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A Numerical Investigation of Localized and Steady Energy Addition to High Speed Airflows

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ABSTRACT: This work presents a numerical analysis of the gas dynamic problem of localized and steady energy addition to uniform high-speed airflows. Firstly, the general effects caused by a localized energy deposition on the flow were investigated, then an extensive parametric analysis concerning the effects of energy deposition rate and dispersion for different free stream flow speeds was performed. As a general result, localized and steady energy deposition generates compression waves and constant property flow stream tube downstream to the source. The parametric analysis results have shown that either increasing the rate or decreasing dispersion in the orthogonal direction to the flow of the deposited energy has the effect of enhancing property flow changes, which is even more pronounced for lower flow speeds. In contrast, energy dispersion in the flow direction has presented very little effect on the flow changes. The results of this numerical analysis should be very helpful in studies of energy addition applications in hypersonic.

KEYWORDS: High speed flow, Energy addition, Flow control, Numerical analysis.

INTRODUCTION

The need of aerospace vehicles for high speeds discloses a series of aerodynamics problems, such as large pressure drag forces and strong shock waves. It is known that, for a blunt body at supersonic speeds, a physical spike placed at its nose modifies the structure of the strong shock wave, which can reduce wave drag in an effective way, although this structure also requires an undesirable additional cooling system (Riggins *et al.*, 1999, Riggins and Nelson, 1999, Knight, 2003).

Another way to control high speed flows, which has also been considered for the reduction of aerodynamic drag of aerospace vehicles, corresponds to energy deposition in a small region of the airflow upstream to the vehicle. This is similarly capable of modifying the properties and path of the fluid elements and consequently of reducing the strength of the vehicle shock wave by modifying its shape (Riggins *et al.*, 1999, Riggins and Nelson, 1999, Knight, 2003). Besides this application, energetic techniques for high-speed flow control have been recently widely studied with several other purposes, such as inlet mass capture increase by scramjet engines operating at off design speeds, attitude control of supersonic vehicles, scramjet isolator shortening, among others. Deposition of energy to airflows has been experimentally accomplished by several different means, such as plasma arcs, laser pulse, microwave, electron beam, glow discharges, and so on (Oliveira, 2008c).

This work is part of some development activities that are being carried out at the Institute for Advanced Studies (IEAv) regarding high-speed airflow control. The advance of

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experimental studies previously performed at the IEAv, with respect to the addition of laser energy pulses to investigate vehicle drag and heat transfer (Minnuci *et al.*, 2005, Oliveira, 2008a, 2008b, 2008c, Salvador *et al.*, 2005, 2007, 2008), has shown the need of numerical analyses to obtain a better understanding of the phenomena generally observed and also to support new experiments. Therefore, in this work, which focused on understanding the properties of an energized flow without the presence of bodies, it is presented a numerical investigation of a localized steady energy addition to high-speed airflows, by varying the energy deposition rate and the spatial dispersion for different free stream airflow speeds (Fraile Jr., 2011). While this subject has already been studied, this paper presents a series of results showing airflow variables — such as velocity, density, pressure, and temperature — when several conditions were modified, and these results can provide information to another ongoing numerical study at IEAv related to wave drag reduction of blunt bodies in supersonic flows using energy addition. Herein, energy addition to high-speed flows is studied from thermodynamics and gas dynamics standpoints by considering that the energy addition effectively represents the direct energy transfer to the air translational (thermal) mode. Therefore, no plasma effects are considered and localized energy addition to the flow is simply treated as a volumetric heat source.

METHODOLOGY

The schematic shown in Fig. 1 represents the numerical problem treated in this work. The analysis performed takes into account a two-dimensional representation in space by considering axial symmetry. The physical (computational) domain, also shown in Fig, 1, contains a cylindrical volumetric heat source representing a localized steady energy deposition in a supersonic uniform airflow. This cylindrical heat source is aligned with the flow.

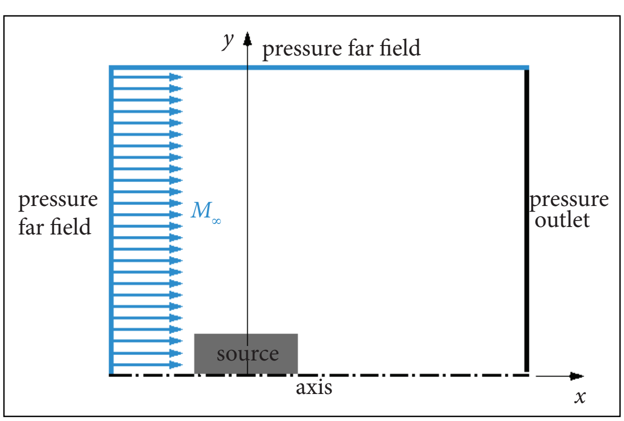

Figure 1. Physical (computational) domain employed for calculation of a steady heat source in a supersonic flow.

The Navier-Stokes equations (Eq. 1), with a volumetric source term representing the energy addition, were used in this work (FLUENT INC., 2006, Fraile Jr., 2011):

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0 \\ \dfrac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\cdot(\bar{\bar{\tau}}) \\ \dfrac{\partial}{\partial t}(\rho E) + \nabla\cdot[\vec{v}(\rho E + p)] = \nabla\cdot[k\nabla T + (\bar{\bar{\tau}}\cdot\vec{v})] + Q \end{cases} \tag{1}$$

where ρ is the flow density, p is the pressure, $\vec{v}$ is the velocity, $\bar{\bar{\tau}}$ represents the influence of viscosity on momentum and energy equations, k is the thermal conductivity, E is the energy per mass unit, and Q is the energy source term (per time and volume unit). Also, a small region of the domain receives energy and the term Q is the mathematical way employed to deposit energy to the airflow.

The tensor $\bar{\bar{\tau}}$ can be written as in Eq. 2 (FLUENT INC., 2006, Fraile Jr., 2011):

$$\bar{\bar{\tau}} = \mu\left[\left(\nabla\vec{v} + \nabla\vec{v}^T\right) - \frac{2}{3}\nabla\cdot\vec{v}I\right] \tag{2}$$

where μ is the molecular viscosity and I is the unit tensor.

The gas is considered ideal, therefore it can be written as in Eq. 3:

$$p = \rho RT \tag{3}$$

where R is the gas constant.

The energy per mass can be defined as Eq. 4 (FLUENT INC., 2006; Fraile Jr., 2011):

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{4}$$

where $dh = c_p dT$.

The numerical solution to this problem is obtained by using the Fluent® solver (FLUENT INC., 2006) for the Navier-Stokes equations, with the conditions of laminar flow and ideal gas, in a square grid that is well suitable for the geometry shown in Fig. 1. Since the numerical domain is axisymmetric, the Navier-Stokes equations are solved in cylindrical coordinates (FLUENT INC., 2006, Tannehill *et al.*, 1997).

The equations are discretized in accordance with an implicit method and a first order upwind spatial scheme. A "pressure-based" numerical method is used with an algorithm of coupling between the pressure and velocity named "coupled", for which the equations of continuity and momentum are solved simultaneously, and then the other ones of the model are solved separately. The boundary conditions employed to solve the problem are also presented in Fig. 1. The addition of energy to the flow in a region of the computational domain is modeled through a user-defined function (UDF), which is an available tool of the solver. The steady-state solution for the problem is sought since only steady energy depositions in the flow are considered (FLUENT INC., 2006).

The supersonic free stream flows from left to right with a static pressure of p_∞ = 1,0x10^5 Pa and a temperature of T_∞ = 300K. While it is intended to use the results of this work for better understanding the effects of energy addition on supersonic airflow, they have been also used to study the effects of energy addition on blunt body wave drag reduction. This fact justifies some of the variables used herein, like the heat source dimensions, which have the same magnitude (millimeters) of those used in shock tunnels, and also of the heat power presented in the following sections, which have been used in recent works at the IEAv.

RESULTS AND DISCUSSION

This section presents the results concerning the modification of a uniform flow due to the presence of an energy source confined to a small flow region in order to understand how the source affects the flow properties.

GENERAL CHARACTERISTICS OF THE FLOW WITH LOCALIZED STEADY ENERGY ADDITION

In order to identify the key changes of the properties of a uniform flow caused by the addition of energy to a small region in space, the physical domain shown in Fig. 1 is used to perform numerical calculations. It is considered that energy is steadily deposited uniformly in a small cylindrical region (length l_0 = 1.0 mm and radius r_0 = 0.5 mm), which is centered at the origin of the reference axes, with total power of 471 W, in a uniform Mach 4 free stream flow. The square grid used in all calculations is 20 cells/mm, which has yielded good accuracy results. The data used to validate this grid will be presented in this section after some basic effects of energy addition to the airflow have been discussed. The results corresponding to the scalar fields of the flow properties, such as pressure (p), temperature (T), density (ρ), as well as the flow movement quantities such as Mach number (M), axial (V_x) and radial velocities (V_y) are presented in Fig. 2. Figure 3 presents the outcomes for the flow variables along the symmetry axis (lower boundary in Fig. 1) and in a cross-sectional plane downstream to the heat source perpendicular to the free stream flow direction (right-hand boundary in Fig. 1).

As can be seen in the scalar fields of Fig. 2 and in the plots of Fig. 3, inside the heat source the flow is heated up with the effect of compressing the flow and diverting some part obliquely with respect to the symmetry axis. The localized energy deposition in the flow generates compression waves that propagate radially with the local sound speed and axially with the flow one. Inside the heat source, the flow density increases only slightly while the Mach number is reduced mainly because of the increase in temperature. The results in Fig. 3 show that there are two distinct flow regions around the symmetry axis downstream to the source: one just behind it, of about six source radius length, where all flow properties change considerably while the flow expands (pressure and density are reduced) and accelerates accompanied by a certain reduction in the temperature; and the other region following the first one, where flow properties are basically constants along the source axis, i.e. the pressure returns to the free stream value while the other flow variables reach values that are different from the free stream ones, even for distances far downstream from the source. Actually, this latter region, as can be observed in Figs. 2 and 3b, is characterized by a long constant property stream tube, aligned to the symmetry axis, of about the same source radius. Also, the wave fronts propagate radially in both regions, but only in the second one the flow between the constant property stream tube and the wave fronts is very close to the free stream one. As can be noticed, in the constant

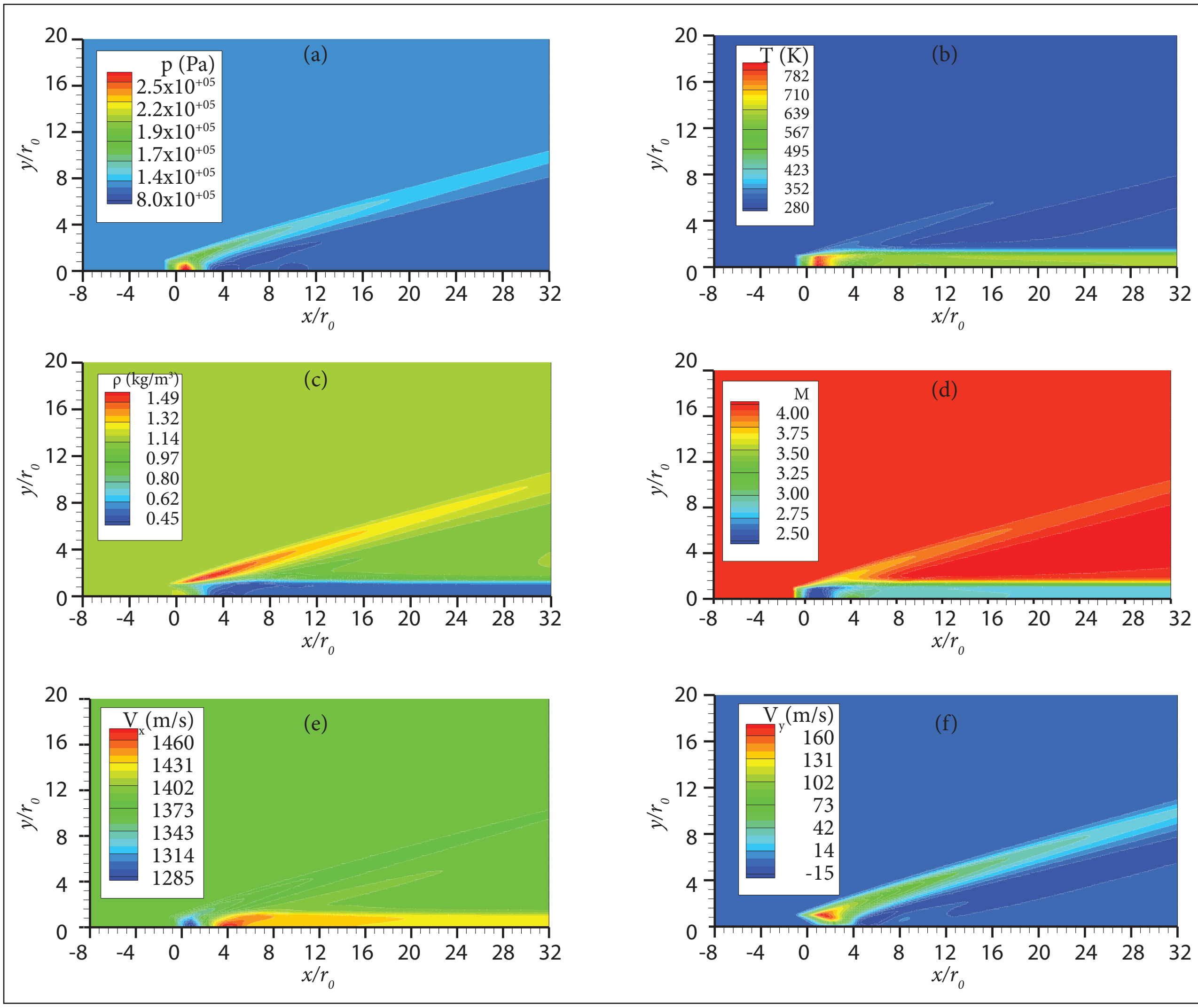

Figure 2. Scalar fields for a Mach 4 free stream and a 471 W heat source, of: (a) pressure; (b) temperature; (c) density; (d) Mach; (e) axial velocity; and (f) radial velocity.

property stream tube, the temperature has doubled whereas the Mach number and density have reduced about 30 and 50%, respectively, of their free stream values. However, it should be noted that the laminar model used in this work does not take into account diffusion and convection effects in flows far from walls, therefore it behaves as an inviscid one that justifies the later results. On the other hand, in real life flows are always at least somewhat turbulent, thus it is expected that the influence of the source on the flow — in terms of the distance from the source that all flow properties return to their free stream values — is smaller than for laminar ones.

The results shown in this work were obtained with a square grid of 20 cells/mm (each millimeter along the source axis or the direction perpendicular to it is divided into 20 parts), which can be validated through comparison with others of different resolutions. Figure 4 presents some flow variables (pressure, temperature, Mach number, and density) along the source symmetry axis when the resolution of the square grid is modified.

Even with the 10 cells/mm mesh, it is already possible to capture the main effects discussed herein, and it is also clear that the use of more refined meshes provides more accurate results. Therefore, it was chosen the 20 cells/mm mesh, instead of the higher resolution one, because this yields enough accurate results, for the present purpose, without being so computationally costly.

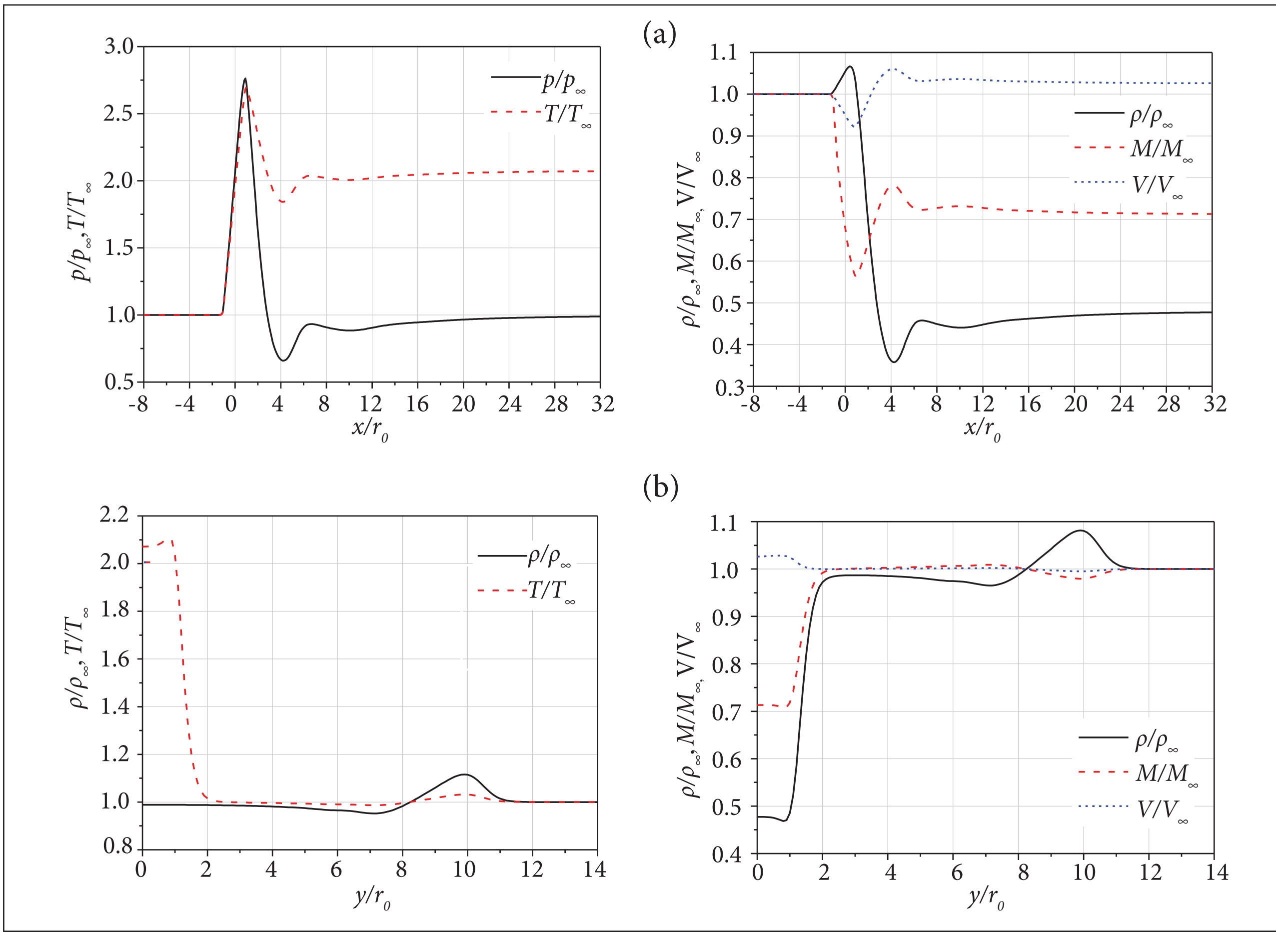

Figure 3. Normalized flow properties for a Mach 4 free stream and a 471 W heat source, along the (a) lower (symmetry axis) and (b) right-hand boundaries of the domain in Fig. 1.

In order to show that the boundary condition of free stream near the energy source is not affecting the results, it is possible to analyze the airflow when the distance between the source center and the left pressure far field boundary shown in Fig. 1 is increased. Figure 5 presents the pressure distribution along the symmetry axis for a Mach 4 free stream and a 471 W heat source when it is centered in the same position of all results of this paper, $x/r_0 = 0$, and when it is centered 12 units of r_0 away from its original position.

When the pressure distribution for $x/r_0 = 12$ is graphically shifted 12 units to the left along the x/r_0 axis (Fig. 5b), both distributions are approximately coincident, which indicates that the far field boundary condition is not affecting the solution. The same analysis was performed for other flow properties (temperature, density, and Mach number) and they showed the same behavior presented in Fig. 5.

In the next sections, the effects of energy deposition rate and dispersion as well as the free stream velocity in supersonic flows are analyzed based on the fluid behavior nearby, inside the source and also in both regions downstream to the source mentioned before, which actually are of more interest for practical applications.

EFFECTS OF ENERGY DEPOSITION RATE (HEAT SOURCE POWER)

When the effects of energy addition to high speed flows are analyzed, it is also of interest to study how the rate of energy deposition changes the flow properties. Figure 6 presents results of the flow properties along the symmetry axis whereas Fig. 7 shows results in a downstream perpendicular plane to the symmetry axis for three different values of energy deposition rate (heat source power).

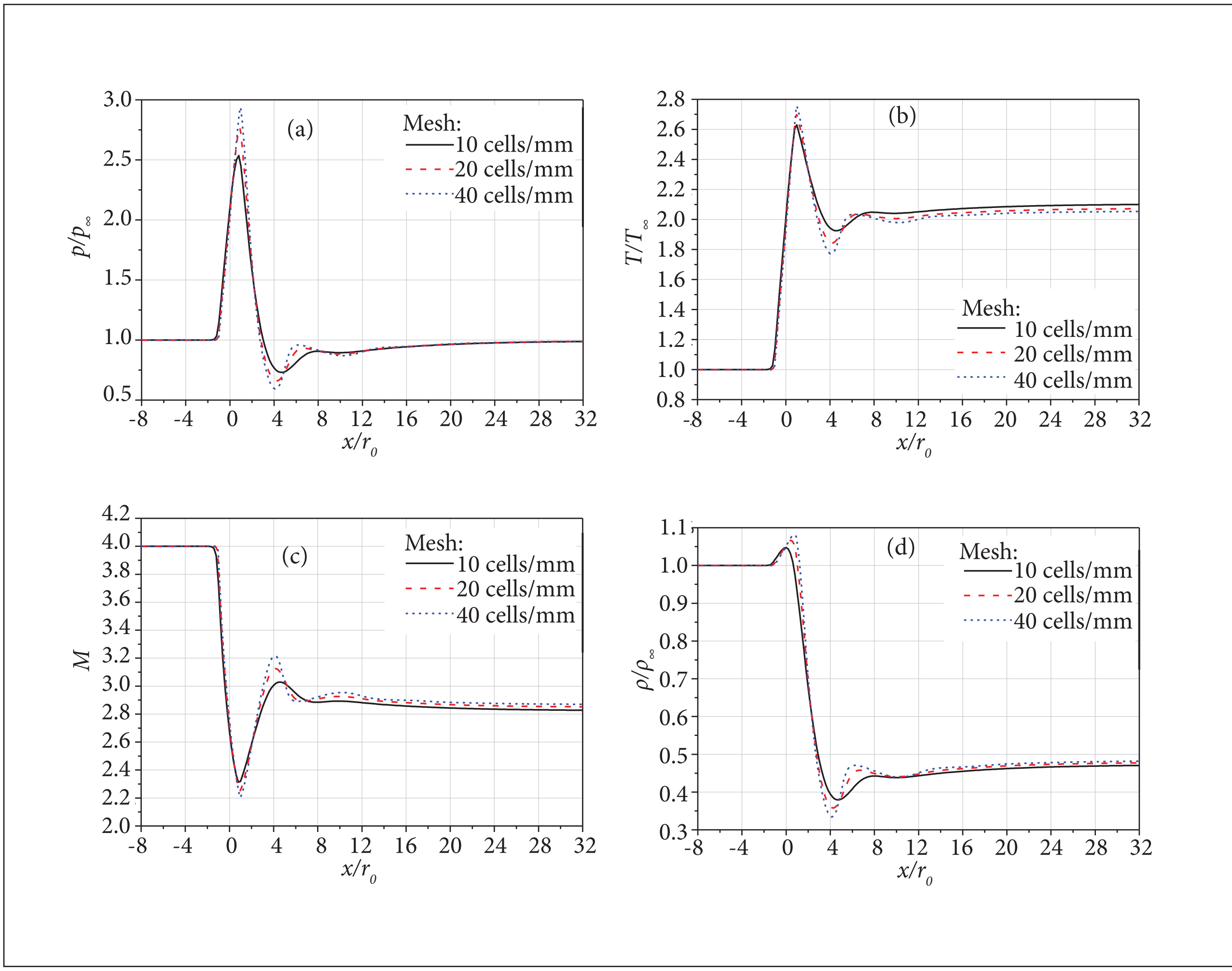

Figure 4. Changes in flow properties for different grids (Mach 4 free stream and 471 W heat source): (a) p/p_∞; (b) T/T_∞; (c) M; (d) ρ/ρ_∞.

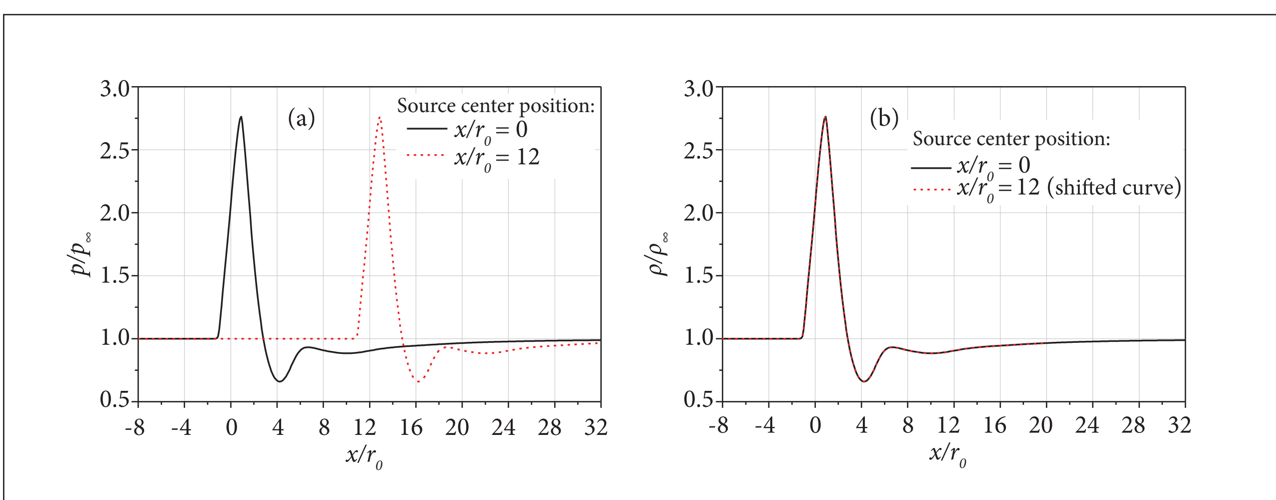

Figure 5. Pressure along the symmetry axis (Mach 4 free stream and 471 W) for different source center positions: (a) original distributions; (b) distribution when source center in x/r_0=12 is shifted 12 units of x/r_0 to the left.

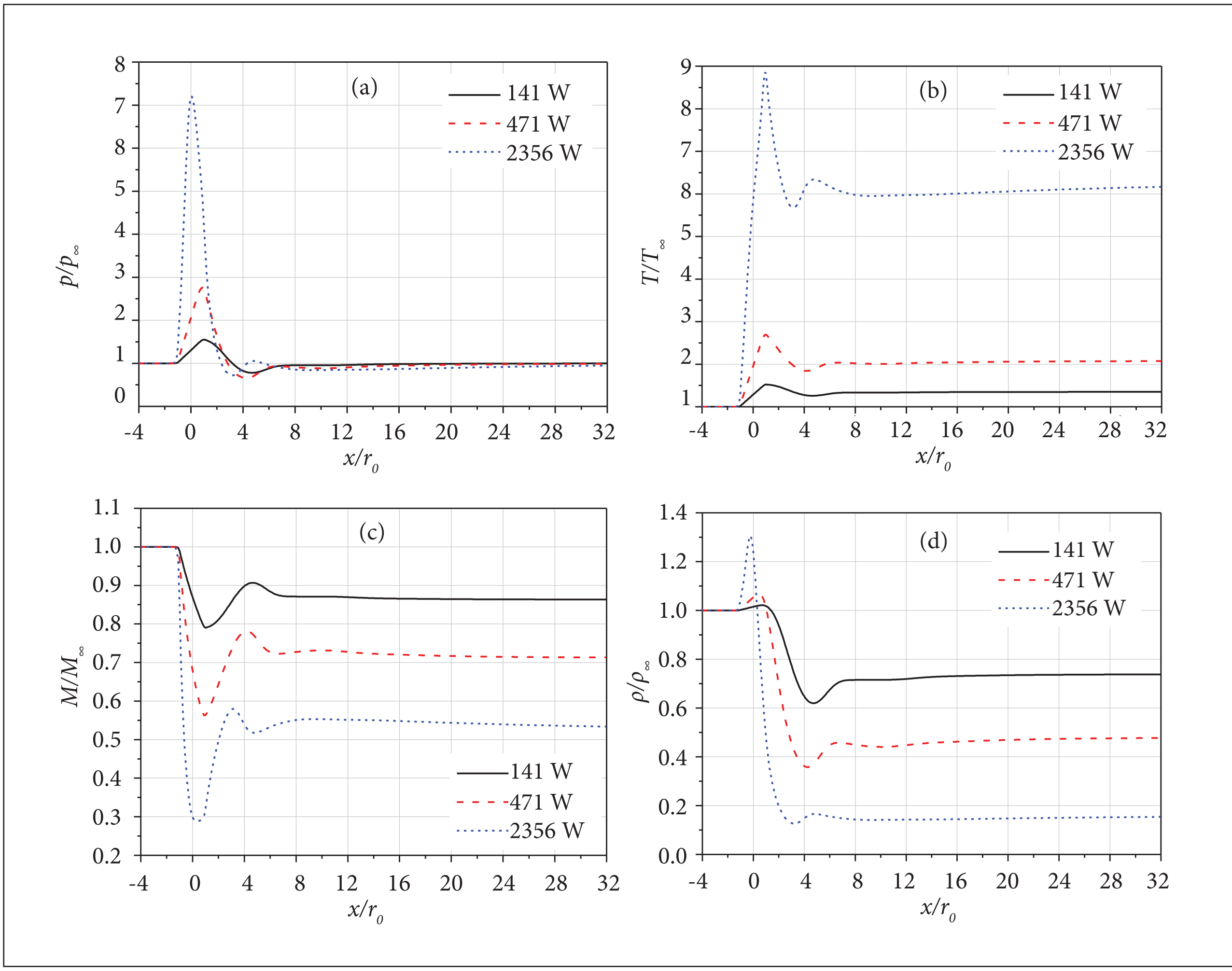

Figure 6. Changes in flow properties with the power (M_∞ = 4,0) along the symmetry axis: (a) p/p_∞; (b) T/T_∞; (c) M/M_∞; (d) ρ/ρ_∞.

It is observed in Fig. 6 that the higher the heat source power the more pronounced the effects on the flow properties, as previously discussed. In other words, increasing the source power, the pressure, temperature, and density also increase inside the heat source, making the flow compression higher and consequently diverting more flow obliquely to the symmetry axis. Furthermore, by increasing the source power, the expansion of the flow is more pronounced (higher variable changes) in the region immediately downstream to the source, although its length is not much affected by the source power for the same free stream velocity. Considering the effects on the flow for distances beyond the downstream expanding region, that is, where the pressure along the symmetry axis has already basically returned to its free stream value, it can be inferred from Figs. 6 and 7 that by increasing the power the axial length of the first region behind the source, where the flow properties are still changing, is not much affected (Fig. 6). The changes in temperature, Mach number and density get more pronounced inside the flow stream tube (Figs. 6 and 7), the radius of the stream tube gets only slightly bigger (Fig. 7), and the wave fronts get stronger and slightly faster (Figs. 7a and d).

EFFECT OF FREE STREAM FLOW SPEED

Another aspect to be considered in this study is the effect of the free stream flow speed on the flow properties with localized steady energy addition to the flow. Figures 8 and 9 show their results along, respectively, the symmetry axis and the right-hand boundary in Fig. 1, corresponding to three values for M_∞ (for the same free stream sound speed) and 471 W power added to the flow.

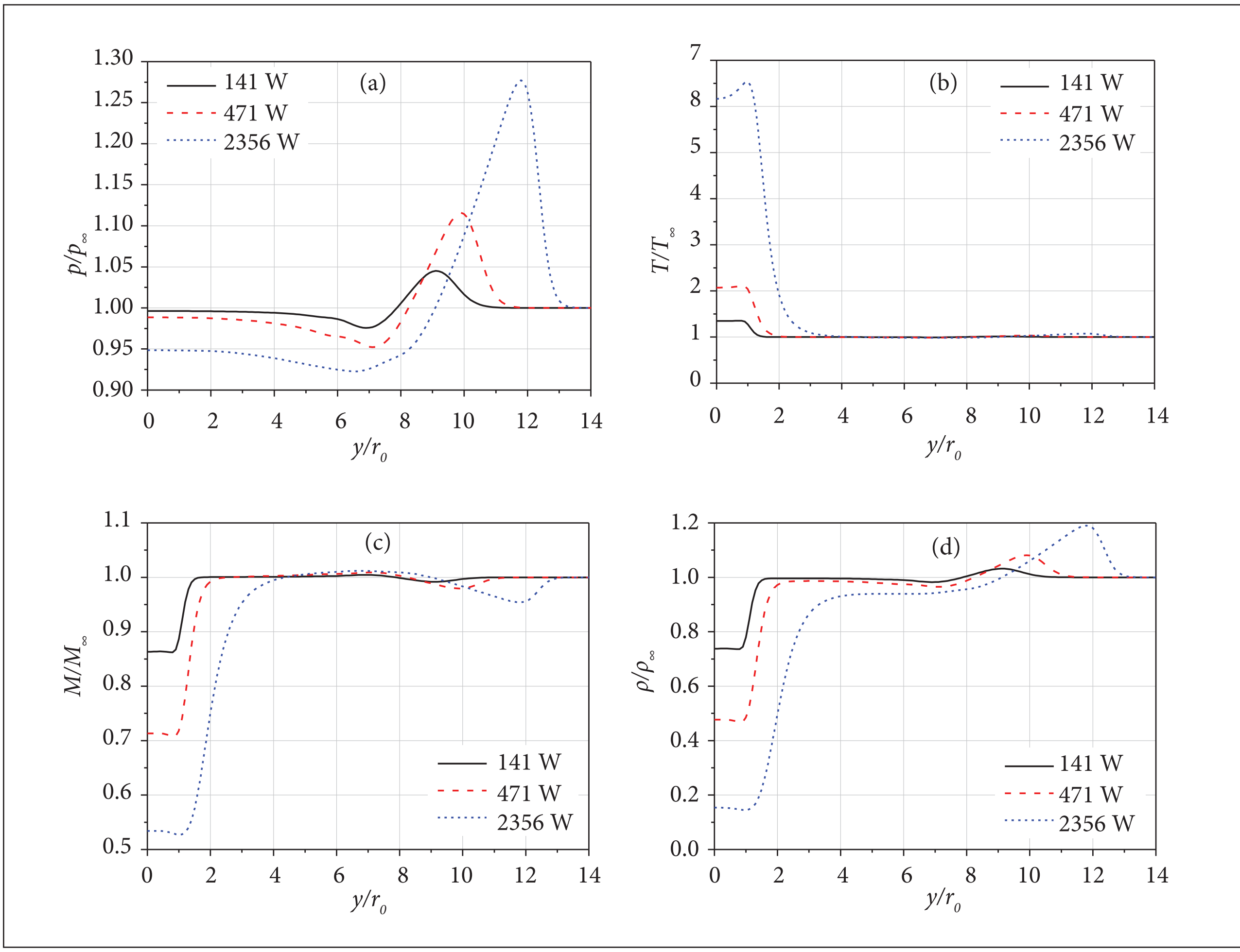

Figure 7. Change of flow properties (M_∞= 4.0) along the cross section plane at the right-hand boundary as a function of power: (a) p/p_∞; (b) T/T_∞ ; (c) M/M_∞; (d) ρ/ρ_∞.

The results in Fig. 8 confirm the trend already observed that the most significant variations of the flow properties occur basically inside the heat source and in a small distance downstream from it. Also, in Fig. 8, it can be seen that the expansion region is elongated for higher Mach numbers, due to the increase in the flow speed, which corresponds to the transport of changes in flow property to greater distances from the source before reaching almost constant values. When the free stream Mach number is higher, due to an increase in the free stream speed, the fluid residence time inside the heat source decreases and so does the rate of temperature change inside the source (lower peak) resulting in smaller alterations to the other flow properties not only inside the source but also downstream of it. For instance (Fig. 8), the Mach number and density reductions in the flow stream tube for M_∞=7 are about 10% smaller than for M_∞=4. Therefore, the higher the free stream velocity the higher should be the rate of energy addition to the flow to keep its property percent changes in the stream tube. Still, as observed in Fig. 9, the stream tube radius is basically not affected by the free stream velocity. However, as shown in Figs. 9a and c, the wave fronts reach the right-hand boundary in Fig. 1 at lower coordinates for higher free stream Mach numbers. This happens mainly because of the higher free stream flow velocity, since the local sound speed is basically the same for all cases. As a consequence, the diverted flow angle is smaller for higher free stream flow velocity. It is also interesting to mention that the strength of the wave fronts is not very affected by the free stream velocity, as can be seen in Fig. 9a.

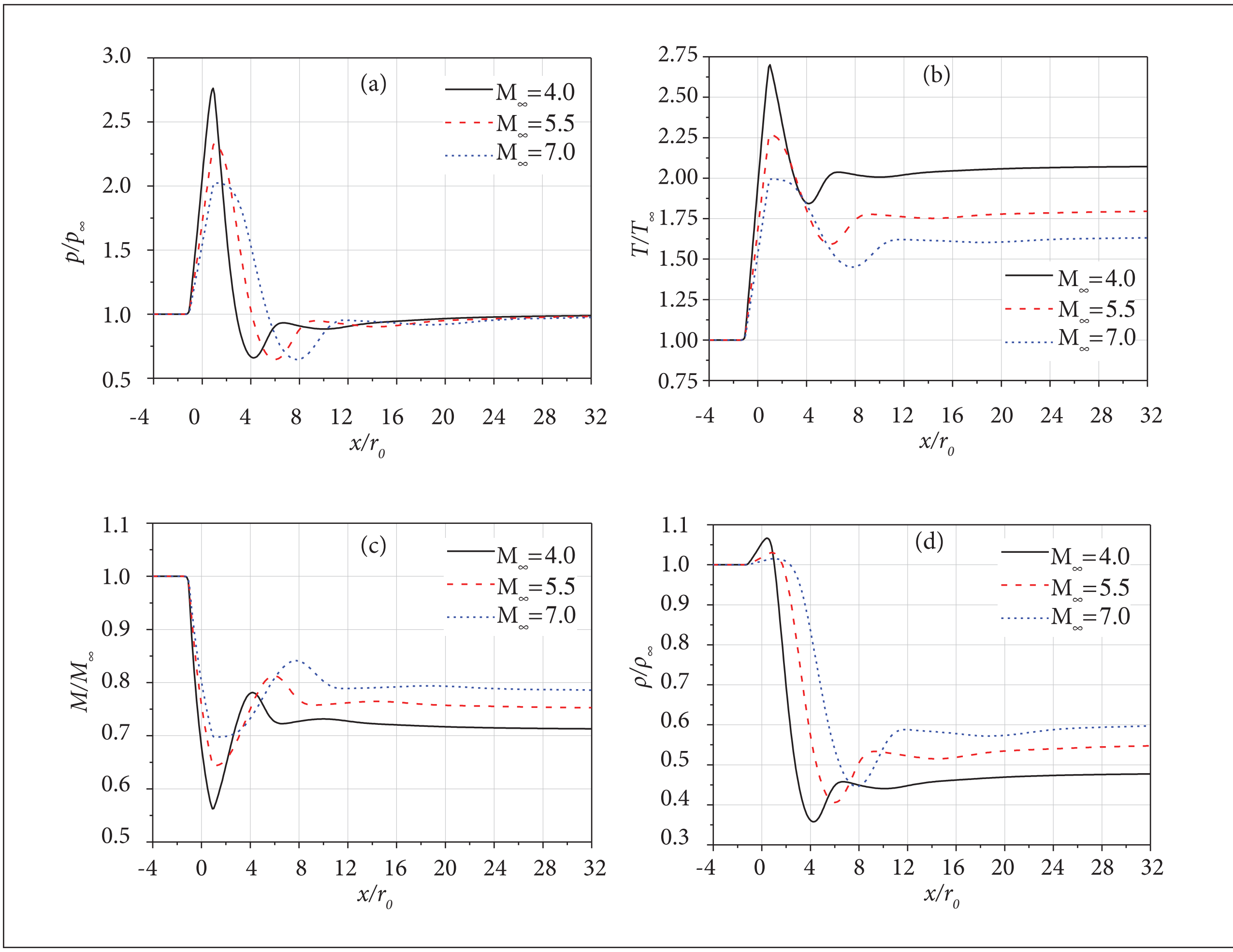

Figure 8. Flow properties (471 W heat source) along the symmetry axis as a function of free stream flow velocity: (a) p/p_∞; (b) T/T_∞; (c) M/M_∞; (d) ρ/ρ_∞.

EFFECTS OF ENERGY DEPOSITION DISPERSION (HEAT SOURCE SIZE)

This section presents the overall results of a study about the effects of the energy deposition dispersion on a supersonic flow. This will be treated here by considering different heat source sizes, that is, by varying the radius (r) and length (l) of the cylindrical source, taking as reference the heat source used in the previous sections (l_0=1.0 mm and r_0=0.5 mm; 471 W total power). For the sake of clarity, the cylindrical source size (length and radius) will be written in the normalized form ($l/l_0 \times r/r_0$). Four different cases have been considered: the reference source (1×1); the double length (2×1); the double radius (1×2); and the double length and radius (2×2). In terms of the source volumetric heat rate, considering that the reference source is q_0, then the others are $q_0/2$, $q_0/4$ and $q_0/8$, respectively.

Figures 10 and 11 show the flow property results along, respectively, the symmetry axis and the right-hand boundary in Fig. 1, corresponding to the four cases mentioned for a Mach 4 free stream and 471 W source total power.

As can be observed in these figures, the source length has very little effect on the main aspects of the flow behavior, although it seems that as the volumetric heat rate gets higher (reducing source radius), the source length begins to show some influence on the flow. On the other hand, the source radius has major effects on the flow behavior, for example, decreasing the source radius: the compression inside the source increases; the expanding region behind the source gets shorter but still about six times the source radius; the differences between the constant flow properties inside the flow stream tube and their respective free stream ones get even bigger; the

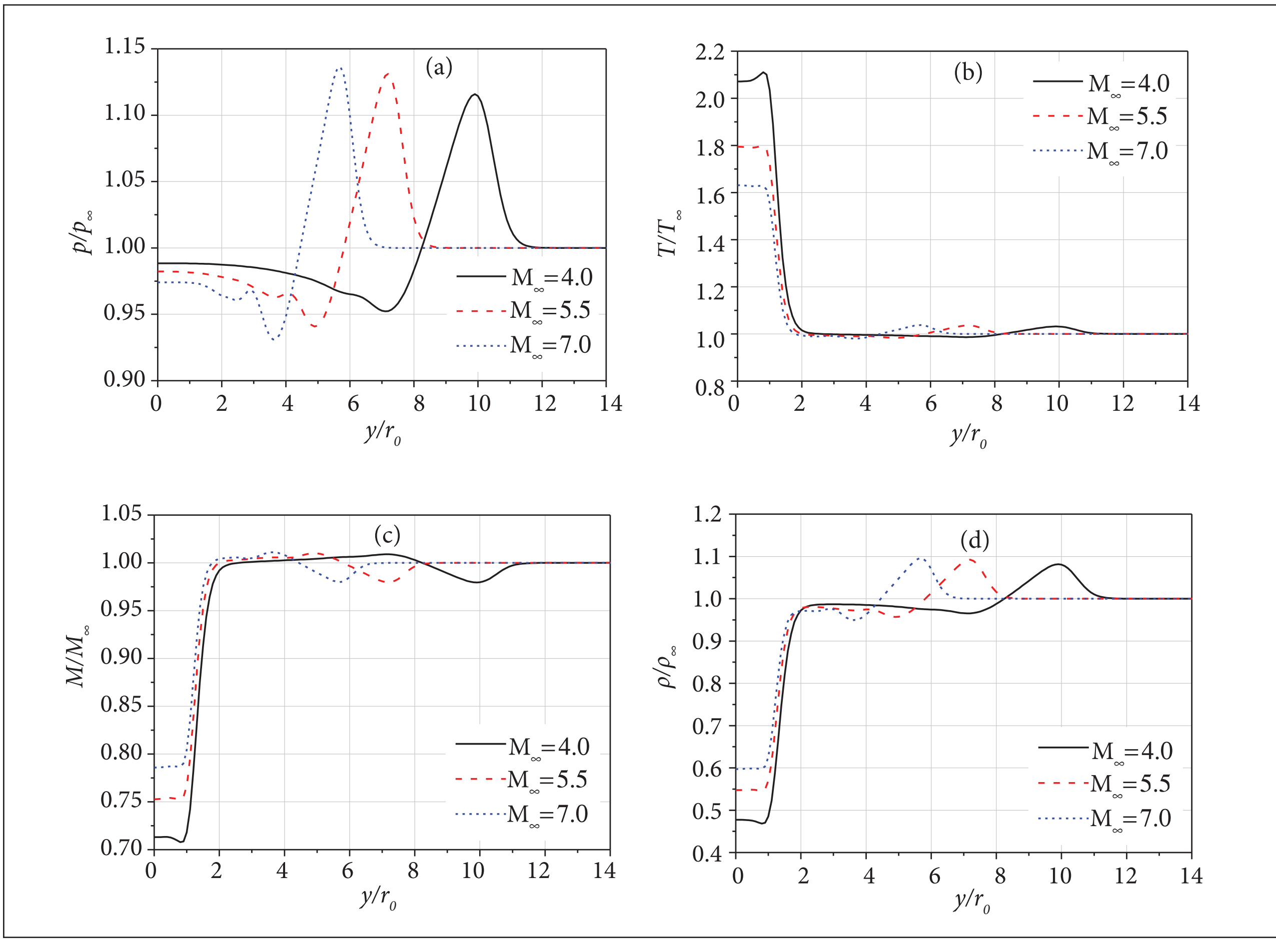

Figure 9. Flow properties (471 W heat source) along the cross-sectional plane at the right-hand boundary in Fig. 1 as a function of free stream flow velocity: (a) p/p_∞ ; (b) T/T_∞ ; (c) M/M_∞ ; (d) ρ/ρ_∞ .

flow stream tube radius is still about the source radius; and the wave fronts gain in strength but with unchangeable wave speed. In conclusion, energy deposition dispersion in the flow direction (x-direction) has little effect on the flow, except for small radial dispersion whereas dispersion in the radial direction (y-direction) has major impact on the flow.

COMMENTS AND CONCLUSIONS

This work has shown the effects on the flow structure of a localized and steady energy addition to uniform supersonic airflows, based only on thermodynamics and gas dynamics standpoints. The knowledge obtained here about the high-speed flow changes due to localized energy addition certainly will be of great importance for the subsequent studies related to the applications of energetics in hypersonics at the IEAv.

The results presented here show that a localized energy source in a uniform high-speed airflow can modify its path lines at oblique angles, generating compression wave fronts whose strength increases with the rate of energy deposition and also with the reduction in radial dispersion. Free stream velocity as well as axial dispersion has shown little effect on the wave front strength, although the oblique wave angle gets smaller for higher free stream speeds. The results have shown that the flow downstream to the heat source may be separated into two distinct regions: one just behind it, which is characterized by considerable flow property variations; and the other, that follows the first one, where the flow properties are basically constants but different from those of the free stream one, with the exception of the pressure that returns to its original value.

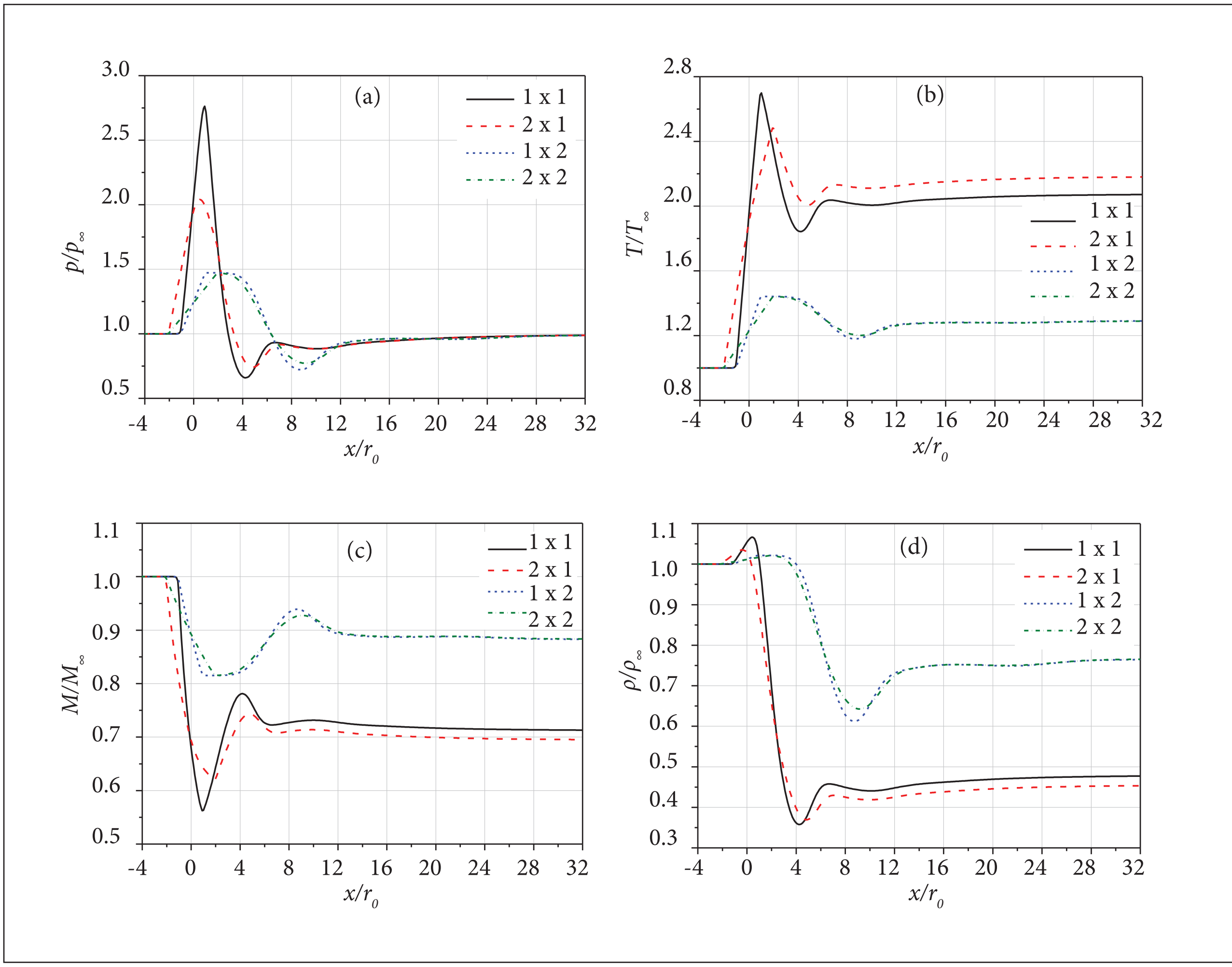

Figure 10. Flow properties (M_∞ = 4,0) along the symmetry axis of the energy source as a function of source geometry: (a) p/p_∞ ; (b) T/T_∞ ; (c) M/M_∞ ; (d) ρ/ρ_∞ .

Actually, this latter region is characterized by a long constant flow property stream tube aligned to the symmetry axis, of about the same source radius, with lower density and Mach number and higher temperature than their respective free stream values. Between these two regions and the wave fronts, the flow remains very close to the free stream one.

The outcomes have also shown that either increasing energy deposition rate, or reducing free stream speed as well as decreasing radial dispersion, has the effect of increasing the changes in the flow properties inside the source and in both mentioned regions around the symmetry axis. In contrast, axial dispersion has presented little effect on the flow, mainly when the radial dispersion is comparable or higher than the axial one. Another important parameter is the first region length, which increases substantially by increasing the free stream speed or source radius. Another interesting result is that for a fixed free stream speed, the length of this region is always given by a fixed number of source radius, for instance, for a Mach 4 free stream, this region length is approximately six times the source radius. Also, it is important to mention that the constant property stream tube radius has always approximately the source radius and is not much affected by source power, free stream speed, or axial dispersion.

It could be observed that the source radius (radial dispersion) has a major effect on the flow properties, whereas its length (axial dispersion) has a negligible one. Therefore, highly focused energy deposition, mainly in the radial direction, will always need less energy deposition rate. As the free stream speed increases, higher energy addition rate, or lower radial dispersion, is required to achieve about the same relative flow changes.

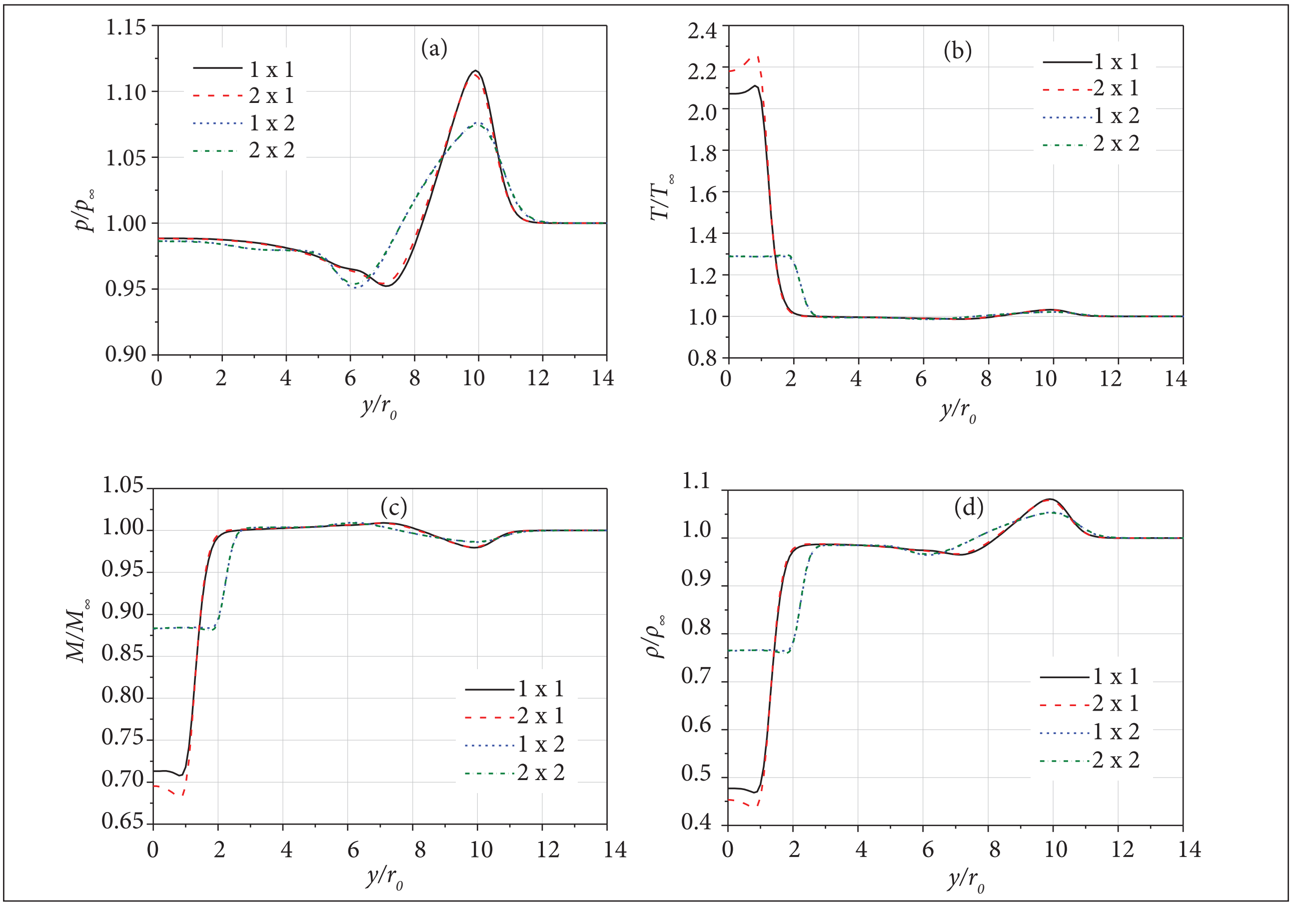

Figure 11. Flow properties (M_∞ = 4,0) in a cross-sectional plane at the right-hand boundary in Fig. 1 as a function of source geometry: (a) p/p_∞ ; (b) T/T_∞ ; (c) M/M_∞ ; (d) ρ/ρ_∞.

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