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

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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

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):

\[
E_b(\lambda, T) = \frac{2\pi c^2\lambda^{-5}}{e^{hc/\lambda kT} - 1}
\]

where \( E_b(\lambda, T) \) is the spectral emissive power (W m\(^{-2}\) \( \mu \text{m} \)^{-1}), \( \lambda \) is the wavelength (\( \mu \text{m} \)), \( h = 6.6256 \times 10^{-34} \) (J s) 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:

\[
E_b(T) = \int E_b(\lambda, T) d\lambda = \sigma T^4 \quad (\text{W m}^{-2})
\]

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:

\[
E_b(T) = \varepsilon \sigma T^4 \quad \text{where} \ \varepsilon \ \text{is the emissivity}
\]

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

\[
\lambda_{\text{max}} \cdot T = \text{constant} = 2897.6 \text{ } \mu\text{m} \text{ K}
\]

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:

\[
NA = (n_{\text{core}}^2 - n_{\text{cl}}^2)^{1/2}
\]

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

\[
\theta = \text{arc} \sin NA
\]

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

\[
\Phi = LA\Omega \quad (\text{radiant flux in watts})
\]

where \( L \) is the radiance in W Sr\(^{-1}\) 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 radiance \( L \) is equal to the total emissive power \( E_b(T) \) from the object divided by 2\( \pi \) steradians, or \( L = E_b(T) / 2\pi \).

Whereas a black body at 5500°C (such as the sun) emits radiation with an important fraction in the visible region of the spectrum, a body at a temperature \( \leq 500°C \) 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 \( \mu \text{m} \), and a very sensitive system is required to detect this radiation.

3 Methods

A 2.5 mm diameter laser probe from Trimedyne Inc. attached to a 600 \( \mu \text{m} \) core 17 feet long fused silica fibre was used in this study. This probe was chosen over the 2 mm probe with a 300 \( \mu \text{m} \) core fibre, currently used for angio-plasty, 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 \( \mu \text{m} \) with a peak at 6.1 \( \mu \text{m} \) 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 3.5 \( \mu \text{m} \). On the other hand, for a temperature of 50°C, emitted radiation starts at 2 \( \mu \text{m} \) with a peak at 9 \( \mu \text{m} \). The fused silica fibre transmits well the visible wavelengths and near infra-red up to 2 \( \mu \text{m} \), but attenuation increases rapidly as wavelength increases beyond 2 \( \mu \text{m} \).

Considering these facts, we were attempting to measure temperature using energy in the wavelengths from 1.5 to 2.5 \( \mu \text{m} \). Attenuation coefficients from 1 dB Km\(^{-1}\) at 1.5 \( \mu \text{m} \) to 35 dB Km\(^{-1}\) at 2 \( \mu \text{m} \) are typical for fused silica fibres (Okoshi, 1982). For a 5 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 \( \mu \text{m} \). However, if we could extrapolate from Fig. 2a, the transmission loss at 2.5 \( \mu \text{m} \) would be close to 400 dB Km\(^{-1}\), which corresponds to 60 per cent transmission through a 5 m long fibre. A sharp drop in transmission is expected.