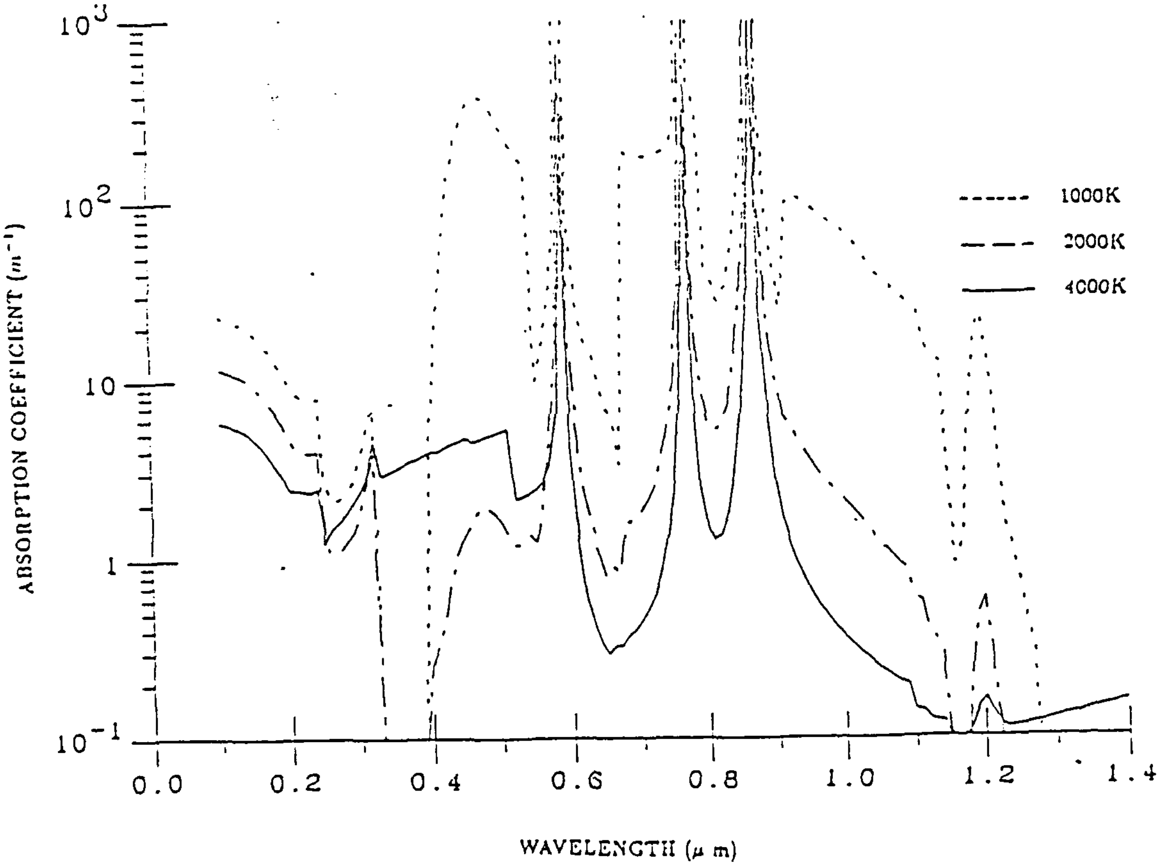

Fig. 1 Complete absorption coefficient of a 5% mixture of Na, K, Cs in Hydrogen. P_0 is 3.0 atms.

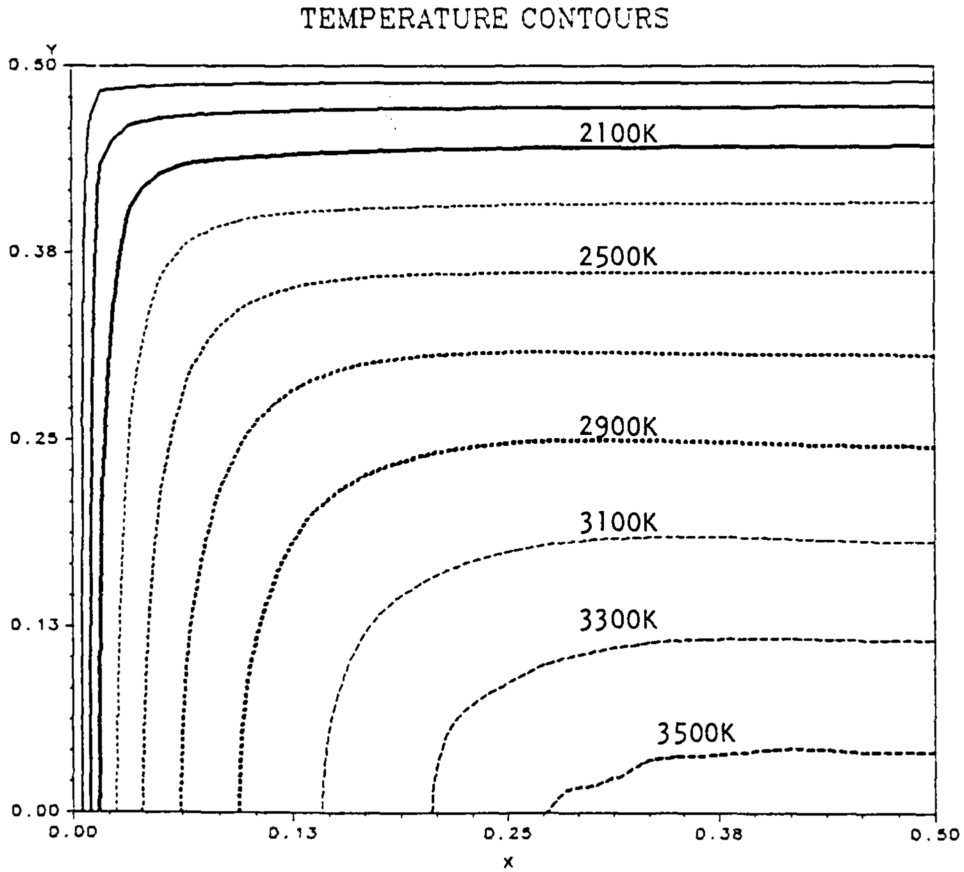

Fig. 2 Temperature contours for the straight duct case. R = 20,000, M = 4×10^{-4}.

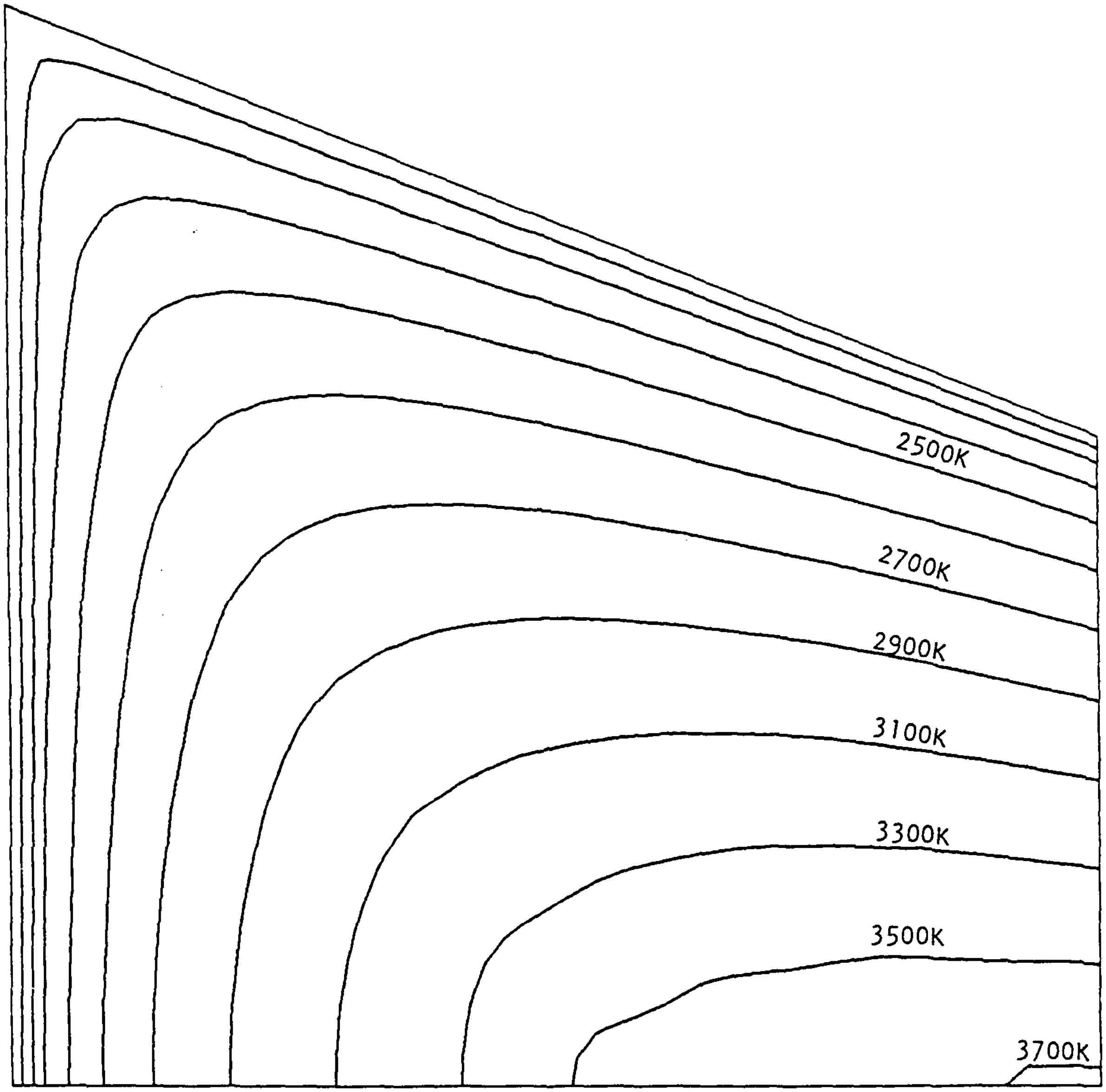

Fig. 3 Temperature contours for the converging duct case. $R = 20{,}000$, $M = 4 \times 10^{-4}$.

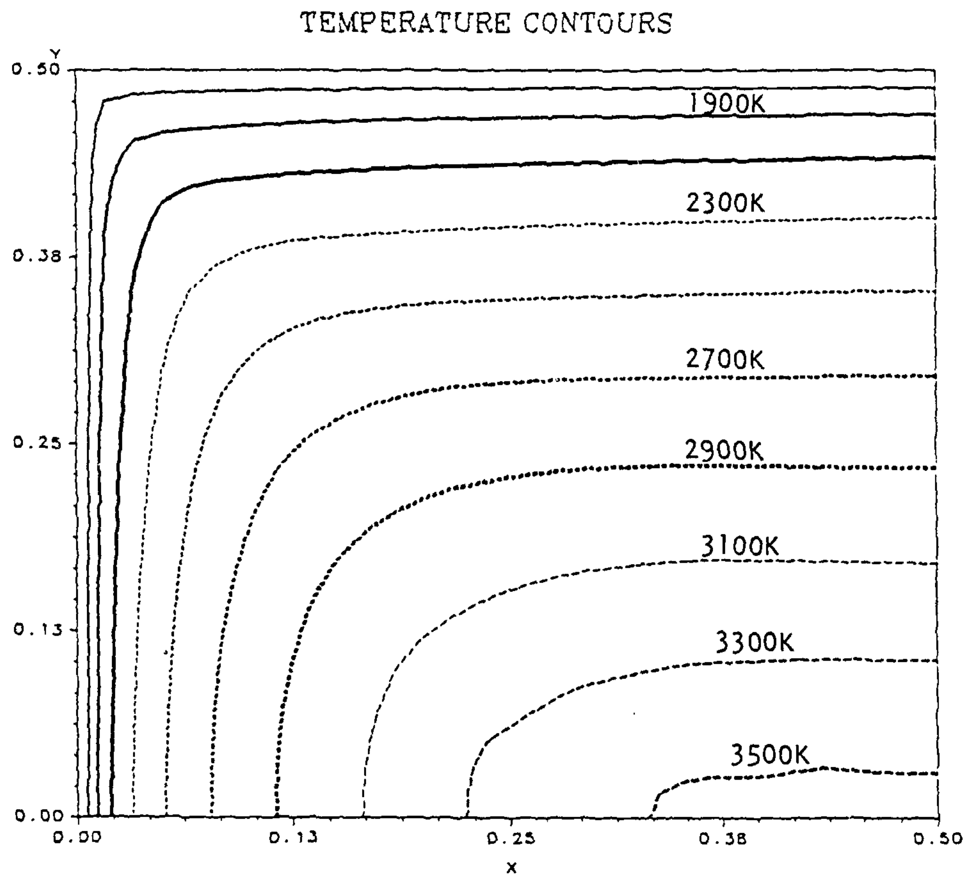

Fig. 4 Temperature contours in straight duct case. R = 20,000, M = 8 x 10^{-4}.

TEMPERATURE CONTOURS

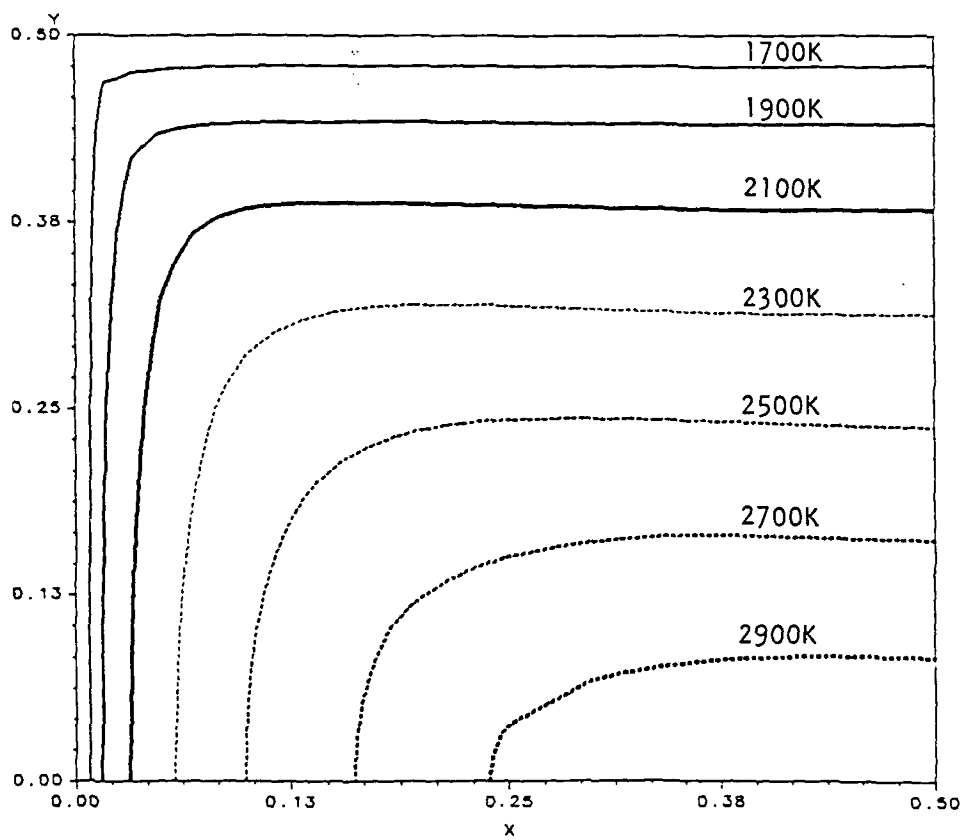

Fig. 5 Temperature contours for the converging duct case.
R = 10,000, M = 4 x 10^{-4}.

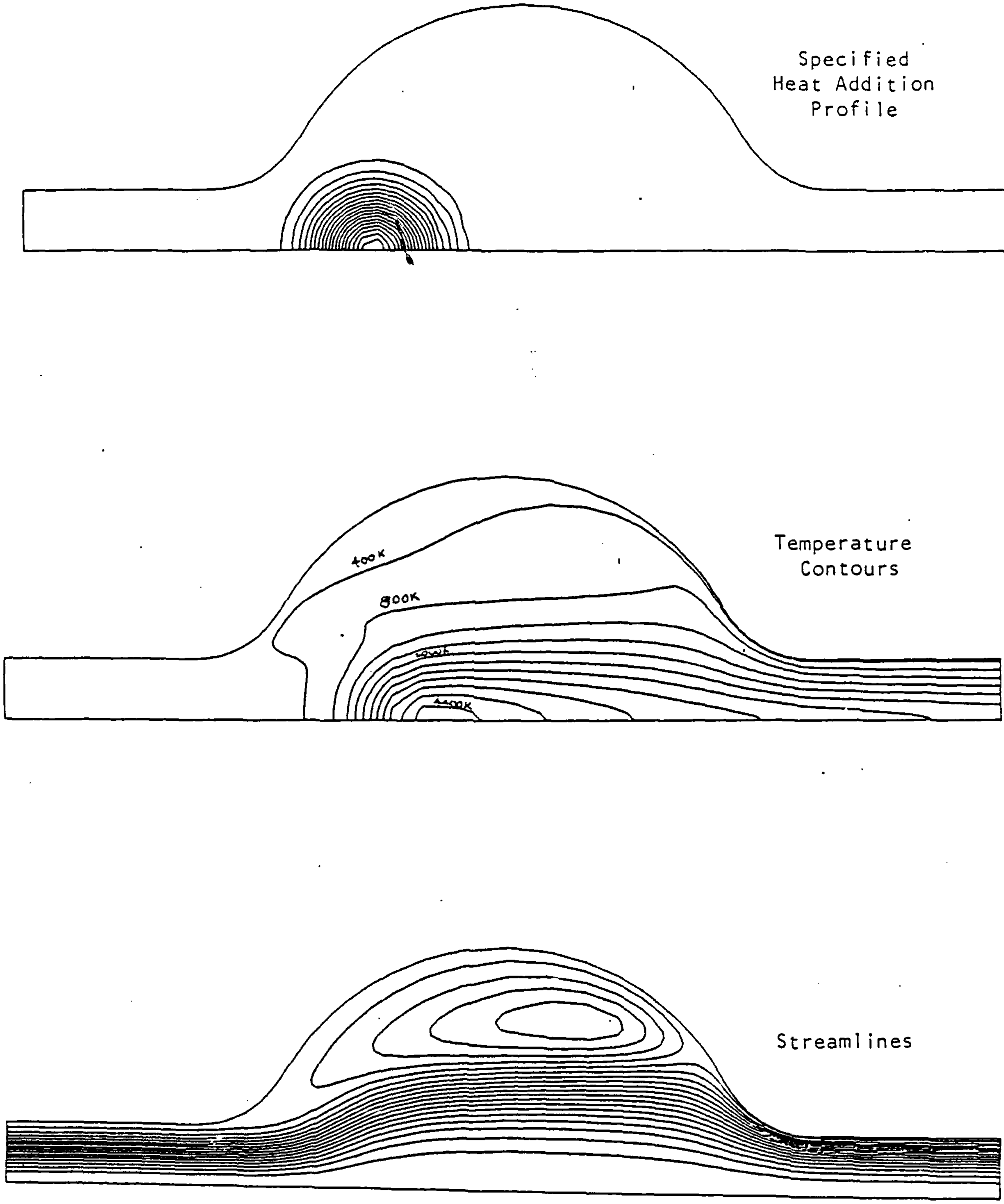

Fig. 6 Effect of specified heat addition on flow through a sphere-cylinder combination. Re = 400; Q = 1500 W.

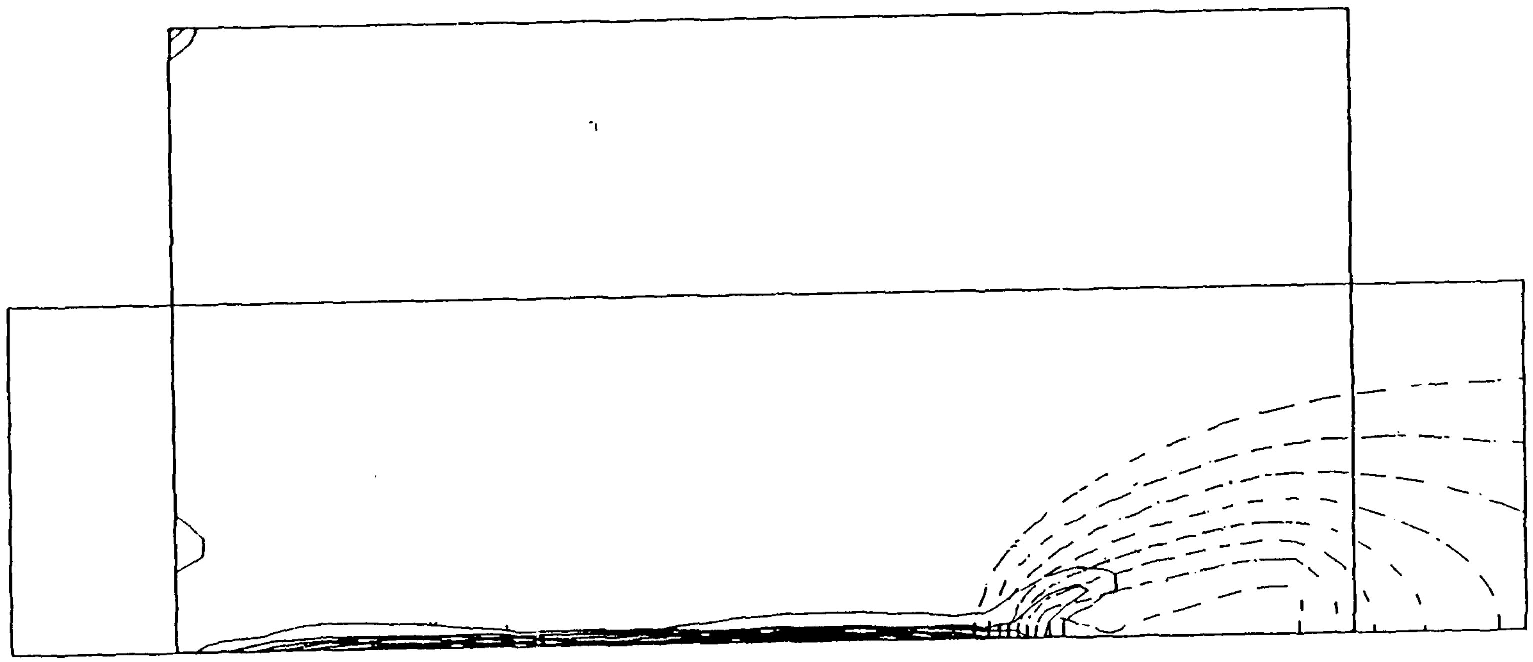

Fig. 7 Temperature contours (dashed lines) and microwave potential lines (solid lines) in coupled microwave-gasdynamic interaction. Re = 90, Q = 2.8 kW, $\dot{m} = 3 \times 10^{-4}$ kg/s (Case 1).

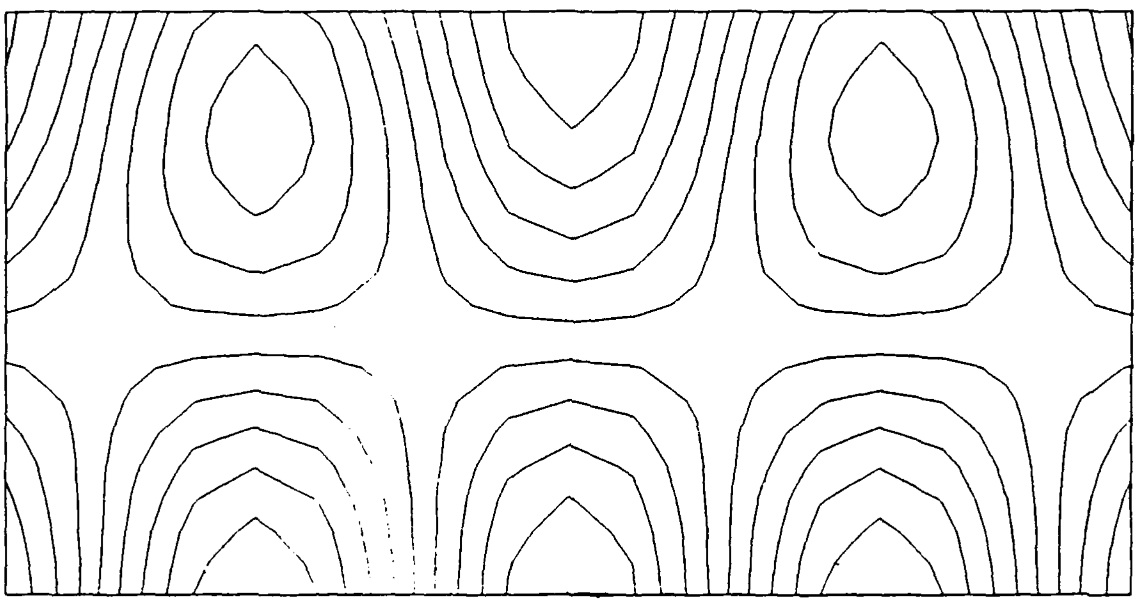

Fig. 8 Standing microwave pattern in cavity in absence of electrically conducting medium.

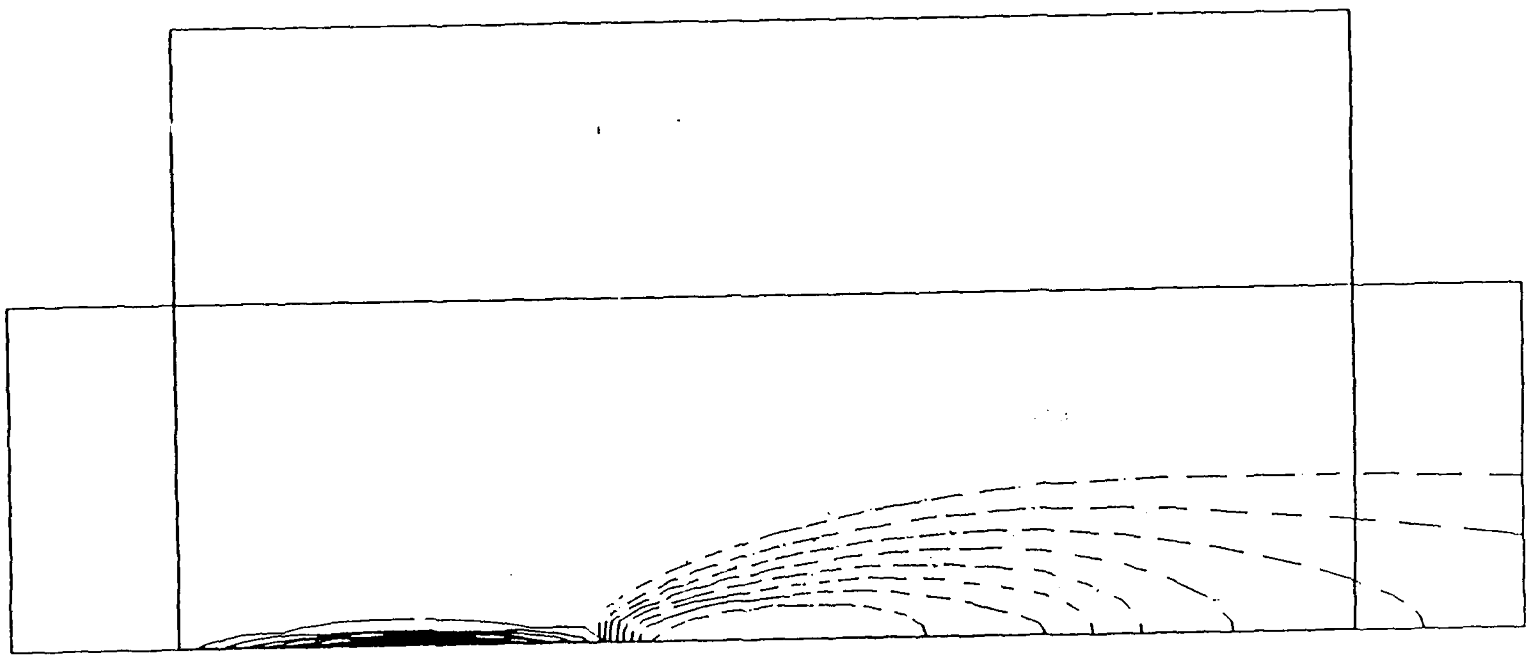

Fig. 9 Temperature contours (dashed lines) and microwave potential lines (solid lines) in coupled microwave-gasdynamic interaction. Re = 450, Q = 3.7 kW, m = 15 x 10^{-4} kg/s. (Case 2).