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A New Calorimeter for Intense Laser Radiation

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Abstract. A new type of laser calorimeter has been developed which provides high measurement sensitivity and accuracy over several decades of input radiation intensity. The approach features a rapidly spinning liquid film as the calorimetric medium, and as such can accommodate a wide spectrum of incident laser radiation, through appropriate selection of the absorbing fluid. Because of the rapidly moving thin fluid technique utilized in the construction, the calorimeter exhibits fast response, even at high or low power levels. The design concept and method of fabrication make the device quite rugged and virtually burn-out proof.

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The ever increasing number of high-powered industrial processing lasers appearing in the marketplace has created a need for a "primary" laser calorimeter, capable of reliable, long-term operation at the multikilowatt power level. The industry has produced a few commercial type secondary radiometers; however most of these have required repeated calibration and generally have been restricted to measurement of cw laser radiation well below the 5 kw level.

This paper reports on the design of a new type of laser calorimeter, which can easily accommodate incident radiation levels from a few watts, up to tens of kilowatts. An additional feature is that, being an absolute instrument, the device does not require calibration.

Background

In the design of calorimeters or power meters for intense radiation it is desirable, whenever feasible, to utilize a flowing fluid as the absorption medium. This approach not only greatly simplifies energy exchange and dissipation but more importantly can negate the difficult problems of calibration and/or recalibration. Water, either by itself or in combination with appropriately selected dissolved dyes or colloids, has been found to be an especially convenient and inexpensive absorbing fluid; one that can be easily incorporated into a relatively simple closed cycle heat exchange system. For this reason water has historically most often been the basic ingredient in calorimeters for electromagnetic radiation. A familiar case in point here is the "water load" of common usage in the microwave field [1].

Liquid calorimeters have also been previously employed for measurement of laser radiation [2–5]. However, high-powered applications have been infrequent and generally limited to the visible spectrum, because of containment vessel and/or window problems.

The utilization of a free-falling surface water film for absorption of CO_2 laser radiation has been reported in the literature [6]. Experience has shown however, that this particular approach is limited essentially to relatively low power levels of a few hundred watts; principally because intense laser beams quickly disrupt and disperse free-falling liquid film flow dynamics. In addition, energy conduction to the substrate can compromise measurement accuracy.

New Calorimeter Design

The design concept utilized for the high-powered calorimeter described herein also features a free-

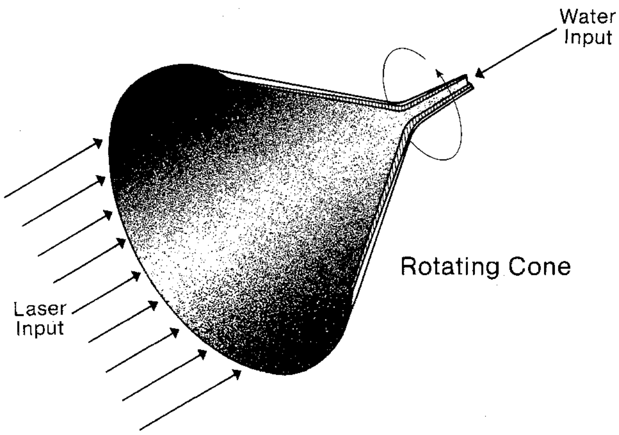

Fig. 1. Basic geometry of spinning cone thin fluid film calorimeter

surface absorbing liquid film. However, in this case the thin fluid film is not free-falling, but rather has been rendered completely stable against beam disruption, through the use of strong centrifugal dynamics. More specifically, as illustrated in Fig. 1, a rapidly spinning cone is used to create a stable and windowless free liquid surface, which is suitable for complete absorption of intense laser beams.

In Fig. 1 the absorbing fluid is fed axially down the center of a hollow shaft, the geometry of which gradually flares out into a conical surface. At a sufficiently high rotational velocity the centrifugal forces imparted to the stream forces it to quickly spread out over the cone's inner surface, into a uniform and rapidly moving free-surface thin film.

In its rapid transit over the cone surface, to an outer collecting annulus, the liquid film experiences enormous axial and radial acceleration. Consequently it becomes exceptionally stable physically. The net effect of this process is the generation of a continuous free-surface thin liquid film, which is unaffected even by strong external forces; including intense laser beams. Due to its high transport velocity, the film can easily absorb tens of kilowatts of cw or pulsed radiation without difficulty.

Thus the measurement of incident radiation is accomplished through simultaneous determination of the fluid flow rate and the temperature differential developed within the absorbing liquid flow, as it quickly crosses the surface of the rapidly rotating cone. These measurements of flow and temperature are performed, repeatedly updated, and correlated by electronic means, such that the real-time power level can be continuously displayed. Details of the electronic package developed for this purpose will be published elsewhere.

Operational Details

The design parameters of this spinning calorimeter sensor head are such that its thermal mass, both cone and fluid film, can be made exceptionally low. This feature, along with a very rapid fluid transport, gives the device an inherent fast response, over an unusually large measurement range. Experiments have demonstrated that the same sensor head can be utilized for precision radiation measurements over many decades of incident power level; from a few watts up to many kw. Maximum sensitivity can be achieved over this extended measurement interval, simply by adjustment of the absorbing liquid flow rate and the sensor head rotational speed.

When operating with a highly absorbing fluid, such as is the case with 10.6 μm radiation and water, near full absorption of the laser radiation occurs within a penetration depth of a fraction of a millimeter. Thus one need only vary the flow rate to accommodate the full range of measurement.

Tests have shown that provided an appropriate absorbing fluid is selected, so that the radiation penetration depth into the transporting film is small, and a very high rotational speed is used, the metallic cone surface becomes effectively isolated from the incident radiation. As a consequence negligible energy is transmitted or absorbed by the non-fluid parts of the system.

Test Results

Typical test data for the device described above is illustrated in Figs. 2 and 3. These curves were taken with a medium powered cw CO_2 laser, and at a constant cone rotational speed of 7000 rpm. Ordinary tap water was used as the absorbing medium. In Fig. 2 the performance of the calorimeter is displayed, for several different fluid flow rates, in comparison to that obtained from a commercial laser power meter. Since the thermopile used as reference (Coherent Radiation Model No. 301) was limited to a maximum cw input of approximately 300 W, it was necessary to utilize a beam splitter to couple only a small portion ($\sim$6%) of the multikilowatt laser beam intensity into it.

Despite the potential sources of error inherent in this technique of measurement, the data of Fig. 2 does indicate that the spinning water cone calorimeter possesses a high degree of linearity, over a wide range of water flow rates and input laser radiation levels.

A further demonstration of the accuracy and linearity of the instrument is afforded by the data displayed in Fig. 3. These curves show the temperature rise experienced by the absorbing water film, in its high velocity transit across the rotating cone surface. The fact that

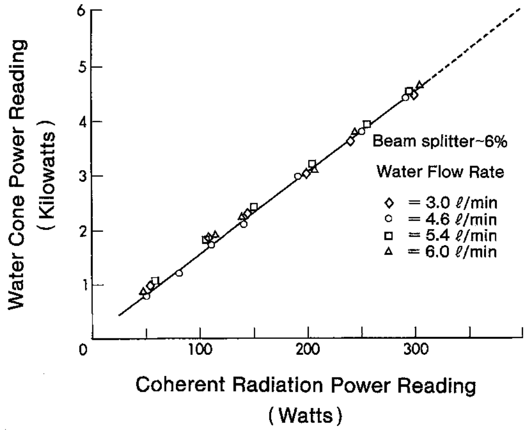

Fig. 2. Performance of spinning cone calorimeter compared to a commercial laser thermopile

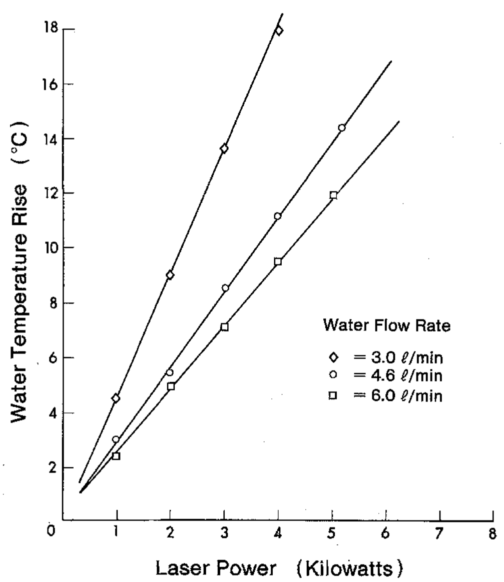

Fig. 3. Laser power vs. rise in water temperature across spinning cone

the data points, for each water flow setting, lie on straight lines, and that these individual lines, upon projection, all pass through the origin, clearly documents that negligible laser energy is being lost to the cone structure or to evaporation. The implications of these facts are that this spinning water cone calorimeter should be capable of high accuracy and speed of measurement. Thus the concept appears to be a viable technique for a wide range of laser radiation measurements.

Discussion

In principle, the response time of the device should be limited essentially by the transit time of the absorbing fluid film across the cone surface. It follows therefore that highest accuracy and speed of response are obtained at the higher rotational speeds. Experience has

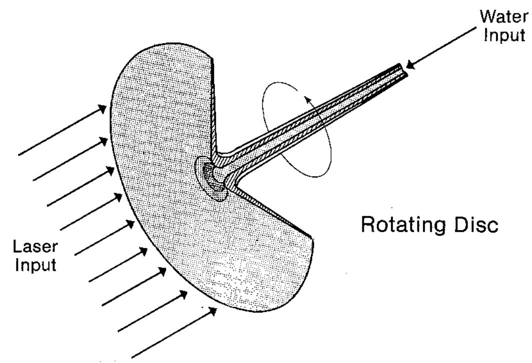

Fig. 4. Simplified spinning water disc calorimeter for CO_2 radiation

shown however, that at a sensor head rotational speed above about 7000 rpm the fluid transit time becomes shorter that the response time of the temperature measuring apparatus. Thus, in actual practice the response time of the calorimeter is limited by thermocouple response and the sampling time of the electronics, typically about one second.

Test have also indicated that the shape of the absorbing surface, included angle, and surface finish of the cone, are not critical parameters; provided that the absorbing fluid has a small penetration depth. Thus, in the case of CO_2 radiation, the near flat disc for Fig. 4 is a fully adequate geometry, which is easier to construct. However, if one utilizes the device in a wavelength range where fluid absorption is not particularly high, then a smaller angled cone of about 60° is preferable. Also in this case a non-absorbing surface finish on the cone is desirable, so that energy absorption is confined essentially only to the moving fluid film.

In conclusion, a simple, reliable and near indestructible rotating water film calorimeter has been developed. The unit features fast response and high measurement accuracy for laser radiation. The device has also an unusually large power measurement range and can be employed with a wide variety of lasers by selection of an appropriate absorbing fluid. When using special dyes or colloidal suspensions it is most convenient to employ a small closed-cycle recirculating liquid system, fitted with a secondary tap water heat exchanger.

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