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DENSITY INHOMOGENEITY IN A LASER CAVITY DUE TO ENERGY RELEASE

by

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ABSTRACT:

Density gradients, which refract laser light within the cavity, degrade beam quality. In addition to wall influences and viscous effects which cause density gradients, there is another mechanism. This mechanism, which is due to wakes and compression waves from heat (vibration energy to translation and rotation) addition in a supersonic stream, appears to have been overlooked. The appropriate equation is stated and discussed. A semigraphical solution procedure is outlined. Contours of constant density have been calculated for circular and rectangular cavities. Graphs of the isodensity contours are given.

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DENSITY INHOMOGENEITY IN A LASER
CAVITY DUE TO ENERGY RELEASE

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Beam quality is degraded when there are density gradients in the lasing medium. The density gradients refract the light within the cavity. Considerable effort has been devoted by engineers and scientists working with gas dynamic lasers to measure and correct density variations arising from wakes, boundary layers and wall irregularities. Another mechanism exists to cause density gradients, and it appears that this mechanism has been overlooked or ignored.

Heat addition in a supersonic stream causes compression waves which radiate from the energy release region. When the laser radiation is created by stimulated emission (e.g. CO_2 laser), there is also a transfer of vibrational energy to translational and rotational degrees of freedom. This is effectively heat addition and can be treated as a energy-per-unit-volume-and-per-unit-time term in the energy equation.

Using the results from the paper by Tsien and Bielock [(1)], the following equation can be derived[(2)] for distributed energy sources

$$\frac{\Delta\rho(x,y)}{\rho} = \frac{(\gamma-1)M}{2a^3\beta\rho} \int_0^S h(x,y)\sin\mu\, dS - \frac{\gamma-1}{a^2 U\rho} \int_{x'}\int_{y'} h(x',y')\,\delta(y-y')\,I(x-x')\,dx'\,dy' \tag{1}$$

Equation (1) is applicable to a planar geometry; planes normal to the beam are considered. The symbols have the following meaning;

γ	ratio of heat capacity of lasing medium
M	Mach number
a	local speed of sound
β	$(M^2-1)^{\frac{1}{2}}$
ρ	density
$h(x',y')$	energy released at (x',y') per unit at volume and unit time
μ	Mach angle equal to arcsin of 1/M
S	distance along a characteristic
U	local flow velocity
$\delta(y-y')$	delta function
$I(x-x')$	unit function, zero for $x-x' < 0$ and unit for $x-x' > 0$

The first integral yields the density variation along a characteristic. When h(x,y) = constant, the change in density is proportional to the length of characteristic imbedded within the energy release region. When h(x,y) is variable, the element of characteristic length dS is weighted by h(x,y).

The second integral results from the wake of the energy release region. Note that it is opposite in sign to the first integral. The change in density is proportional to the length of streamline imbedded in the energy release zone upstream of the observation point. This is true if h(x,y) is a constant. These facts concerning the proportionality of $\Delta\rho/\rho$ to the length of characteristic and streamline traversing the energy release region suggest a semigraphical calculation procedure. This is illustrated in Figure 1 for point P with a flow at $M = 4$. As illustrated, the right running characteristic R has a length of 7.0, the wake streamline W has a length of 8.5, and the left running characteristic L, a length of 10.2. The length of characteristics must be multiplied by $\sin \mu$. It has been assumed that $h(x,y)$ is a constant within the circle and zero outside the circle. Waves reflected from the walls have been neglected.

It is necessary to evaluate the value of h for typical laser operating conditions. A gas dynamic laser has an efficiency of approximately 1 percent based on the chemical energy which increased the medium temperature from a room value to $1500^{\circ}K$ or so. The increase in enthalpy of the gas mixture is 550 BTU/lbm. Consider the flow of gas through a volume with a shape of a cube having 1 ft sides. For typical conditions this gives a flow of 40 lbm/sec through the cube. Assume the cube is the laser cavity and that 1 percent of the energy is removed as radiation. A CO_2 laser has a quantum efficiency of 40%. It is assumed that 1.5% of the energy, which had been frozen in vibration, is transferred to translation and rotation. For these conditions h has a value of 330 BTU/sec ft^3. Using appropriate values for M, a, ρ, etc., it is found that

$$\frac{\Delta\rho}{\rho} = 0.023 \text{ per foot of characteristic length}$$

and

$$\frac{\Delta\rho}{\rho} = -0.052 \text{ per foot of streamline in cavity}$$

Using these values of $\Delta\rho/\rho$ per foot of length, the density contours were calculated for both a square and a circular cavity. Figure 2 shows the results for a circular cavity. Flow is from left to right. At the top of the cavity there is a region of large positive $\Delta\rho/\rho$ due to the fact the wake is small and the left running characteristic within the cavity is long. At the extreme downstream edge of the cavity $\Delta\rho/\rho$ is large negative. For this position there is a long wake within the circle which dominates the compression due to characteristics. At the top of the cavity the 0, +.001, +.002, and +.003 contours have a slope nearly equal to the slope of a left running characteristic. This causes a near loop in the +.003 contour.

In Figure 3 the feature most readily obvious is the slope of the density contours in the upper part of the figure. These might be diagnosed as resulting from waves originating at the upper wall. However, these are due to energy release in a supersonic stream. Along the upper surface the density decreases going downstream. Along the laser centerline the density increases slightly as one moves downstream. In the upper downstream corner there is a strong density gradient.

The analysis of this note has focused on two cases where h(x,y) is constant. For the circular case with a real laser, the value of h is best described as Gaussian. This solution is straightforward but extremely tedious. A computer program seems appropriate for the problem of variable h(x,y).

This note has demonstrated that the energy release can cause $\Delta\rho/\rho$ values somewhat less than viscous flow effects but nonetheless significant. Furthermore, since the $\Delta\rho/\rho$ may be oriented nearly along characteristics, these may be confused with waves originating at a wall.

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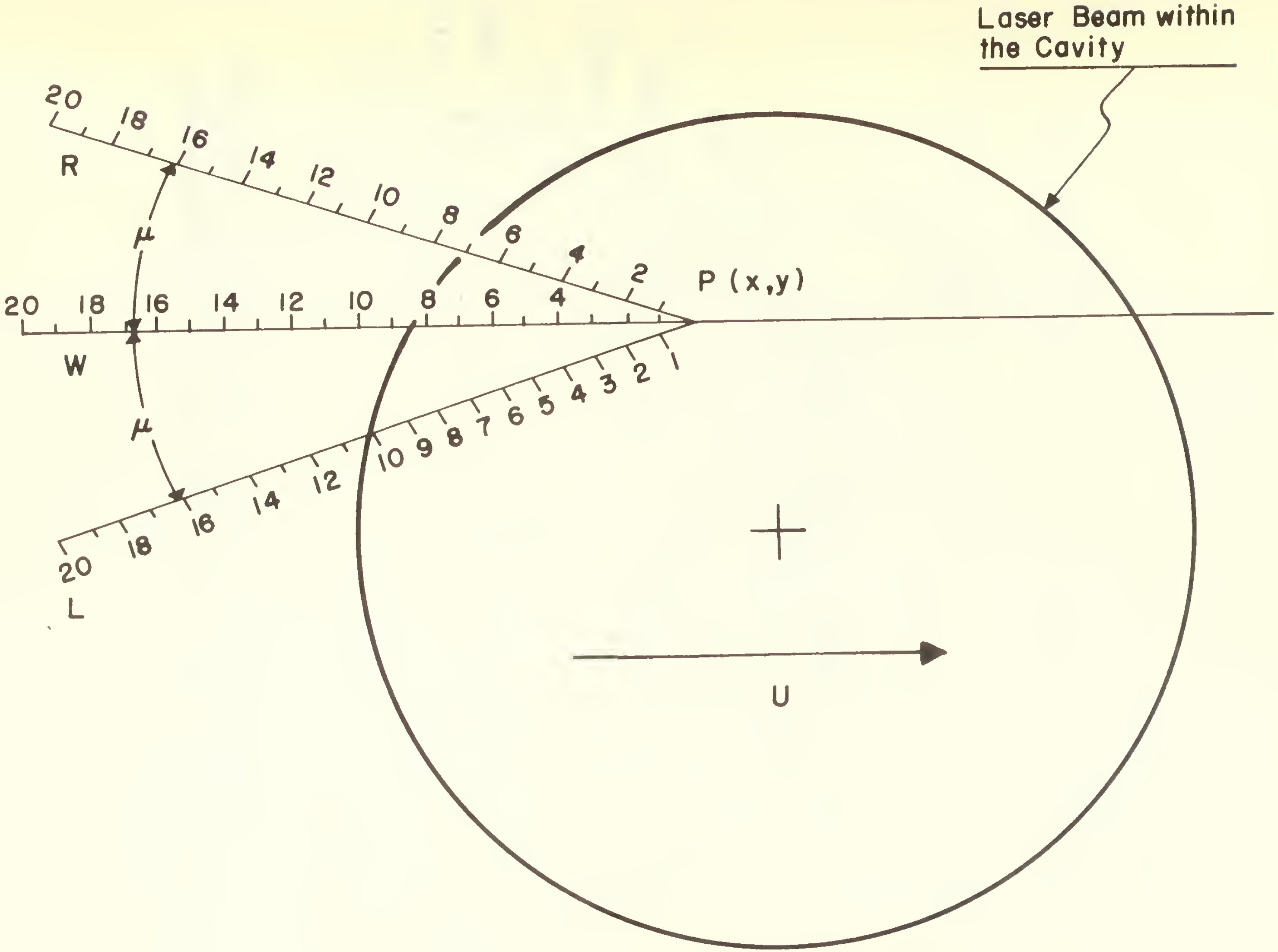

Fig. 1. Illustration of computational procedure.

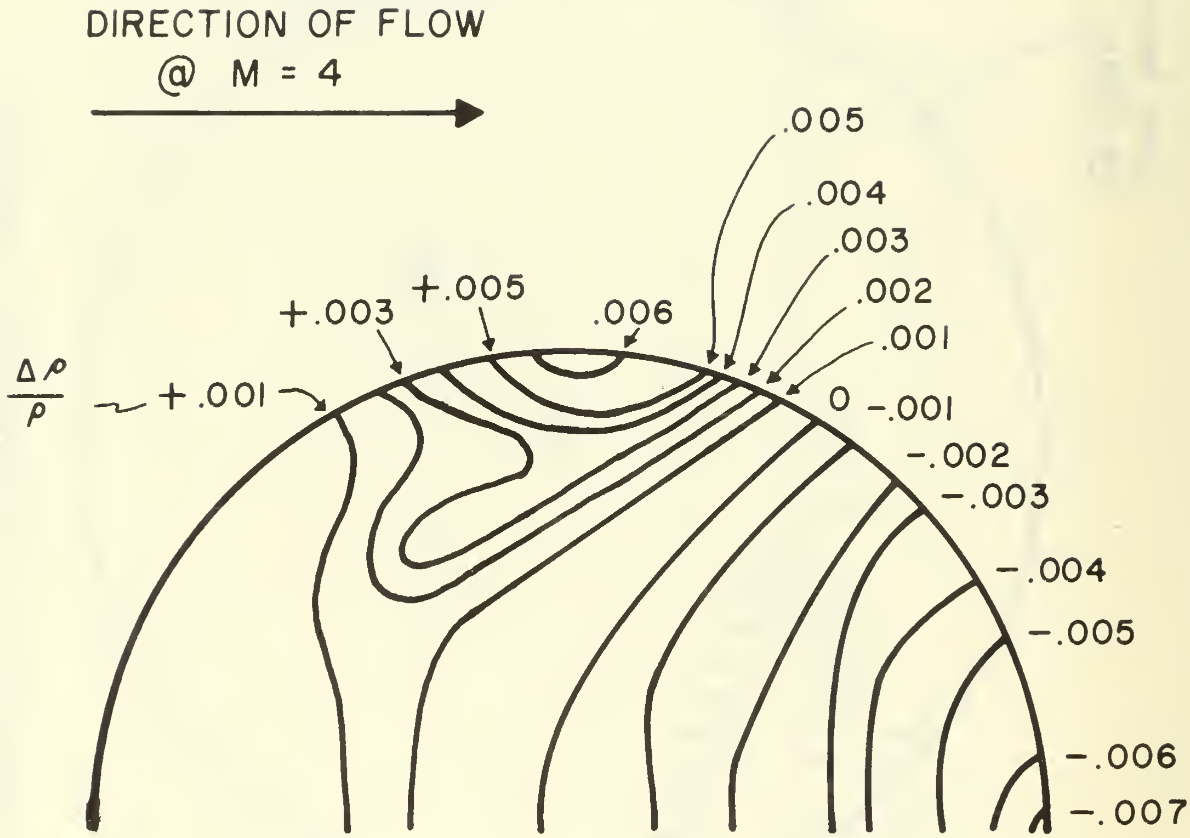

Fig. 2: Fractional density contours due to energy release in a circular laser cavity. Only top half is shown due to symmetry.

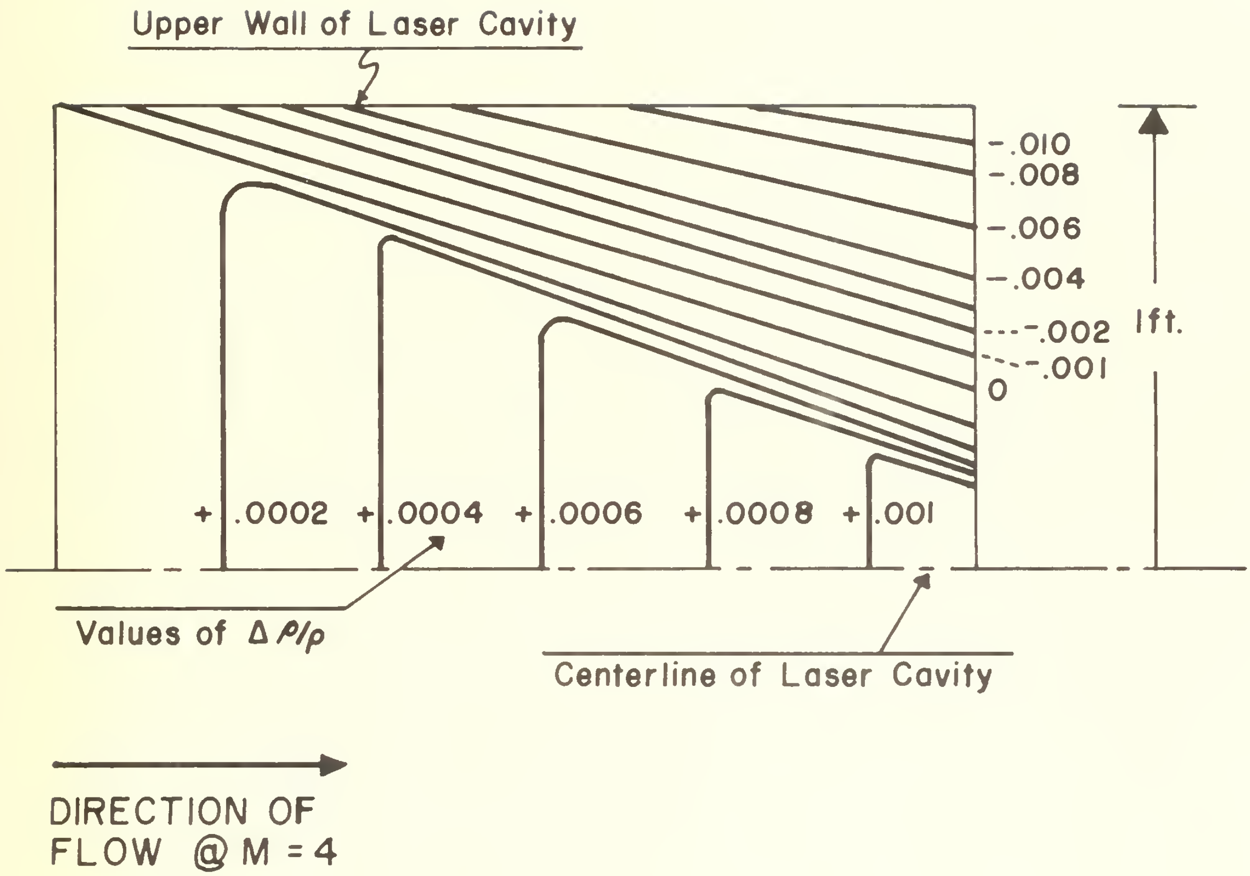

Fig. 3 : Fractional density contours due to energy release in a square cavity.

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