



A simplified cavity analysis for estimating energy coupling during laser ablation and drilling of solids – theory

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Abstract

A radiative cavity analysis is developed to estimate the change in laser energy coupling with a solid opaque target as a function of the cavity shape and size, and the heat transfer in a target. The approach of the analysis is to examine the departure in the net energy absorbed by a target due to the formation of a cavity, from that absorbed by a flat surface. The development of a general departure function, f , is presented, complete with the assumptions made and their implications on the resulting analysis. A specific f for a typical laser ablation process and common cavity geometry is also given in algebraic form. The meaning of the terms contained within f are discussed with respect to laser energy coupling in solids, and the range of validity of the theory is examined. © 1998 Elsevier Science B.V.

Keywords: Cavity analysis; Energy coupling; Laser ablation

1. Introduction

Many laser–material processes generate cavities, such as laser drilling of fine holes, micromachining, and repetitive solid sampling. The interaction between the laser light and the target material is often dependent on the amount of laser energy absorbed, particularly at high laser intensities. The amount of laser energy coupled to a material determines various factors, such as the amount of material removed and its temperature, phase, and degree of ionization. Moreover, both thermophysical and optical properties of the material and ambient medium depend on these factors, as well as the propagation of the laser

beam itself as it interacts with the ejecta. Regarding this work, it is a well-known phenomenon that laser energy coupling to a solid increases as a cavity is formed in the laser target. Unfortunately, the increase of laser energy coupling due to the presence of a cavity with respect to a flat surface is very difficult to predict. In general, laser energy coupling is highly non-linear and depends on the temperature, reflectivity, morphology, and material composition of the target, as well as the incident laser light and surrounding medium. Measuring laser energy coupling directly is not trivial, and separating various confounding factors can be quite difficult [1].

The author desired a way to obtain reasonable analytical estimates of laser energy coupling due to the formation of a cavity using easily obtained observables, without resorting to a full numerical analysis. The approach described in this article is to

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examine the departure in the net laser energy absorbed when cavities are formed. The basic concept is that if the net energy absorbed by a flat target can be estimated using the material's optical and thermal properties, plus the emission from the target, then the energy absorbed when a cavity is present can be estimated. The departure function, f , is defined as the ratio of the net laser energy absorbed in a cavity over the net energy absorbed on a flat surface. The observables required to compute f are the incident laser power, the thermal emission from the surface, and the size and shape of the cavity. A measure or estimate of the material's reflectivity is also required. A key result of this analysis is that when a cavity is irradiated, the net energy absorbed depends on *both* the geometry of the cavity *and* the heat that is transferred within the cavity.

2. Theoretical development

The analysis employs a straight-forward application of radiative heat transfer [2,3], with modifications specifically made for laser irradiation. Background theory is first presented, followed by the development of a departure function. The goal of the analysis is to provide a tractable and physically meaningful function that relates the net radiant heat absorbed by a cavity to the case when there is no cavity. The departure from the flat surface is defined as:

$$f \equiv \frac{q_{\text{net}}/q_{\text{in}}}{q_{\text{net}}/q_{\text{in}}|_{\text{flat}}} \quad (1)$$

2.1. Surface heat balance

For an opaque, diffuse, isothermal surface, shown conceptually in Fig. 1, the heat transfer in the solid at the k th surface, Q_k , is equal to the amount of absorbed radiation, $Q_{a,k}$, such that:

$$Q_k = Q_{o,k} - Q_{i,k} \rightarrow q_k A_k = A_k q_{o,k} - A_k q_{i,k}, \quad (2)$$

giving:

$$q_{o,k} = q_{i,k} + q_k$$

where $q_{i,k}$ is the incident radiative power per unit area, and $q_{o,k}$ is the radiosity. The radiosity $q_{o,k}$ can also be defined as the sum of the heat emitted from

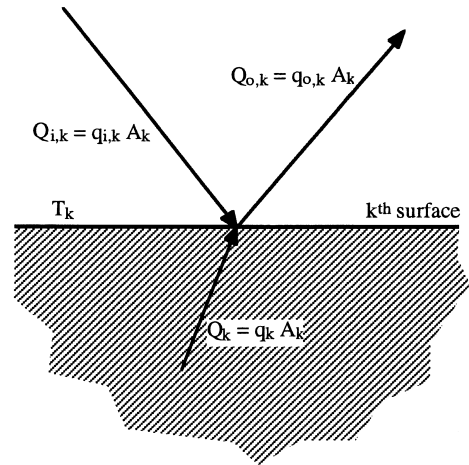


Fig. 1. Heat balance at an isothermal surface of an opaque solid.

the surface, $q_{e,k}$, and amount of incident heat reflected, $\rho_k q_{i,k}$, from the diffuse surface, or:

$$q_{o,k} = q_{e,k} + \rho_k q_{i,k} \quad (3)$$

where ρ_k is the total hemispherical reflectivity. The incident flux arrives from the radiosity from all other objects or surfaces, and that irradiated in from other sources, $q_{\text{in},k}$. For this work, $q_{\text{in},k}$ comes from the heat radiated from the surroundings and from the incident laser light. Note that in general, $q_{\text{in},k}$ is directional. The incident flux can be expressed as:

$$Q_{i,k} = A_k q_{i,k} = A_{\text{in}} q_{\text{in},k} + \sum_{j=1}^n A_j F_{j \rightarrow k} q_{o,j} \quad (4)$$

where $F_{j \rightarrow k}$ is the view factor from the j th to the k th surface. Applying reciprocity, $A_j F_{j \rightarrow k} = A_k F_{k \rightarrow j}$, the incident flux can be written as:

$$q_{i,k} = \frac{A_{\text{in}}}{A_k} q_{\text{in},k} + \sum_{j=1}^n F_{k \rightarrow j} q_{o,j}. \quad (5)$$

Eq. (5) explicitly shows the dependence of the incident flux on the laser irradiation and the radiosity from the other cavity surfaces. Eq. (5) is used indirectly to gage the validity of the following cavity analysis, as will be discussed in Section 3.

2.2. Cavity heat balance

For a cavity comprised of diffuse, isothermal surfaces, shown conceptually in Fig. 2, the net heat

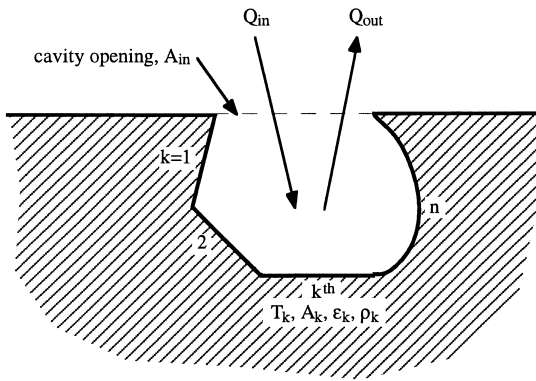


Fig. 2. Concept of an arbitrarily shaped cavity of n isothermal opaque surfaces.

balance can be simply written $Q_{\text{net}} = Q_{\text{in}} - Q_{\text{out}}$, where $Q_{\text{out}} = A_{\text{in}} q_{\text{out}}$. The outgoing heat flux, Q_{out} , is the sum of all the radiant power from each surface that leaves through the cavity opening, such that for n surfaces:

$$Q_{\text{out}} = A_{\text{in}} q_{\text{out}} = \sum_{k=1}^n A_k F_{k \rightarrow \text{in}} q_{o,k}. \quad (6)$$

Therefore, the ratio of the net heat flux passing through the cavity opening to the incident irradiation can be expressed as:

$$q_{\text{net}} = q_{\text{in}} - \sum_{k=1}^n A_k / A_{\text{in}} F_{k \rightarrow \text{in}} q_{o,k}. \quad (7)$$

An expression for $q_{o,k}$ is desired that depends on the emissivity from each surface, $q_{e,k}$, and the flux supplied to each surface due to heat transfer from all mechanisms other than thermal radiation, q_k . From Eqs. (2) and (3), the radiosity can be expressed as:

$$q_{o,k} = \frac{1}{1 - \rho_k} q_{e,k} - \frac{\rho_k}{1 - \rho_k} q_k \quad (8)$$

which when put into Eq. (7) yields:

$$\frac{q_{\text{net}}}{q_{\text{in}}} = 1 - \sum_{k=1}^n A_k / A_{\text{in}} F_{k \rightarrow \text{in}} \times \left(\frac{1}{1 - \rho_k} \frac{q_{e,k}}{q_{\text{in}}} - \frac{\rho_k}{1 - \rho_k} \frac{q_k}{q_{\text{in}}} \right). \quad (9)$$

The ratio of the net to the incident flux in Eq. (9) is derived for n isothermal, diffuse-gray surfaces, with no participating medium. This analysis can be

extended to non-isothermal cavities with continuously varying temperatures by writing the summation in Eq. (9) in an integral formulation, taking the limit as the number of surfaces $n \rightarrow \infty$ and the areas $A_k \rightarrow dA$. A more general formulation can be obtained which accounts for variations in irradiation, temperature, emission, and morphology, such that:

$$q_{\text{net}} = q_{\text{in}} - \int_{A_{\text{cavity}}} dA / A_{\text{in}} F_{dA \rightarrow \text{in}}(\mathbf{x}) \times \left(\sigma T^4(\mathbf{x}) - \frac{\rho(\mathbf{x})}{1 - \rho(\mathbf{x})} q(\mathbf{x}) \right) \quad (10)$$

where \mathbf{x} is the position in the cavity, and the emission follows a Stefan–Boltzmann relation, $q_e = \varepsilon \sigma T^4$, with ε being the total emissivity. Note that the temperature T and the heat flux q depend on the distribution in irradiation $q_{\text{in}}(\mathbf{x})$ even though Eqs. (9) and (10) explicitly show only the total q_{in} (c.f. Eq. (5)).

While Eqs. (9) and (10) are complete as written, they are not practical for determining the net laser energy coupling into an arbitrary cavity. Among the unknowns are the changing shape and size of the cavity, the temperature distribution and reflectivity of the cavity walls, and the heat transferred to each surface. Hence, we cannot directly compute q_{net} , even if A_{in} and q_{in} are reasonably known. However, the goal of this analysis is to provide an estimate of the energy coupling in a cavity with respect to a flat surface. For a flat surface, Eqs. (9) and (10) become:

$$\frac{q_{\text{net}}}{q_{\text{in}}} \Big|_{\text{flat}} = 1 - \sum_{k=1}^n A_k / A_{\text{in}} \times \left(\frac{1}{1 - \rho_k} \frac{q_{e,k}}{q_{\text{in}}} - \frac{\rho_k}{1 - \rho_k} \frac{q_k}{q_{\text{in}}} \right) = 1 - \nu \quad (11a)$$

or in integral form:

$$\frac{q_{\text{net}}}{q_{\text{in}}} \Big|_{\text{flat}} = 1 - \int_{A_{\text{in}}} dA / A_{\text{in}} \times \left(\frac{\sigma T^4(\mathbf{x})}{q_{\text{in}}} - \frac{\rho(\mathbf{x})}{1 - \rho(\mathbf{x})} \frac{q(\mathbf{x})}{q_{\text{in}}} \right) = 1 - \nu \quad (11b)$$

where v is a dimensionless heat transfer parameter defined by the second term in Eq. (11a) or Eq. (11b). Importantly, the only values v may take range from 0 to 1. To illustrate this, in the limit of zero reflectivity of a uniformly irradiated surface (where $A_k = A_{in}$) at steady-state, the ratio of $q_{net}/q_{in}|_{flat} = 1 - q_e/q_{in}$. When $q_e \ll q_{in}$, $v \rightarrow 0$ and when $q_e \rightarrow q_{in}$ (the maximum possible value for laser only heating), then $v \rightarrow 1$. Similarly, in the limit of total reflectivity (i.e., a perfect mirrored surface), the emitted radiation is due only to the finite temperature of the body, which must be supplied by heat transfer from the body (c.f. Fig. 1). Thus, $q = q_e$, leading to the same results for $q_{net}/q_{in}|_{flat}$ and v as with the perfect absorber. All other cases must fall between these same limits, provided that the analysis remains valid.

The amount of energy coupled to a cavity with regards to the departure functioned defined in Eq. (1) is estimated as $q_{net}/q_{in} = f q_{net}/q_{in}|_{flat}$ with f now of the form:

$$f = \frac{1}{1-v} \left[1 - \sum_{k=1}^n A_k/A_{in} F_{k \rightarrow in} \times \left(\frac{1}{1-\rho_k} \frac{q_{e,k}}{q_{in}} - \frac{\rho_k}{1-\rho_k} \frac{q_k}{q_{in}} \right) \right] \quad (12a)$$

or:

$$f = \frac{1}{1-v} \left[1 - \int_{A_{in}} dA/A_{in} F_{dA \rightarrow in} \times \left(\frac{\sigma T^4(x)}{q_{in}} - \frac{\rho(x)}{1-\rho(x)} \frac{q(x)}{q_{in}} \right) \right]. \quad (12b)$$

Note that as $v \rightarrow 0$, the departure from the flat case is not zero, in general. Furthermore, as $v \rightarrow 1$, the departure grows without bound. As will be discussed later, when $v \rightarrow 1$, the validity of the analysis breaks down, thus $f \rightarrow \infty$ is not physically meaningful.

Eqs. (12a) and (12b) are fairly general departure functions which can be computed for various laser irradiated cavities. To compute f , we must now fully describe the conditions for the laser irradiated cavity, including the temporal and spatial intensity distribution of the incident laser light. In practice, though, computing f requires more knowledge of the laser-material interactions than is generally available. However, some broad, physically reasonable as-

sumptions can be made that simplify the analysis considerably, giving results that can help accurately describe the effect of cavity formation on laser energy coupling. To illustrate, a special case for calculating f from Eq. (12a) is shown below since the essential aspects remain in the discrete formulation, making the analysis more tractable for finding analytical solutions. More complicated laser conditions (i.e., a cw Gaussian laser beam drilling a deep hole) can also be calculated from Eq. (12b) using numerical methods, but this case is beyond the scope of this article.

2.3. Example

The example is a fairly typical case of UV laser ablation of a solid target, which starts at a flat surface and ablates a circular cavity as the laser is repetitively pulsed. The laser beam is apertured and has a top-hat intensity profile. The laser beam is focused through a lens to uniformly irradiate the base of the laser cavity, which is placed before the focal plane. As shown in Fig. 3, the cavity is mod-

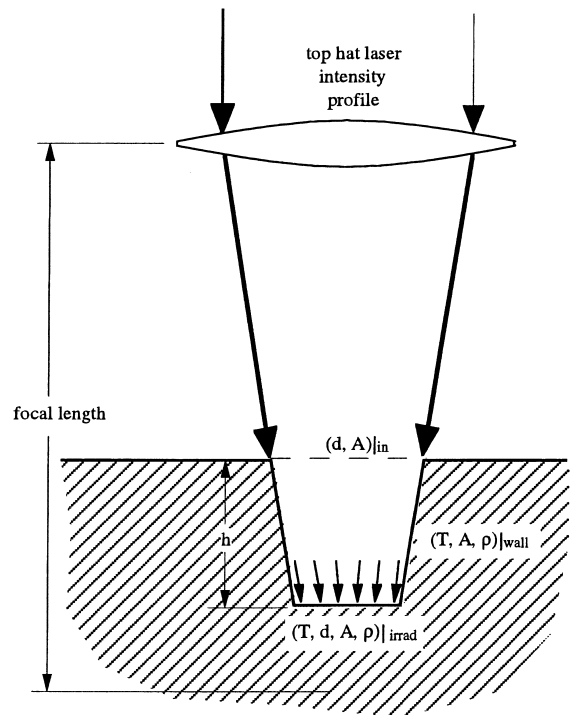


Fig. 3. Model of top-hat laser profile abating a truncated conical cavity. The irradiated surface is assumed to be the base of cavity.

eled as a truncated cone due to the converging focus. The UV laser light is assumed to negligibly interact with the gaseous medium in the cavity (i.e., $\omega_{\text{laser}} \gg \omega_{\text{plasma}}$), so that the assumption of non-participating medium is approximately valid. The laser pulse is also assumed to be short enough ($\tau_p < 100$ ns) that heat diffusion through the solid target from one cavity surface to another is negligible during the laser pulse, even for good thermal conductors such as copper. For poor conductors, pulse lengths can be considerably longer and the results to follow will still apply. For repetitive pulsing, the time between pulses is also assumed to be large ($> 10\tau_p$) compared to the pulse length so that significant overall heating of the cavity is minimized. The change in shape of the cavity during each pulse is neglected.

The first task in computing f is to evaluate v . Since the assumed laser beam has uniform intensity, the flat surface is irradiated uniformly, thus $A_{k=\text{irrad}} = A_{\text{in}}$. Application of either Eq. (11a) or Eq. (11b) gives the same result, assuming that radial transfer of heat can be safely neglected during the laser pulse as discussed above, giving:

$$v = \frac{1}{1-\rho} \frac{q_e}{q_{\text{in}}} - \frac{\rho}{1-\rho} \frac{q}{q_{\text{in}}} = \frac{\sigma T_s^4}{q_{\text{in}}} - 1 \frac{\rho}{1-\rho} \frac{q}{q_{\text{in}}} \quad (13)$$

where T_s is the average temperature of the surface and ρ is the total reflectivity at T_s . The heat transfer parameter can be estimated from Eq. (13), if T_s , ρ , and q can be evaluated. T_s and ρ can be estimated from optical pyrometer and reflectivity measurements, or from values given in the literature. The heat transfer to the target, q , is more difficult to estimate without performing a full heat transfer analysis, though several assumptions can give reasonable bounds on the estimates. Assuming an adiabatic surface ($q = 0$) will give a lower bound on v . Assuming that all the energy that goes toward changing phase from solid to liquid and vapor ($q = (-)\dot{m}h_{sv}$) is transferred *into* the target will give an upper bound. However, by plotting the solutions vs. v , the qualitative behavior on f is clearly seen, as will be shown in Section 3.

For the walls of the conical cavity, the heat transfer term is approximately zero compared to the

irradiated surface and q_{in} , and for this special case can be neglected. To verify this claim, consider the difference in the heat transfer parameter Δv_j between the irradiated surface and the j th surfaces, defined as:

$$\Delta v_j = \frac{1}{1-\rho_j} \frac{\Delta q_{e,j}}{q_{\text{in}}} - \frac{\rho_j}{1-\rho_j} \frac{\Delta q_j}{q_{\text{in}}} \quad (14a)$$

where:

$$\Delta q_{e,j} = q_{e,j} - \frac{1-\rho_j}{1-\rho_{\text{irrad}}} q_{e,\text{irrad}}$$

and

$$\Delta q_j = q_j - \frac{\rho_{\text{irrad}}}{\rho_j} \frac{1-\rho_j}{1-\rho_{\text{irrad}}} q_{\text{irrad}}. \quad (14b)$$

For high-power short-pulse laser material interactions, the temperature of the non-irradiated j th surface is on the order of temperature of the solid target ($O(300$ K), and the temperature of the irradiated surface is generally much higher, $> O(1000$ K). Due to the T^4 dependence on emissive power, $q_{e,\text{irrad}}$ is four or more orders larger than $q_{e,j}$. Similarly, the heat transferred at the surface is due primarily to the temperature gradient and phase change. Again, the irradiated surface generally sees orders of magnitude higher temperature gradients and mass removal than the non-irradiated surfaces. Thus, the irradiation terms in Eq. (14b) will be orders of magnitude larger than the j th terms, unless $\rho_{\text{irrad}} \rightarrow 0$ and $\rho_j \rightarrow 1$. Practically, these constraints on reflectivity do not occur. Additionally, both $q_{e,j}$ and q_j are orders of magnitude smaller than the incident laser intensity, q_{in} , for high-power laser beams. Combine these effects and the non-irradiated walls of the cavity may be safely neglected in computing f for this case considered.

Therefore, following these arguments, the summation in Eq. (12a) is now over m irradiated surfaces, such that $k = \text{irrad}$ and $n = m$ irradiated surfaces. Similarly, the area of integration in Eq. (12b) is now over A_{irrad} , rather than the entire cavity. Even with these modifications, Eqs. (12a) and (12b) are still quite general. While greater accuracy is obtained if

they are numerically computed with the coupled heat transfer calculations, a key assumption is now made to obtain an analytical solution for this example. One may argue that for a non-participating medium, if the laser intensity is approximately the same at the top and base of the cavity, the difference in heat transfer between the irradiated surface and the flat surface case is very small, i.e., $T_{\text{irrad}} \approx T_s$, and $q_{\text{irrad}} \approx q_s$. For this special case, Eqs. (12a) and (12b) simply become:

$$f = \frac{1 - a}{1 - v} + a \tag{15}$$

where a is a purely geometric factor given by:

$$a = \sum_{k=\text{irrad}}^m A_k/A_{\text{in}} F_{k \rightarrow \text{in}}$$

or

$$a = \int_{A_{\text{irrad}}} dA/A_{\text{in}} F_{dA_{\text{irrad}} \rightarrow \text{in}} \tag{16}$$

Evaluating the departure function is now as straight-forward as computing a and v . For the truncated cone, a can be shown to be, using the view factor between two collinear disks [2]:

$$a = \frac{1}{2 d_{\text{in}}^2} \left\{ d_{\text{irrad}}^2 + d_{\text{in}}^2 + (2h)^2 - \sqrt{(d_{\text{irrad}}^2 - d_{\text{in}}^2)^2 + 2(d_{\text{irrad}}^2 + d_{\text{in}}^2)(2h)^2 + (2h)^4} \right\} \tag{17}$$

where d_{in} , d_{irrad} , and h are shown in Fig. 3. Note that a can only take on the values $0 \leq a < 1$. Some limits on f that are of interest are: (i) the flat cavity – $h \rightarrow 0$ gives $f = 1$ regardless of v , i.e., there is no departure; (ii) the deep cavity – $h \rightarrow \infty$ gives $f = 1/(1 - v)$ such that $1 \leq f < \infty$, i.e., there can be a large departure, depending on v as will be discussed later; and (iii) the cavity due to a sharply focused beam – $d_{\text{irrad}} \rightarrow 0$ gives the same result as the deep cavity, regardless of h (though the assumption of approximately equal intensities top and bottom is no longer strictly valid). To give an lower bound estimate for v , we can set $v \leq \sigma T_s^4/q_{\text{in}}$ using an esti-

mate or measurement of T_s . If the mass, m , removed during a laser pulse can be estimated, then an upper bound estimate is $v \leq \sigma T_s^4/q_{\text{in}} + m/\tau_p h_{\text{sv}}/q_{\text{in}}$, where h_{sv} {kJ/kg} is the energy required for phase change from a solid to a vapor for the material being considered. The positive sign on the second term results from negative sign on $(-)$ h_{sv} due to phase change.

3. Results and discussion

A major result of this analysis is that not only is geometry important in energy absorption by a cavity, but the heat transfer that occurs at a surface is also important in determining the net absorption, as seen in both the numerators and denominators of Eqs. (12a) and (12b). The simplified departure function f for the example above is plotted in Fig. 4 vs. the non-dimensional heat transfer parameter v . The values that f may take are shown in the shaded area, bounded by the limits given above. Note that as $v \rightarrow 1$, f appears to $\rightarrow \infty$, implying that q_{net} for the cavity is infinitely larger than $q_{\text{net}}|_{\text{flat}}$. However, the maximum q_{net} can reach is q_{in} , thus, if $q_{\text{net}}|_{\text{flat}}$ is finite, then f must be finite. The other condition where $v = 1$ is when $\rho = 1$. In this case, the emission is only due to the heat transferred to the surface, and thus, is not a physically valid limit. How close v

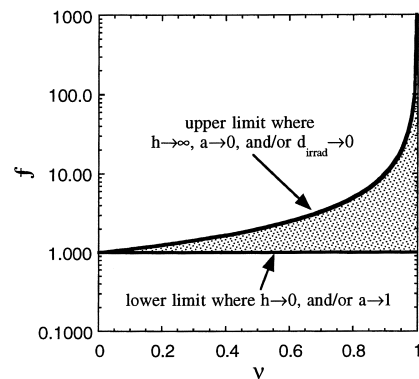


Fig. 4. The departure function f plotted as a function of the heat transfer parameter v for the special case detailed in text. The shaded area shows the region of validity, and the upper and lower bound limits are shown by the solid lines.

can approach 1 and still keep the analysis valid is an open question; however, Fig. 4 clearly shows the effect of heat transfer on laser energy coupling in a cavity. As more heat is thermally radiated and transferred non-radiatively, the greater the effect that a cavity has on laser energy coupling to the target. This increase is due to the cavity recapturing heat that would otherwise be lost to the surroundings, as is the case with flat surfaces. Of course, determining this non-linear relationship between q_k and q_{in} will improve the estimate of $f=f(v)$ beyond bracketing v by the upper and lower bounds given above.

Fig. 4 also shows the bounds on f due to the geometry of the cavity. Infinitely deep cones and sharp cones absorbed the maximum possible irradiation for a given v . Fig. 5 shows explicitly the effect of the aspect ratio, h/d_{in} , on f for cone cavities. Departures for three different v (0.1, 0.5, and 0.9) are plotted between the two limits for converging cones, the sharp cone and right cylinders, at aspect ratios ranging from 0 to 5. One clear trend that is apparent is that the departures grow rapidly with increasing aspect ratio, and essentially reach an asymptote by h/d_{in} of 5. The asymptotic limit is defined by the sharp cone case. Therefore, the greatest rate of change in laser energy coupling from the flat case occurs just as the cavity is formed.

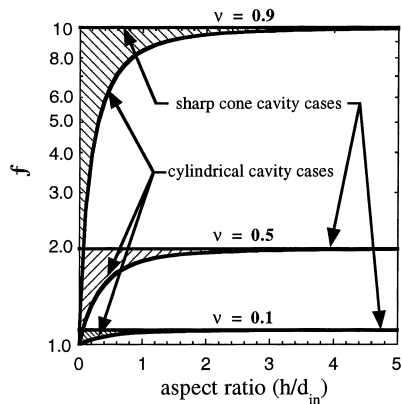


Fig. 5. The departure function f plotted as a function of the aspect ratio of the cavity for three different heat transfer parameters v . Two limits of the truncated cone, the sharp cone and the cylinder cases are plotted in dark lines, with all other cones shown by hatches between the limiting cases.

An important question is the range of laser intensities for which this analysis is valid. At low intensities, the main issue is the length of irradiation. If significant heat transfer occurs between the cavity walls, the simplified analysis will tend to over predict the departure, and is no longer valid. To obtain more reasonable estimates, Eqs. (12a) and (12b) must be solved more generally considering heat transfer analysis. At high laser intensities, the main issue is the temperature of the laser-induced plume inside the cavity. High-temperature plumes, but where $\omega_{laser} \gg \omega_{plasma}$ still holds, emit significant energy across a broad spectrum. The incident radiation at each surface of the cavity given in Eq. (5), $q_{in,k}$, not only comes from the summation of radiosity terms, but will now receive significant energy from the plume itself. This additional heating effect can act to increase the departure from the flat case, particularly for high aspect ratio cavities. Therefore, the above simplified case will tend to under predict the energy coupling. At even higher temperatures, when significant plasma shielding occurs as $\omega_{laser} \rightarrow \omega_{plasma}$, then $q_{in,k}$ becomes diffuse, and Eq. (5) and the subsequent analysis breaks down. The simple formulation is no longer valid. Adjustments to the general formulation are possible to account for a diffuse source of a radiatively participating medium, but is beyond the scope of this article.

A final point on this analysis is that a coupling exists between the cavity depth and size, and the heat transfer that affects the net energy absorption. As seen in Fig. 5, as the aspect ratio (h/d_{in}) increases, so does f and thus, the amount of energy absorbed, albeit slowly for small v . However, in Fig. 4, we can see that as f increases, the tendency is for v to increase, thereby increasing the amount of energy absorbed. Clearly, this coupling between geometry and heat transfer can, under certain circumstances, drive the net laser energy absorbed rapidly forward until breakdown occurs. This analysis may help explain some well-known instabilities of laser material interactions near the physical ablation threshold, if a cavity begins to form due to damage.

The author hopes that other investigators find this simplified cavity analysis of laser–energy coupling useful. A subsequent paper will compare the theory with experimental results, and will detail the techniques used to predict laser energy coupling within a

cavity, along with a first order stability analysis with respect to cavity formation.

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