International Journal of Heat and Mass Transfer 105 (2017) 723–740

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Two-dimensional numerical simulations on laser energy depositions in a supersonic flow over a semi-circular body

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ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form 26 September 2016
Accepted 7 October 2016

ABSTRACT

Two-dimensional numerical simulations are carried out to investigate the effect of laser energy deposition (single pulse, 10 mJ, 50 mJ, and 100 mJ of absorbed energy) ahead of a semicircular body immersed in a Mach 3.45 free-stream. The temperature, pressure, and species composition of the laser energy deposition zone after cessation of the laser pulse is determined by a new and easy method based on Helmholtz free-energy minimization. Either five (O_2, O, N_2, N, and NO) or seven species (O_2, O, N_2, N, NO, NO^+, and electron (e^-)) are assumed to exist in the energy deposition zone after cessation of the pulse. It is observed that the energy deposition zone quickly separates itself into a hot core region and a near circular blast wave which travels radially outward while being convected by the flow. Upon interaction of the blast wave and the hot core region with the bow shock ahead of the body, lensing of the bow shock is observed. A small region of reverse velocity field (opposite to the free-stream flow direction) in the interaction region is found to be responsible for the lensing. The pressure jump across the lensed portion of the bow shock decreases and the streamlines passing through the lensed portion with a lower pressure jump is found to be responsible for the wave drag reduction on the body. The hot core region divides itself into two counter-rotating vortices and gets convected by the flow. The line contours of pressure, temperature, Mach number, species concentrations, and vorticity along with numerical schlieren images during the evolution of the energy deposition zone and its interaction with the body bow shock are given. The time histories of nose static pressure, wave drag on the body for the three cases of laser energies are plotted. The average wave drag on the body is found to decrease with increase in laser energy within 10–100 mJ. Some important points on the difference between the existing experimental data (in the open literature) and the results from the present simulations are highlighted.

1. Introduction

Over the last few decades, there has been a large number of published articles in the open literature on supersonic flow-field alternation using energy deposition. The energy is deposited mainly by optical, microwave, and electric discharge techniques. The energy deposition is used for both global effects e.g. aerodynamic drag reduction, lift and moment control as well as for local flow-field alternation e.g. reduction in local pressure and heat transfer peaks, surface pressure fluctuations, etc. The supersonic flow field alternation by energy deposition is described elaborately in the literatures [1–5].

In the present work, we concentrate on energy deposition by a single laser pulse. The energy is deposited ahead of a semi-circular body immersed in a supersonic flow-field. In one of the earliest work, Kandala et al. [6] reported numerical results on the use of laser energy deposition for supersonic (Mach 3.45) flow control. In the simulations, first, a steady supersonic flow was established over a sphere. The plasma formation and its evolution into a pressure wave till 0.5 μs due to laser energy deposition in a quiescent air was achieved in a second simulation independent of the first. Then the two flow-fields were superimposed to predict the effect of laser energy deposition in a supersonic flow-field over a sphere. In the flow simulations, the Navier–Stokes equations along with the species conservation equations, the vibrational-electron energy conservation equation, and the electron energy conservation equation were solved. Substantial reduction in peak surface pressure on the sphere was observed due to energy deposition and the reduction was higher for a real gas than a perfect gas, which was attributed to the delayed release of the chemical energy to the flow for the former. In the numerical simulations of Zheltovodov et al. [7] and Schülein et al. [8] on laser energy deposition in a supersonic flow, the energy deposition zone was modeled on the basis of the amount of actual absorbed energy by the air and not the deposited energy. Here, it is worth mentioning that, in pulsed laser

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.10.025
0017-9310/

energy deposition process, part of the laser energy is transmitted and reflected, and the rest is absorbed by the working gas. In [7] and [8], the Euler equations were solved in conservative form with a perfect gas model. The modified Harten-Lax-van Leer-Einfeldt (HLLEM) algorithm was used to find the inviscid fluxes with extension to third order accuracy in space by the use of Monotonic Upstream-Centred Scheme for Conservation Laws (MUSCL) reconstruction technique with a min-mod limiter. The absorbed energy was modeled as a source term in the energy equation. Single laser pulse of energies 151 mJ, 264 mJ, 333 mJ, 548 mJ, 666 mJ and two successive laser pulses having energies of 333 mJ and 87 mJ or 215 mJ or 333 mJ were deposited at 76 mm and 46 mm from the body (hemisphere-cylinder) in a Mach 2 flow. The distribution of density gradients obtained from numerical simulations and shadowgraph images were compared for both single and double laser pulses. The agreement was reasonably good for single pulse cases despite the fact that some approximations were made regarding instants of time at which the shadowgraphs were captured. Also, the time histories of the experimentally obtained stagnation pressure were shown for the single pulse cases. However, the numerical predictions deviated from experimental results for the double pulse cases with a higher energy of the second pulse. The authors of [8] recommended inclusion of a turbulence model and improvements in the modeling of the source term for better numerical predictions of the flow-field. Mortazavi et al. [9] reported results from numerical simulations on the interactions between a laser generated plasma and the Mach 3.45 flow-field over a hemisphere-cylinder. The numerical method is same as that of [7] and [8]. A momentary decrease in the drag coefficient was observed. The thermal efficiency of the laser was estimated by matching the experimentally observed peak centerline pressure on the hemisphere surface with the numerical predictions. It was concluded that the solution of Euler equations with a perfect gas model of the plasma is incapable of accurately predicting the surface pressure on the hemisphere and hence the drag reduction. Golbabaei-Asl et al. [10] carried out numerical simulations of high-temperature filament interaction with the Mach 3.5 flow-field over a blunt cylinder. The filament modeled the combined effect of microwave and laser discharges. The unsteady axisymmetric Euler equations were solved with a perfect gas model. The temperature increase (ΔT) over the free-stream temperature (T_∞) due to the energy deposition was expressed as $\Delta T/T_\infty$ and parametric studies were carried out for various values of the $\Delta T/T_\infty$ and the filament length to cylinder diameter ratio (L/D) on drag reduction. A saturation effect on the maximum drag reduction was observed in the numerical results and it was found that the discharge location of the filament did not significantly impact the drag force. A one-dimensional analytical tool was also used to give interpretations of the numerical results. Azarova et al. [11] reported results of inviscid numerical simulations on laser energy depositions (13 mJ, 127 mJ, and 258 mJ) into supersonic flow past a hemisphere cylinder. The energy deposition zone was approximated by combining the hot rarefied channels. Also, the optimized characteristics of the energy sources were achieved by analysis and comparison of the experimental and numerical results. Using the results of [11], two cases of non-combined and combined filaments as the deposited laser energy source, and the complex conservative difference schemes of Azarova [12], flow past a hemisphere-cylinder were numerically simulated by Azarova et al. [13]. Results were provided on drag force dynamics for various free-stream Mach numbers, rarefaction degrees and deposited laser energies.

On the basis of the findings and recommendations of the previous reports [7–12], it may be inferred that any new simulation should take into account the chemical equilibrium/non-equilibrium that prevails during the formation of the plasma through laser energy deposition in air and in the subsequent description of the flow-field after the cessation of the laser pulse. In [6], the plasma formation process was modeled, which was a bit involved and the chemical and thermal non-equilibrium were taken into account in the study of the flow-field, after cessation of the laser pulse. The success of [6] was based on the comparison between numerical and experimental results on the blast wave radius with time after laser energy deposition in quiescent air. No comparisons between numerical predictions and experimental results were made on the stagnation pressure history for supersonic flow over the sphere at various values of the deposited energy. In the other reported work [7–11,13], simple correlations between the deposited laser energy and characteristics of the breakdown zone (plasma) were made, e.g. temperature rise is proportional to the absorbed energy. However, it is reported in [14,15] that the energy absorbed by the working medium is not fully converted into thermal energy. Part of the absorbed energy goes into the blast wave and the rest is lost in thermal radiation. In the present work, results from a new and easier method (described in the Appendix A2) are used in determining the conditions of the breakdown zone after cessation of the laser pulse. The method determines the temperature, pressure, and species composition of the breakdown zone for various values of absorbed energy after cessation of the laser pulse. Then, the effect of laser energy deposition into a supersonic flow (Mach 3.45) over a semicircle is studied. The Navier–Stokes equations along with species conservation equations are solved (in a chemical non-equilibrium framework) for the study of the flow-field subsequent to the laser energy deposition. The computer program which was developed in-house, used for this study was validated against experimental results in [14]. The reasons for the difference among the predictions from present work and the reported experimental results are highlighted.

2. Methodology

In the study of flow-fields involving laser energy deposition, it is necessary to know the pressure, temperature, and species composition of the energy deposition zone after cessation of the laser pulse to study the subsequent flow-field. In the present work, a fundamental principle of thermodynamics, namely the method of minimization of Helmholtz free-energy subject to certain constraints is used to determine the above variables. The constraints are (a) conservation of elements in the gaseous mixture, (b) conservation of energy which includes the energy absorbed by air from the laser pulse, and (c) constant volume of the deposition zone, which is equal to the focal volume of 3 mm^3. The required variables are the natural outcomes of the minimization process. The procedure is discussed in Appendix A2. It is worth mentioning here that the energy absorbed by air during energy deposition by a laser pulse and the approximate focal volume are determinable from experiments.

The steps followed in the numerical simulations are the following. First, a steady supersonic flow field is established numerically over a semi-circle of radius 12.7 mm. The free-stream Mach number is 3.45 and the curved surface of the semicircular body faces the flow. Then, the laser energy deposition is introduced instantaneously in the flow-field at a distance of 25.4 mm from the nose of the semi-circle. The reason behind this instantaneous introduction is that the pulse width ($\sim$1 ns) of the laser is very small compared to the time scale of the flow ($\sim$1 μs). Then the flow field is allowed to evolve in time. The details of the flow-field geometry, free-stream conditions, and the deposited laser energies are given in Table 1.

The supersonic flow-field over the semicircular body before the laser energy deposition is simulated by solving the Navier–Stokes equations with air as a perfect gas. The flow-field after the laser