Laser probe temperature control by measuring the returning infra-red radiation

J. H. Torres  S. Ghaffari  A. J. Welch
The University of Texas at Austin, Biomedical Engineering Program, ENS 610, Austin, Texas 78712, USA

Abstract—The metal-tipped fibre or 'laser probe' developed for angioplasty comprises a metallic probe at the end of an optical fibre. The probe is heated by an argon or Nd:YAG laser and applied against the tissue to be vapourised. The heated probe generates infra-red radiation which is proportional to the temperature of the probe. The paper investigates the feasibility of a feedback control system that measures the temperature of the probe by detecting the infra-red radiation transmitted back through the fibre. The probe was initially heated by physical contact with a hot surface, and then by an argon laser via the optical fibre. The returning IR radiation was sensed by a lead sulphide detector, while probe temperature was simultaneously measured by a thermocouple. Temperatures as low as 200°C were measured through a 5 m long fibre during the laser heating of the probe. The detector signal increased in an exponential fashion as the probe temperature increased. A resolution of 1°C was obtained at a probe temperature of 400°C. It can be concluded that, for the laser probe, it is feasible to use a feedback control system which measures the infra-red radiation transmitted back through the same fibre that carries the heating laser light.

Keywords—Angioplasty, Atherosclerosis, Feedback, Infra-red, Laser probe, Temperature

1 Introduction

With the increasing use of lasers for medical applications, optical fibres have become a useful tool for delivering the laser beam to targets inside the body. In many applications a specific temperature of the irradiated tissues is required to obtain the desired effect (for example coagulation at about 70°C for vessel welding). A remote fibre-optic thermography system to measure the temperature of those internal tissues during irradiation is being investigated presently by Sinofsky and Dumont (1988). They have been able to measure temperatures as low as 40°C by measuring the infra-red radiation transmitted through 200 µm core 40 cm long silica-based fibres.

On the other hand, a metal tipped fibre or 'laser probe' has been developed for some specific applications, especially in angioplasty (Lee et al., 1984; Hussein, 1986). The metallic tip is heated by a laser and applied against the tissue to be ablated. In this way, the thermal effect is produced by the hot metal rather than the laser light. The laser probe has been used successfully in clinical trials for treatment of obstructive vascular disease in peripheral arteries (Cumberland et al., 1986a; b) and it has been suggested that this device is safer than a bare fibre for angioplasty (Sanborn et al., 1984; Abela et al., 1985). It has also been reported that the probe optimally ablates tissue at 400–500°C (Welch et al., 1987). If this temperature is exceeded, excessive thermal injury to the tissue may occur. Also, temperatures over 650°C can damage the probe, and may result in its detachment from the fibre (according to the manufacturer, Trimedyne Inc.). In addition, if probe temperature is lower than 200°C the effects on tissue are poor, and sticking becomes a problem (Welch et al., 1987).

For these reasons, monitoring probe temperature to control the laser output may enhance the results of the medical treatment. A thermocouple welded to the probe is a simple and effective method of measuring the probe temperature. However, it requires the addition of wires from the probe to carry the temperature signal, and becomes difficult to manufacture for very small probes (< 1.5 mm in diameter). Another method to measure probe temperature while keeping the manufacturing of the laser probes as simple as possible is to measure the infra-red radiation emitted by the hot probe.

The purpose of this work is to study the feasibility of a feedback control system that measures the temperature of the metallic probe by detecting the infra-red radiation coming back through the fibre. Silica-based fibres highly attenuate infra-red radiation and do not transmit wavelengths beyond 5 µm. For that reason, this method of detection is not an easy task. The method is similar to the
remote fibre-optic thermography system of Sinofsky and Dumont (1988), except that in our particular case a laser beam is coupled and passes through the same fibre to heat the metallic cap which is the target of our measurements.

2 Background

All objects radiate energy according to their temperature above absolute zero, and in proportion to the emissivity of their surface relative to that of an ideal 'black body'. A black body is a body which absorbs all radiation incident upon it and reflects or transmits none. It also emits the maximum possible amount of energy at any specific temperature and wavelength. The spectral distribution of the energy emitted by a black body is given by Planck's law (INCROPERA and De Witt, 1985):

$$E_b(\lambda, T) = \frac{2\pi h c^2}{\lambda^5 (e^{h c / \lambda k T} - 1)}$$

where $E_b(\lambda, T)$ is the spectral emissive power (W m$^{-2}$$\mu$m$^{-1}$), $\lambda$ is the wavelength ($\mu$m), $h = 6.6256 \times 10^{-34}$ (Js) is Planck's constant, $k = 1.3805 \times 10^{-23}$ (J K$^{-1}$) is Boltzmann's constant, $c = 2.998 \times 10^8$ (m s$^{-1}$) is the speed of light in vacuum, and $T$ is the absolute temperature (K). Plotting the spectral emissive power as a function of wavelength and temperature results in the well known black body radiation curves. Integrating over all wavelengths, the total emissive power at a specific temperature is given by the Stefan-Boltzmann law:

$$E(T) = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}$ (W m$^{-2}$ K$^{-4}$) is the Stefan-Boltzmann constant. Actual bodies, however, are 'grey bodies' with an emissivity less than that of a black body. Emissivity is defined as the ratio of the radiant energy emitted by an object at a specific temperature to the radiant energy emitted by a black body at the same temperature. An ideal black body has an emissivity of 1.0. Then, for a grey body:

$$E(T) = \varepsilon \sigma T^4$$

Wien's displacement law provides a relationship between the temperature $T$ (K) and $\lambda_{max}$, the wavelength at which the radiation becomes a maximum at that temperature:

$$\lambda_{max} T = \text{constant} = 2897.6 \mu m K$$

Fig. 1 Spectral black body emissive power (from INCROPERA and De Witt 1985, with permission)

The amount of radiant energy that can be collected by an optical fibre placed in front of a 'hot' object depends on the acceptance angle $\theta$ and the cross-section of the fibre $A$, and is only a fraction of the total radiant energy emitted by the object. The acceptance angle $\theta$ depends on the numerical aperture of the fibre $NA$, which is defined as:

$$NA = (n_{core}^2 - n_{cl}^2)^{1/2}$$

where $n_{core}$ and $n_{cl}$ are the indexes of refraction of the core and the cladding of the fibre, respectively. The acceptance angle is then

$$\theta = \arcsin NA$$

Sinofsky and Dumont used the following equation to calculate the fraction of energy collected by the fibre:

$$\Phi = LA\Omega$$

where $L$ is the radius in W Str$^{-1}$ mm$^{-2}$, $A$ is the area of the fibre core in mm$^2$, and $\Omega = 2\pi(1 - \cos \theta)$ is the solid angle in steradians. The radiation $L$ is equal to the total emissive power $E(T)$ from the object divided by $2\pi$ steradians, or $L = E(T)/2\pi$. Whereas a black body at 5500°C (such as the sun) emits primarily infra-red radiation. A plot of spectral blackbody emissive power is shown in Fig. 1. In our study we are interested in temperatures below 600°C. Unfortunately, fused silica fibres presently in use (including the fibre attached to the laser probe) highly attenuate the infra-red radiation beyond 2$\mu$m, and a very sensitive system is required to detect this radiation.

3 Methods

A 2.5$\mu$m diameter laser probe from Trimedyne Inc. attached to a 600$\mu$m core 17 feet long fused silica fibre was used in this study. This probe was chosen over the 2$\mu$m probe with a 300$\mu$m core fibre, currently used for angioplasty, because of its larger diameter fibre that permits the transmission of more infra-red energy for the feasibility study. The probe was heated initially by physical contact with a hot surface and then by an argon laser via the optical fibre. The returning IR radiation was sensed by a lead sulphide (PbS) detector, and the temperature was simultaneously measured by a Chromel-Alumel thermocouple welded to the probe. The energy emitted by a hot body at 200°C falls between 1.5 and 100$\mu$m with a peak at 6.1$\mu$m according to the black body radiation curves. When a temperature of 500°C is reached, the emitted energy moves toward the visible spectrum with a peak at 3.75$\mu$m. On the other hand, for a temperature of 50°C, emitted radiation starts at 2$\mu$m with a peak at 9$\mu$m. The fused silica fibre transmits well the visible wavelengths and near infra-red up to 2$\mu$m, but attenuation increases rapidly as wavelength increases beyond 2$\mu$m.

Considering these facts, we were attempting to measure temperature using energy in the wavelengths from 1.5 to 2.5$\mu$m. Attenuation coefficients from 1 dB Km$^{-1}$ at 1.5$\mu$m to 35 dB Km$^{-1}$ at 2$\mu$m are typical for fused silica fibres (Okoshi, 1982). For a 5$\mu$m long optical fibre, this corresponds to 99-95 per cent transmission, respectively. A curve of the transmission loss for low-loss silica fibres is shown in Fig. 2a. For the fibre used in this study, attenuation characteristics are not available beyond 2$\mu$m. However, if we could extrapolate from Fig. 2a, the transmission loss at 2.5$\mu$m would be close to 400 dB Km$^{-1}$, which corresponds to 60 per cent transmission through a 5$\mu$m long fibre. A sharp drop in transmission is expected