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A Review of Radiation Heat Transfer Measurement for Diesel Engines Using the Two-Colour Method

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Abstract— **Understanding the heat transfer processes of compression-ignition engines requires attention to both convection and radiation components. Although a number of correlations for convective heat transfer in engine environments have been implemented in simulations with some accuracy, reliable correlations for the radiant heat transfer are yet to be developed. Most radiant heat transfer correlations are configuration-dependent and fail to accommodate important physical aspects of the radiant heat transfer process in diesel engines. The development of reliable radiation heat transfer correlations requires reliable data. The two-colour method for radiation measurement has provided valuable insight into the combustion process inside direct-injection compression ignition engine. The two-colour method is a popular approach because it is cost effective and simple approach that can provide time-resolved data. The objective of this paper is to present a review of radiation heat transfer measurement in the diesel engine environment using the principles of the two-colour method. The theory, approach, issues and complications associated with the two-colour method are discussed.**

Keywords-Radiation measurement; diesel engines; two-colour method

I. INTRODUCTION

With the gloomy prospect of fuel resource scarcity and the imminent global warming phenomena, the call for highly efficient and environmental friendly internal combustion engine is now louder than ever. Diesel engines, which are the widely used not only in automobiles but also in heavy vehicles and other machines such as trucks, boats, mining, manufacturing and construction equipment, require special attention. Heat transfer in internal combustion engines has a significant impact on energy efficiency and emissions, and in the case of diesel engines, radiation heat transfer within the cylinder has been identified as a significant component of the total heat transfer process. Soot, which is formed during diesel droplet burning, emits radiation which is transmitted to the walls of the combustion chamber [1]. The relationship between the radiation heat transfer from the soot and the engine operating and performance parameters has to be investigated to understand the key processes and thereby optimize engine efficiency and emissions for new fuel blends.

Since the 1960s, researchers have mainly applied two types of radiation heat transfer measuring methods: (1) shielded surface junction thermocouple technique; and (2) the two-colour method. For the shielded surface junction thermocouple technique, a fast-response surface junction thermocouple or pyrometry detector is located behind a quartz or sapphire window to receive only radiation heat transfer from the combustion zone. The window acts as a filter for convective heat transfer. The measurement technique relies on the fact that the only source that changes the temperature of the thermocouple during the combustion cycle is the radiant energy from the combustion gases. Hence, only changes in temperature with respect to time are measured, and these can be converted to values of transient heat flux provided an appropriate model for the substrate convection is adopted. The primary advantage of the technique is its simplicity. Only polycrystalline window are needed to filter the convection heat transfer and transmit the radiation signals to the sensor [2].

The two-colour method has been used extensively to study the in-cylinder radiant heat flux, in-cylinder flame temperature and soot volume fraction [3-12]. The two-colour method, utilizing an assumed soot emissivity, relies on the Hottel-Broughton equations [6] in order to deduce flame temperature and soot concentration with the assumption of uniformity of temperature and soot concentration within a particular volume. There are three principal advantages of the two-colour method. First, the method detects the light emission from soot particles so that there is no need for an external light source. Second, as a non-intrusive method, it makes use of an optical probe which causes minimal interference with the combustion process and finally, use of fast-response photodetectors enables real-time monitoring of soot concentration.

II. THE PRINCIPLE OF TWO COLOUR METHOD

The goal of the two-colour technique is to obtain instantaneous in-cylinder flame temperature and a relative soot concentration by an optical technique. Two simultaneous equations for measured spectral emissive power at two different wavelengths are solved for the flame temperature and the *KL* factor, which is related to soot concentrations. These two values at two specific ranges of wavelength can be used to calculate total instantaneous radiation intensity. The two-colour method is founded on optical pyrometry and relies on measurements of emission intensity from incandescent soot particles which are produced during the combustion process.

The spectral emissive power from a black body as function of wavelength can be predicted based on the Plank's Law [6].

$$\dot{q}_{\lambda} = \varepsilon_{\lambda} \frac{C_1}{\lambda^5 \left(e^{\frac{C_2 \cdot T}{\lambda}} - 1 \right)} \tag{1}$$

where $\dot{q}_{\lambda}$ is the spectral emissive power in units of W/m^2/μm, C_1 is a constant of value 3.7413 × 10^8 W·μm·m^2, C_2 is constant of value 1.4388× 10^4 μm·K, T is the temperature of the body, λ is the wavelength in μm, and ε is the emissivity of the body.

The value of the emissivity is 1 for a black body which is the ideal case for a radiating object. The spectral emissive power is a unique function of wavelength for any given temperature [10].

Hottel and Broughton as mentioned by Adommatos et. al. [6], demonstrated that soot does not behave as a black body. They proposed that the emissivity of soot as a function of wavelength can be described by

$$\varepsilon_{\lambda} = 1 - e^{\left(-\frac{K \cdot L}{\lambda^{\alpha}} \right)} \tag{2}$$

where λ is the wavelength, KL is a value pertaining to soot concentration, K is soot absorption coefficient, L is the optical path length and α is a parameter that relates to the wavelength and the type of fuel. The α values have been obtained through experimentation. Hottel and Broughton as mentioned by Adommatos et. al. [6] produced a value of $\alpha = 1.39$ from direct measurements of steady state luminous flames, for visible wavelengths. Using spectroscopic analysis of soot layers formed on pyrex glass window in diesel engine, Matsui,et.al [15] measured a value of 1.38, for visible wavelengths. For the near infrared region, the values of α obtained seemed to be varied greatly with the wavelength. Hottel and Broughton as mentioned by Adommatos et. al. [6] measured a value of 0.9 for wavelengths higher than 0.8 μm while Matsui, et. al. [15] obtained values in the range of 0.91 to 0.97 for a range of wavelengths from 1 to 5 μm. A compilation of values of parameter α produced by researchers is shown in Table 1.

Thus, the spectral emissive power of soot is

$$\dot{q}_{\lambda,soot} = \left(1 - e^{\left(-\frac{K \cdot L}{\lambda^{\alpha}} \right)} \right) \cdot \frac{C_1}{\lambda^5 \cdot \left(e^{\frac{C_2 \cdot T}{\lambda}} - 1 \right)} \tag{3}$$

In the two-colour method, spectral emissive power measurement at two different but known wavelengths λ_1 and λ_2 are obtained: $\dot{q}_{\lambda 1,soot}$ and $\dot{q}_{\lambda 2,soot}$. By considering (3), it is possible to deduce the soot temperature T and the value of $K.L$ (relating to the density of soot cloud). The solution for T and $K.L$ is unique and this is the foundation of the two-colour method [7].

TABLE I. Values of the Parameter α [6, 8, 16]

Researcher	**Wavelength constant, α**		
	Visible wavelengths	**Infrared wavelengths**	**Fuel or flame type**
Hottel and Broughton, 1932	1.39	0.95 (λ>0.8 μm)	Steady Luminous flame
Rossler and Behrens, 1950	1.43 1.39 1.29 1.23 1.14 0.66-0.75		Acetone Amyl acetate Coal gas/air Benzene Nitrocellulose Acetelyne/air
Siddal and McGrath, 1963		0.89, 1.04 0.77 0.94,0.95 0.93 0.96, 1.14, 1.25 1.06 1.00 α=0.91 +0.28lnλ	Amyl acetate Avtur kerosene Benzene Candle Furnace Sample Petrotherm Propane Various Fuels
Liebert and Hibbard, 1970		0.94-0.96 (λ>0.8 μm)	
Matsui et al, 1980	1.38	0.91-0.97 (λ=2-4 μm)	Diesel Engine Soot
Yan and Borman, 1988	1.39	-	Diesel Engine Soot
Xi Li and J.S. Wallace, 1995	1.38		Diesel Engine Soot
Struwe and Foster, 2003	1.39	0.95 (λ=0.83 and 1μm)	Diesel Engine Soot

In the two colour method, optical bandpass filters are typically placed in front of the photodiodes and hence measurements are not obtained precisely at two different wavelengths but over a range of two different wavelengths. Because of this, the spectral emissive power across a bandwith must be considered and is given by [10]

$$\dot{q}_{\lambda,soot} = \int_{\lambda_2}^{\lambda_1} \left(1 - e^{\left(-\frac{K \cdot L}{\lambda^{\alpha}} \right)} \right) \cdot \frac{C_1}{\lambda^5 \cdot \left(e^{\frac{C_2 \cdot T}{\lambda}} - 1 \right)} d\lambda \tag{4}$$

where the upper and lower limits of integration are

$$\lambda_1 = \lambda_0 + \frac{\Delta\lambda}{2}$$

$$\lambda_1 = \lambda_0 - \frac{\Delta\lambda}{2}$$

where $\Delta\lambda$ is the spectral width of the bandpass filter. Provided the spectral width of the filter is sufficiently narrow, the integral can be approximated by simply multiplying the integrand by the spectral width [8, 10, 11, 12] giving the spectral emissive power as

$$\dot{q}_{\lambda,soot} = \Delta\lambda\left(1-e^{\left(-\frac{K\cdot L}{\lambda^{\alpha}}\right)}\right)\cdot\frac{C_1}{\lambda^5\cdot\left(e^{\frac{C_2\cdot T}{\lambda}}-1\right)} \qquad (6)$$

III. EXPERIMENTAL ARRANGEMENT

A typical two-colour method experimental arrangement is shown in Fig. 1. The cylinder head is machined to place the radiation heat transfer probe system flush in the cylinder head. A window at the tip of the probe allows the radiation signals to pass into a fibre optic cable which directs the signals to a bifurcated or trifurcated fiber optic cable where the signals are filtered according using spectral bandpass filters before being received by the photodetectors. The sensitivity and frequency response characteristics of the photodectectors are selected to matched the selected wavelength and the required speed of signal recording. The photodetectors change the radiation signals into an electrical output which is then amplified and recorded with a suitable data acquisition system.

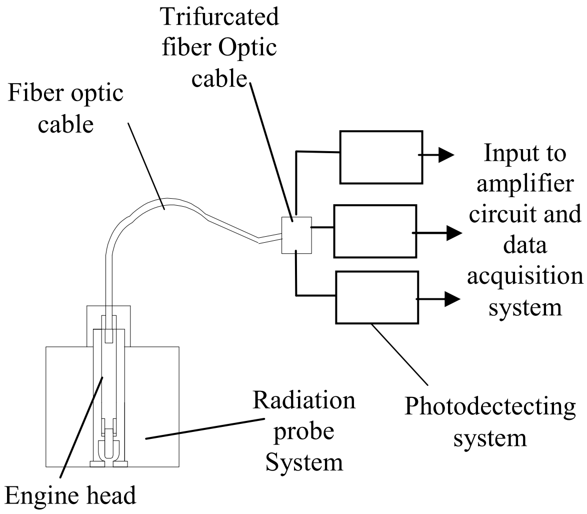

Figure 1. Optical two-colour method experimental arrangement

IV. RADIATION HEAT TRANSFER PROBE SYSTEM

Figure 2 shows a radiation heat transfer probe for use inside a small direct-injection diesel engine currently being developed at University Southern Queensland, Australia. The rod window provides access for light signals from combustion chamber to enters the probe and consequently to the fiber optic. Researchers have used several materials for the window including quartz, sapphire and polycrystalline sapphire which is known to have good transmissivity and refractive index [4, 9]. Boggs and Borman [13] trialed a windowless radiation heat transfer probe which included a pulsed wall jet to decrease the convective flux to the sensor, but this method failed because the rapid pressure change in the cylinder compressed the wall jet.

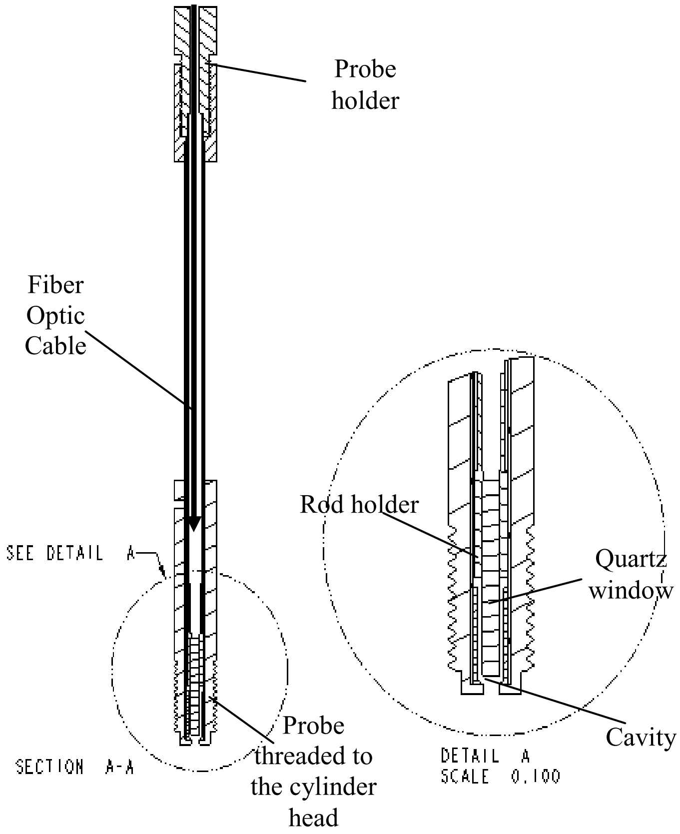

Figure 2. Cross section view of two-colour method probe developed at USQ

The main problem of radiation heat transfer probe is the soot deposits on the window surface. Soot, solid particles that comes from unburned fuel in fuel-rich region in vapour phase, causes attenuation of the signals [1]. Nagase and Funatsu [12] who investigate radiation heat transfer from flames diesel engines used removable windows to quantify the effect of soot adhesion. The fiber tip window was removed from the engine after measurements, and the effect of soot on the signals before and after cleaning was recorded. The correlation of amplitude of loss signals were recorded as a function of time as shown in Fig. 3 and this was taken into account in the measurement of the radiation signals.

Another method of reducing the soot deposits on the window comes through the design of a cavity feature surrounding the rod window. Yan et al. [14] and Struwe [8] designed a self-cleaning radiation heat transfer probe by introducing a cavity surrounding a sapphire rod window. Fig. 4 shows a cutaway view of the probe by Yan et al. [14]. During the compression process, air fills the cavity. The soot is cleaned off the window by gas discharging from the cavity during the combustion and expansion process. The gap size between the window surface and the bottom of the restriction sleeve seems to be very critical. In the experiments of Yan [5], the gap used was about 1.27 mm while a range of gaps of between 0.76 mm and 1.2 mm was tested by Struwe [8] with success.

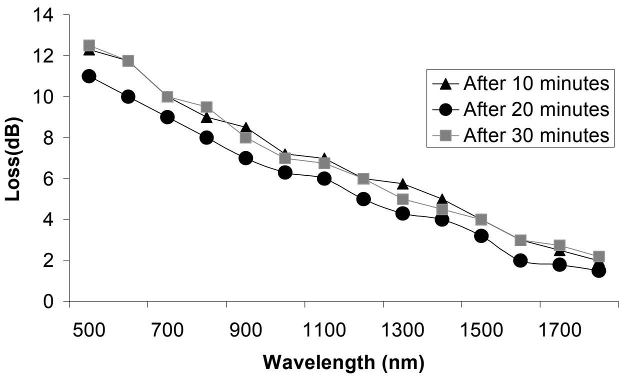

Figure 3. Signals attenuation correlation due to soot [12]

Another mechanism that prevents soot deposits on the window surface is the use of a rod window with minimal heat transfer dissipation [8]. Sapphire is one of the materials that can remain sufficiently hot during engine operation and act as a passive soot minimization feature. Shure [17] has demonstrated that thermopherosis – the motion of particles due to a temperature gradient – is the major cause of in-cylinder soot deposition: soot tends to deposit on the relatively cold engine walls.

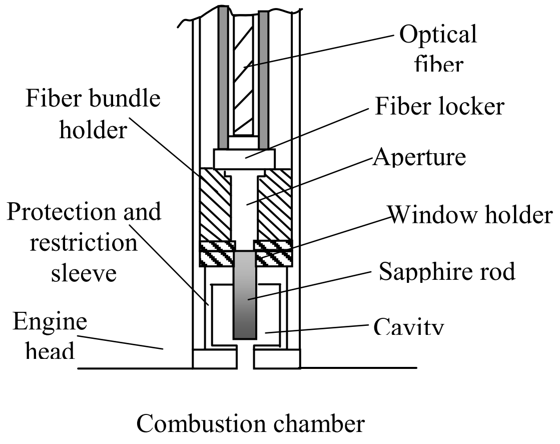

Figure 4. Radiation probe with cavity [14]

Another consideration in designing the probe is the field of view. For the period of combustion when soot cloud fills the field of view, the measured temperature and *KL* factor will be a good representation of the flame. However, during combustion events when the flame does not completely filled the field of view, such as when in beginning and the end of combustion, the soot distribution will be highly non-uniform. Hence, for accurate measurement of the *KL* factor and flame temperature at specific location, a small field of view is preferred. However, for radiant heat transfer measurements, a large field of view is desired, so as to maximize sensitivity to radiant energy. A large field of view is generally preferred for radiant heat flux measurement [8, 10].

V. CALIBRATION

In order to relate the voltage output of the probe system to the radiant heat transfer incident into the probe, calibration is necessary. The voltage output, *V* of the probe can be defined as [7]:

$$V = \int_{\Delta\lambda} \int_{\omega}\int_{A} \tau R_d B \varepsilon_b i_{b,\lambda} \cdot dA \cdot d\omega \cdot d\lambda \tag{7}$$

where τ is the transmissivity including bandpass filter, condensing lenses and the rod window, R_d is responsivity of detector as a function of wavelength, B is the amplification factor of amplifiers, ε_b is the emissivity of radiant source, $i_{b,\lambda}$ is the spectral intensity of radiation source, A is the actual detecting area, ω is the solid angle viewed by the probe and λ is the wavelength.

With the use of filter with a narrow bandwidth (0.010µm-0.020µm), the transmissivity, responsivity of photodetector and the emissivity of the radiant source are considered constant. Together with the assumption of uniform radiant intensity over the solid angle, ω, equation (7) can be simplified as:

$$V_\lambda = H \cdot \left(\varepsilon_b i_{b,\lambda}\right)$$

where calibration constant is $H = \tau R_d B A \omega \Delta\lambda$ (8)

Several voltage readings are taken corresponding to different values of spectral intensity in order to produce a calibration curve at respective wavelengths. A typical calibration curve produced by Yan et. al [14] is shown in Fig. 5 below:

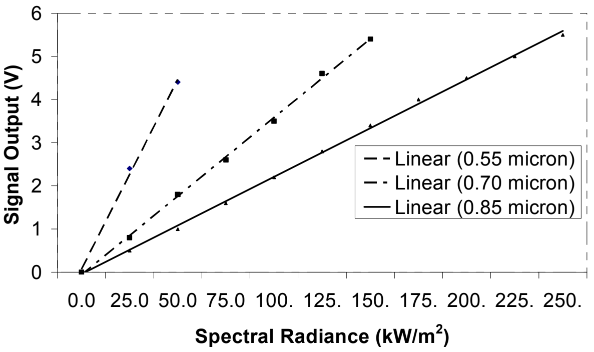

Figure 5. Calibration curve [14]

Previous researchers have used a disappearing filament optical pyrometer to first measure an apparent temperature of the black body furnace or tungsten filament lamp. Then, using the apparent temperature values, the spectral intensity, $i_{b,\lambda}$ is calculated by using the Plank's Law equation[6, 7, 8, 10]. However in 2003, Struwe et al. [8] eliminate the need for measuring the apparent temperature of the radiant source by using a digital radiant power meter instead of the disappearing filament optical pyrometer, to measure directly the spectral intensity, $i_{b,\lambda}$ of the radiant source.

VI. DATA RECORDING AND ANALYSIS

Matsui et al. [15] observed cyclic irregularity from the radiation intensity of the flame and estimated flame temperature during direct injection diesel operation. In order to obtain the radiant emission characteristics of one representative engine cycle, a data averaging technique is needed. Matsui et al. [15] took voltage outputs for each crack angles at two wavelengths from 1000 engine cycles and then ensemble-averaged the values to provide average voltage output for the combustion period.

A different method of radiant emission analysis was adopted in [7]. Signals from each engine cycle were used to calculate the temperature distribution and the *KL* factor for each crank angle degree [7]. Each of the temperature and *KL* factor values were averaged over many cycles to obtain ensemble averaged values for each crank angle degree of the combustion process.

Using ensemble averaged voltage outputs appears to be the better approach. Li and Wallace [16] examined the two methods to check the effectiveness of both in eliminating noise and found out the ensemble-average on the voltage outputs can effectively remove noises in the signal. The temperature and *KL* factor average methods give similar results except for low cases of signal strength where the effect of noise is shown to be severe. Matsui et al. [15] also points out that it is more computational efficient to use the ensemble-average on the voltage outputs method.

VII. SAMPLE RESULTS AND DISCUSSION

It is observed from that as the injection timing is advanced, the peak magnitudes of radiant heat transfer curve increase in magnitude and occurs earlier. Referring to Fig. 6, 'injection timing 1' represents the earliest timing of fuel injection whiles the 'injection timing 4' represents the latest timing of fuel injection. There is a common shape of the radiant heat flux for all experimental configurations.

Using two-colour method, one can exhibit changes of radiation heat flux while changing the engine load. In Fig. 7, for the load cases of 1200 rpm, the shape of radiant signal is significantly different although the peak magnitude remains relatively the same. This shows that the development of soot radiant emission is load dependent. The higher the load, the longer will be the duration of the radiant emission.

Fig. 8 exhibits no effect on the peak of radiation heat flux profile of diesel engine when engine speed is increased, albeit different shape of heat flux found. The increase of 25% of engine speed operating at 100% engine load does not produce any change on the slope of soot formation (curve before the peak) and oxidation (curve after the peak). However the secondary peak that is seen on 1200 rpm seems to disappear on the 1500 rpm.

In Fig. 9, it is shown that with the increase of speed of 25% from 1200 rpm to 1500 rpm produces the same findings as in figure 7. The increase of load will increase the peak radiation heat flux. By injecting the fuel later into the combustion chamber, the peak radiation will be reduced, as shown by the declining slope for both engine loads.

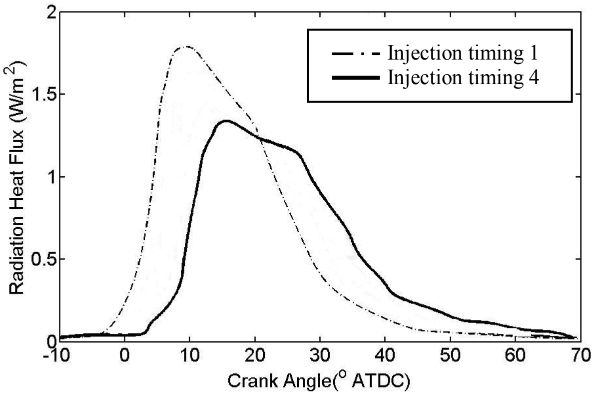

Figure 6. Effect of injection timings at full load [8]

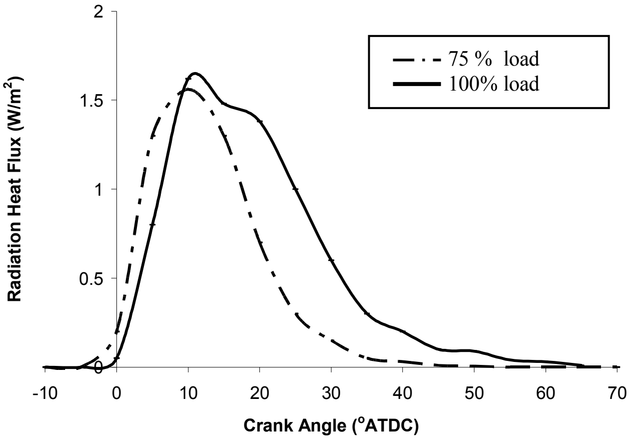

Figure 7. Effect of load on shape radiation heat flux profile at 1200 rpm[8].

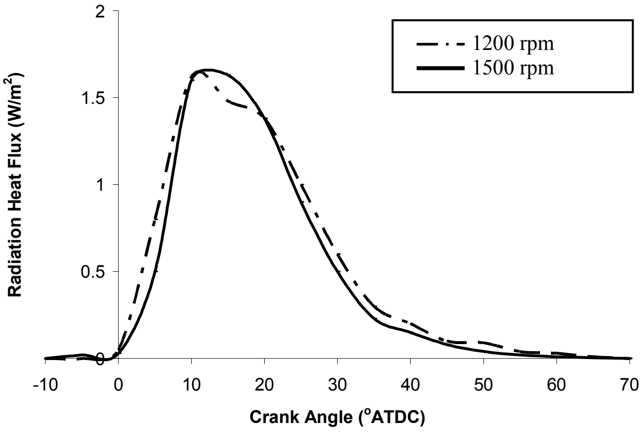

Figure 8. Effects of speed on shape radiation heat flux profile at 100% load[8]

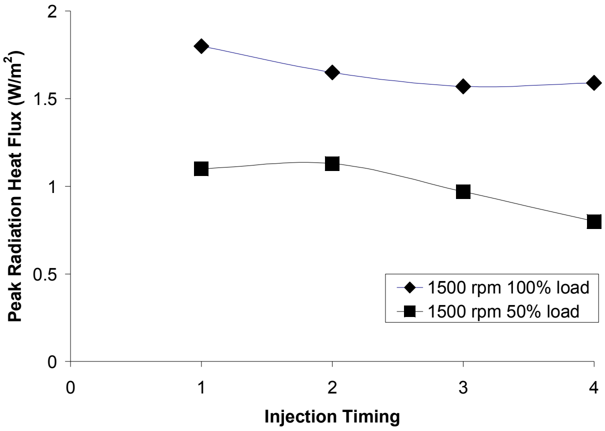

Figure 9. Effects of load on peak radiation heat flux [8]

VIII. CONCLUSION

The two-colour method relies heavily on the Hottel-Broughton assumption of uniform soot density and flame temperature. However, the method still able to produce useful information of radiant emission characteristics from soot particles and the soot conditions during engine operation. The limited field of view and the soot deposits on the window surface can be significant problems that affect the measurement of radiant heat transfer and these problems require further investigation.

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