Laser-Heated Hypersonic Wind Tunnel

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Theme

RECENT developments in high-power CO_2 lasers have made it feasible to consider adding large amounts of energy to a gas flow via the absorption of 10.6μ laser radiation. This method of creating high-enthalpy gas streams through laser-gas coupling has direct application to hypersonic wind tunnels that require high stagnation temperatures and pressures to simulate orbital re-entry conditions.

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Typical stagnation conditions required to simulate the orbital re-entry corridor are $P_0 > 1000$ atm and $T_0 > 5000°K$. Although it is not feasible to have such stagnation conditions in a reservoir operating under nearly continuous conditions, it is feasible to obtain high stagnation temperatures in a gas flowing from a relatively cool high-pressure reservoir by adding laser energy to the flow. In this new approach, two important advantages are realized: 1) the energy source (i.e., the laser) is physically separated from the wind tunnel and is not temperature-limited as compared to direct heating devices, and 2) the laser beam can be accurately aimed down the central core of the flow, avoiding direct heating of the tunnel walls.

A conceptual wind-tunnel configuration is illustrated in Fig. 1. The laser beam enters the tunnel system through a window near the plenum chamber and propagates downstream through the subsonic flow region of the nozzle. Under reservoir conditions of, say, 1000 atm and 1000°K, a 10.6μ laser beam requires hundreds of meters of path length in air for a significant amount of absorption to take place, assuming gas breakdown does not occur (typical breakdown thresholds $\simeq 10^8$ w/cm^2). However, if "seed" electrons of sufficient number are added to the flow, the gas readily starts absorbing the laser energy via inverse neutral Bremsstrahlung, which is a very effective absorbing mechanism at high pressures. As the gas heats up, electrons produced by thermal ionization further increase the absorption of the laser energy, resulting in total attenuation of the laser beam within several centimeters.

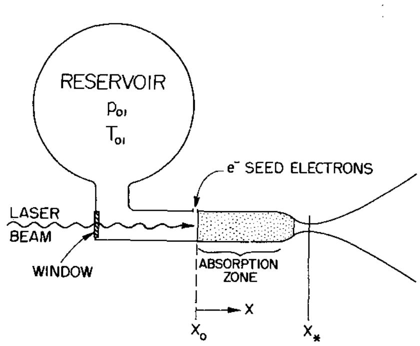

Fig. 1 Conceptual model of the laser heated wind tunnel.

The flow from the reservoir to the electron seeder location X_0 may be considered to be nearly isentropic. The distance between the electron seeder and the nozzle throat, X_*, the seed electron density, and the area variation can be chosen to insure that all the laser energy is absorbed in a reasonably short distance upstream of the throat at subsonic Mach numbers in order to avoid large convective, radiative, and viscous losses associated with pipe flow, laser damage to the throat, and high losses in stagnation pressure. Beyond the throat the flow can be considered to be nearly isentropic again. The laser heated wind tunnel is desirable as a test facility if, and only if, it is capable of producing long testing times (seconds or minutes) at large test areas (~ 1 sq. m). Long test times and large test areas are necessary to fully study heat-transfer effects and ablative effects on new composite materials that cannot be scaled easily. Hence, a continuous wave high-power CO_2 laser is desirable. Although laser systems other than the CO_2 system and rapid multipulsed lasers are not ruled out as potentially effective laser sources, they are not considered in this study.

A continuously operating system justifies a steady-state analysis of the problem. The analytical model is thus formulated on the basis of quasi-one-dimensional, equilibrium steady flow in a converging-diverging nozzle with a collimated continuous wave 10.6μ laser beam propagating in the downstream direction. The fluid conservation equations for the flowfield, neglecting viscous dissipation, diffusion, and thermal conduction, but including radiative heat transfer, are

$$\text{Mass:} \quad (d/dx)(\rho u A) = 0$$

$$\text{Momentum:} \quad dp/dx + \rho u \, du/dx = 0$$

$$\text{Energy:} \quad \rho u[(dh/dx) + u \, du/dx] = \alpha I e^{-\tau}$$

Constitutive relations are the thermal equation of state, $h(p, \rho)$, the absorption coefficient, $\alpha(p, \rho)$, and the optical depth τ given by

$$\tau = \int_0^x \alpha \, dx$$

The incident laser power intensity is denoted by I, and h, p, ρ, u, and A are the enthalpy, pressure, density, velocity, and nozzle cross-sectional area, respectively. This set of equations was solved numerically by transforming to the optical depth plane

$$d\tau = \alpha \, dx$$

and assuming an $A(\tau)$ and a minimum area location τ_*. By transforming to the optical depth plane, the fluid mechanical problem could be solved independently of any knowledge of the absorption coefficient. Transformation back to the real plane x is accomplished by

$$x = \int_0^\tau \frac{d\tau}{\alpha} + X_0$$

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The absorption coefficient was calculated on the basis of classical microwave theory for slightly ionized air (i.e., inverse neutral Bremsstrahlung). Assumptions involved in the modeling of α will tend to underestimate its value and, hence, overestimate the length of the absorption zone and thus are regarded as conservative. Numerical studies were performed using both real air models and ideal gas models. The ideal models were used to explore regions of interest and formulate the basic model configuration. Initial stagnation conditions were taken to be 1000 atm and 1000°K for real air studies.

The results followed the general behavior of volume heat addition in a one-dimensional flow. Reference 1 gives details of the flow properties, laser parameters, and absorption zone lengths. The essential conclusions of the feasibility study are:

1) In order to prevent large losses in stagnation pressure, subsonic heating of the flow (laser beam propagating downstream) appears to be the preferred approach. Supersonic heating (beam propagating upstream), even at Mach numbers near 1 results in unacceptable stagnation pressure losses, whereas subsonic heating results in losses of only 10% or less.

2) Special tailoring of the subsonic section of the nozzle in order to reduce head losses (e.g., by holding Mach number constant) did not result in substantial reduction of the stagnation pressure loss as compared to a constant area channel.

3) For throat areas of 0.1 cm^2, 10.6μ laser powers of tens of megawatts and total mass flow rates of hundreds of grams/second are capable of producing stagnation temperatures of 10,000°K with initial stagnation conditions of 1000°K at 1000 atm. The area of the subsonic portion of the nozzle where the laser energy is absorbed is 1 cm^2 and the nozzle test section size at the Mach 16 station is about 1 m^2.

4) Subsonic laser absorption zones for air are 10 cm or less in length with inverse neutral Bremsstrahlung as the absorbing mechanism. Absorption must be initiated by an artificial source of "seed" electrons. This source must produce electron number densities on the order of 10^{13} to 10^{14} cm^{-3}. Air temperatures of 3500°K or higher at 1000 atm will produce sufficient thermal electrons to sustain high absorption rates.

5) In order to propagate the laser beam into the subsonic portion of the nozzle in the downstream direction, a laser window or port capable of transmitting high laser powers is necessary. The window or port must also be capable of containing the high-pressure gas flow. High temperatures near the window can be avoided by locating the window at a sufficient distance upstream of the hot absorption zone.

6) Heat-transfer rates at the throat appear to have the most limiting effect on the operation of the wind tunnel. Radiative and convective heat-transfer rates are approximately 5 kw/cm^2 (polished wall) and 280 kw/cm^2, respectively, for stagnation pressures of 1000 atm. By using helium injection at the throat, the convective rate can be reduced to 50 kw/cm^2, a marginal value for a continuous-flow tunnel. At higher pressures, heat-transfer effects at the throat may be unacceptably high.

This feasibility study indicates that high-power lasers should be considered for the production of useful high-enthalpy hypersonic flows. Although very large (10^7 w) continuous wave 10.6μ laser power sources are required, existing continuous-wave laser systems are presently capable of being used for exploratory experimental work. Scalability of these laser systems does not indicate any major barrier to obtaining the desired power fluxes.[2] Practical solutions to the problems of initiating absorption and providing for a high-pressure laser window or port are also necessary. Ultimately, the problem of heat transfer at the throat probably presents the most severe constraint upon the operation of such a tunnel.

References

[1] Buonadonna, V. R., Knight, C. J., and Hertzberg, A., "The Laser Heated Wind Tunnel, A New Approach to Hypersonic Laboratory Simulation," AIAA Paper 73-211, Washington, D.C., 1973.

[2] Gerry, E. J., "Gas Dynamic Lasers," *IEEE Spectrum*, Vol. 7, No. 11, Nov. 1970, pp. 51–56.