EMISSIVITY MEASUREMENTS OF STEEL EXPOSED TO A JET FIRE

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ABSTRACT

An infra-red imaging camera has been used to determine the surface emissivity of a steel pipe during the cool-down period immediately after impingement by a two-phase propane jet fire. Values for emissivity showed little dependence upon the temperature of the steel pipe, but typically varied between 0.7 and 0.9 depending on local surface conditions which were affected by the extent of jet fire engulfment.

1. INTRODUCTION

Jet fires resulting from accidental high-pressure hydrocarbon leaks represent a major hazard, particularly in the confines of an offshore platform. Structures and vessels impinged by a jet fire can heat up rapidly, with consequent loss of strength and ultimately loss of integrity. Heat transfer between the fire and impinged object is by a combination of convection and radiation, and therefore accurate prediction of the rate of temperature rise in a jet fire requires knowledge of the surface absorptivity and emissivity.

In a real jet fire impingement situation, the precise surface properties of steel vessels and pipework are unlikely to be known. The steel may be oxidised and even a minimal layer of oxide can change the radiative properties considerably. For bare steel, the degree of surface oxidation will almost certainly vary as a result of jet fire impingement, depending on fuel combustion properties, physical environment and surface temperature. Actual steel emissivity varies considerably (from 0.1 to 0.95) [1] according to the type of steel used, the state of corrosion and temperature.

In this work, values for emissivity were obtained by detection of near infrared radiation emitted from a hot carbon steel pipe, which was heated through impingement by a jet fire. It was assumed that any spectral variations in steel surface emissive properties were negligible so that the steel approximated to a directional grey body. Under these conditions [2], by Kirchhoff's Law, the directional total emissivity, ε, and absorptivity, α, are equivalent. Thus:

$$\alpha(\theta, \varphi, T_{surface}) = \varepsilon(\theta, \varphi, T_{surface}) \quad (1)$$

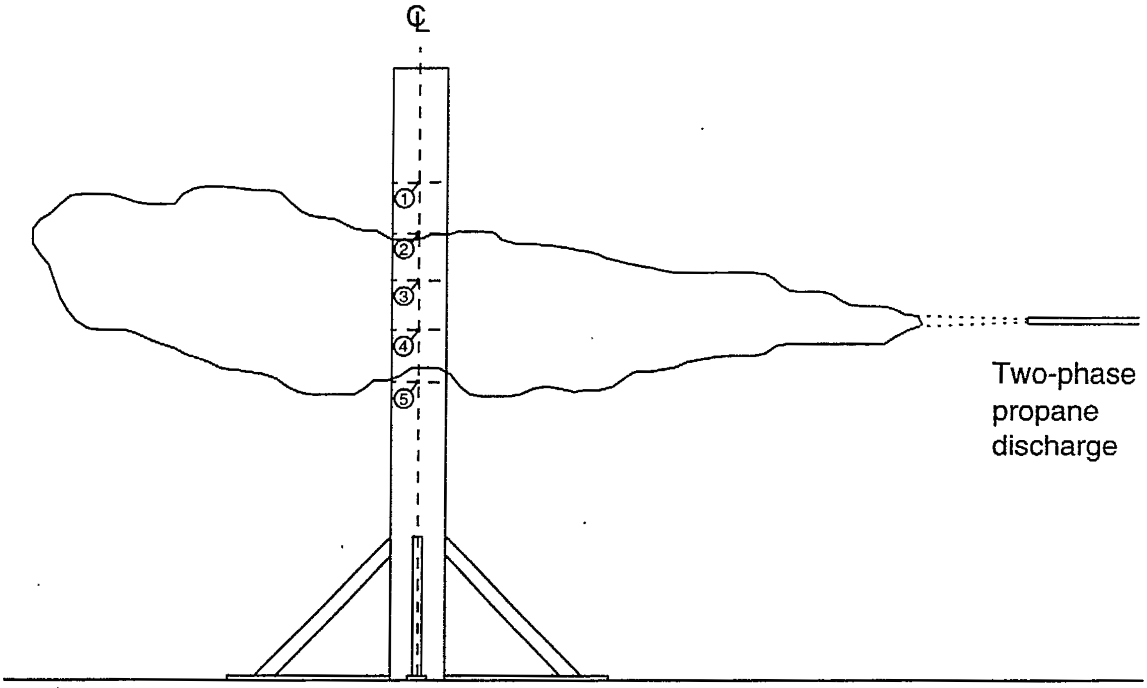
where $T_{surface}$ is the surface temperature, and θ, φ represent polar and azimuthal angular co-ordinates respectively.

For thermal response modelling purposes, an additional approximation is often made, by assuming that the angular dependence of emissivity is sufficiently weak that the steel surface can be treated as a diffuse grey body. Only the temperature dependence of total hemispherical emissivity then remains, and again by Kirchhoff:

$$\alpha(T_{surface}) = \varepsilon(T_{surface}) \quad (2)$$

2. EXPERIMENTS

A carbon steel pipe with 275 mm outside diameter and 10 mm wall thickness was mounted vertically and impinged by a propane jet fire, Figure 1. The pipe was instrumented with thermocouples located in the wall at the five positions shown,



Numbers 1-5 mark embedded thermocouple positions

Figure 1, Jet fire impingement of a steel pipe

250 mm apart. These thermocouples were embedded 2 mm beneath the steel surface to ensure good thermal contact, and at positions 2 and 4 additional thermocouples were fixed at 5 mm depth. The exterior surface of the pipe was prepared to a uniform finish by grit blasting.

The jet fire was fuelled by 0.07 kg s^{-1} of commercial propane delivered at 6 barg as a two-phase flashing jet from a 3.7 mm diameter orifice. The jet flame was directed toward the pipe at a distance of 3 m, and was aimed slightly off-axis to ensure that any cold liquid or gas in the central core of the jet did not impinge.

The region of impingement in the area containing the instrumentation was viewed using an infra-red imaging camera (Agema Thermovision 900). It was not feasible to determine steel emissivity during actual jet fire impingement because of interference from flame radiation. Although it would have been possible to spectrally filter out near infra-red molecular band emissions from the principal hot combustion products, such as CO_2 and H_2O, there was sufficient soot content in the flame to produce a significant emission signal across all wavelengths. As it was impossible to discriminate between the steel grey body continuum and the soot continuum, all measurements made with the Agema camera took place during the cool-down period immediately after the jet fire was terminated.

The Agema camera was positioned 4.5 m away from the pipe and with a resolution of 204 pixels by 128 lines covering the entire field of view, each pixel corresponded to an area of 15 mm by 15 mm in real space. Radiation based measurements, assuming that the pipe was radiating as a black body, were made at five single pixel points chosen to overlap to within ± 3 mm of thermocouple positions in the target (thermocouples 1-5 in Figure 1). From these measurements, temperatures were calculated which were then compared with thermocouple measurements to yield values for emissivity at each thermocouple location.

3. ANALYSIS

The signal generated by the Agema system incorporated contributions from all incident radiation sources, including the object being measured, reflections from the surroundings, and the atmospheric radiation, and is thus treated by the Agema according to the relation:

$$I_{signal} = I(T_{obj})\tau\varepsilon + \tau(1-\varepsilon)I(T_{amb}) + (1-\tau)I(T_{atm}) \qquad (3)$$

where I_{signal} is the total signal, T_{obj}, T_{amb} and T_{atm} are absolute temperatures of the object surface, the surroundings of the object and atmosphere between the object and the Agema respectively. τ is the transmissivity of the atmosphere due to attenuation by water vapour which is a pre-programmed function of atmospheric temperature, relative humidity and distance between the pipe and front lens of the camera. The correlation used to correct for atmospheric attenuation is based on results given in reference [3]. ε is the emissivity of the steel pipe and the $I(T)$'s are the contributing 'thermal values' (equivalent signals) which are related to the absolute temperatures of contributing sources according to:

$$I(T) = \frac{R}{e^{B/T} - F} \qquad (4)$$

Here R is a linear response factor valid over a particular wavelength range; B and F are spectral response factors and T is the absolute temperature. Values for calibration constants R, B, and F were pre-determined by the manufacturer. The validity of the overall calibration function has been verified independently by using the Agema camera to view a black-body furnace and comparing Agema temperatures derived from equation (3) with the known furnace temperatures.

Since, for these experiments, the thermal value of the object (pipe) was large in comparison to those of the surroundings and the atmosphere, these terms can be neglected such that:

$$I_{signal} = I(T_{obj})\tau\varepsilon \qquad (5)$$

With the particular detector, lens and filter combination used, the Agema system was able to respond to radiation in the wavelength range 2 μm to 5.6 μm. If the response of the Agema had been uniform over all wavelengths then it would have been possible to determine emissivity by the following relation:

$$\varepsilon = \left(\frac{T_A}{T_{pipe}} \right)^4 \qquad (6)$$

where ε is the emissivity, T_{pipe} is the actual temperature of the pipe, obtained from the thermocouples, and T_A is the temperature of the pipe if it were emitting as a black body, as determined by the Agema system. However, given the finite optical bandwidth and non-linear response of the Agema, emissivity must instead be calculated from the measurement formula (equation(5)).

From equation (5), using the temperature of the pipe as measured by the thermocouples:

$$I_{signal} = I(T_{pipe})\tau\varepsilon \qquad (7)$$

Similarly from equation (5), using the temperature of the pipe as determined by the Agema assuming that the pipe emitted as a black body:

$$I_{signal} = I(T_A)\tau \qquad (8)$$

Therefore from equations (7) and (8):

$$\varepsilon = \frac{I(T_A)}{I(T_{pipe})} \qquad (9)$$

Finally, substituting equation (4) for $I(T)$ gives:

$$\varepsilon = \frac{\exp(B / T_{pipe}) - F}{\exp(B / T_A) - F} \qquad (10)$$

Equation (10) was used to determine spot surface emissivity values every 20 seconds as the steel cooled down for all five thermocouple positions as shown in Figure 1.

4. RESULTS

Eight jet fire impingement tests were undertaken and a typical set of steel temperature-time profiles measured by thermocouples 1 to 5 is shown in Figure 2. Plate 1 shows a temperature distribution map recorded by the Agema during the early stages of cool down immediately after the fire impingement ceased. Initial temperature rise rates during jet fire impingement varied between 0.8 ^{o}C s^{-1} near the edge of the flame and 2.2 ^{o}C s^{-1} near the centre. By comparing thermocouple readings at two different depths within the steel, temperature gradients normal to the surface were estimated to be $\leq$ 2.7 ^{o}C mm^{-1} during heat up, $\leq$ 0.7 ^{o}C mm^{-1} during the initial stages of cool down between 750 ^{o}C and 400 ^{o}C, and $\leq$ 0.4 ^{o}C mm^{-1} during cool down below 400 ^{o}C. Any systematic corrections to emissivity values due to this effect would therefore be less than 2%.

Other factors affecting the overall uncertainty in emissivity values include errors in quantifying T_A and T_{pipe} ($\leq$ 5% combined as random errors); geometric effects due to the separation of the thermocouples (~1%); spatial resolution of the Agema and overlap precision with thermocouple locations (negligible). Uncertainty in the atmospheric transmission factor, τ, was estimated to contribute an additional 2% to the overall error. The total uncertainty in final emissivity values due to all these effects was therefore less than 10%.

Emissivity results for each thermocouple position as a function of temperature are shown in Figure 3 and reveals a significant distribution of values over the area of impingement. These results are consistent with different surface properties which are clearly visible from a photograph taken just after jet fire impingement (Plate 2). Lowest emissivity

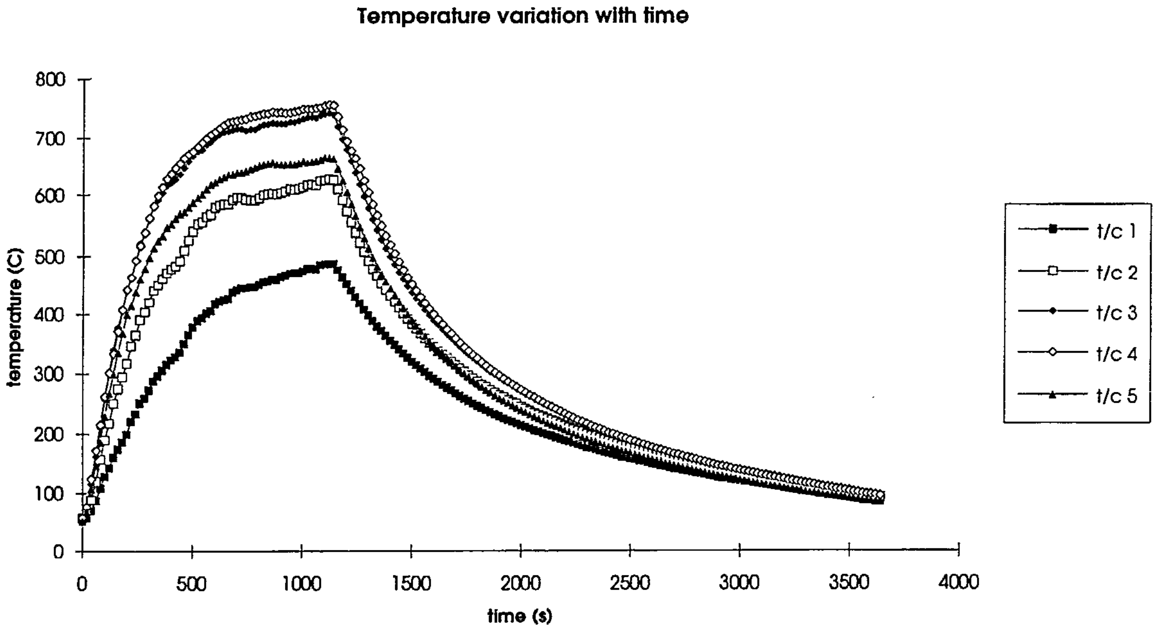


Figure 2, Variation of temperature with time for thermocouples 1 to 5 (t/c 1 denotes thermocouple position 1 etc..)

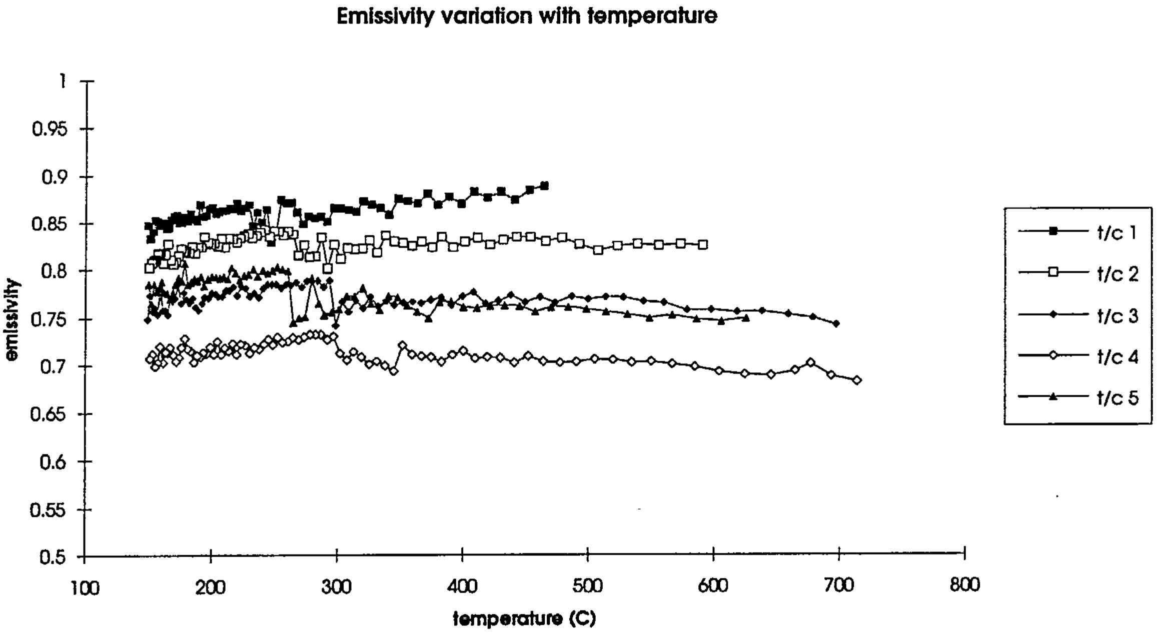


Figure 3, Variation of steel emissivity with temperature for positions close to thermocouples 1 to 5

values (~ 0.7 near thermocouple no. 4) were measured in the central region of impingement where the steel appears to be relatively clean. There was an increase in emissivity with radial distance from this region, rising to $\varepsilon \sim 0.9$ at thermocouple no.1 where the steel surface was noticeably sooty. However, there was little temperature dependency of emissivity within the wavelength and temperature ranges investigated.

5. CONCLUSIONS

The emissivity of a steel pipe exposed to a jet fire was deduced from temperature measurements using embedded thermocouples and radiative emission measurements using an infra-red camera. The resultant emissivities lay between 0.7 and 0.9, depending on the position and correlated with the visual appearance of the surface. The results showed little temperature dependence over the range 150 °C to 750 °C.

Since emissivity is an important parameter in predictive thermal response modelling, reliable values for steel vessels and structures must be known. Assuming these results are applicable during impingement itself, then this work shows that actual values can vary considerably over the region impinged by a jet fire. Therefore, it is not possible to recommend a single particular value for emissivity in the region of jet fire impingement, but rather at least two values characteristic of the distribution in emissivity are required for the thermal response modelling of bare steel. Only then can the overall sensitivity of the model to these values for particular fire loading conditions be assessed.

It is accepted that bare steel surfaces as tested here are rarely found in practice, particularly offshore where most surfaces would be protected by a paint system. In the event of an impinging jet fire, the paint would burn rapidly but could leave a char residue which would then dictate the emissivity. This residue may persist, at least up to temperatures where the strength of the steel is critically impaired. Further work to determine the emissivity of such surfaces may therefore be necessary.

6. NOMENCLATURE

6.1. Symbols

B	Spectral response constant for IR camera	(K)
F	Spectral response constant for IR camera	(dimensionless)
I	Agema camera 'thermal value' signal	(arbitrary units)
R	Linear response constant for IR camera	(arbitrary units)
T	Temperature	(K)
α	Absorptivity	(dimensionless)
ε	Emissivity	(dimensionless)
φ	Azimuthal angle	(radian)
θ	Polar angle	(radian)
τ	Atmospheric transmissivity	(dimensionless)

6.2. Subscripts

A	Agema IR camera
amb	ambient
atm	atmosphere
obj	object
pipe	steel pipe
surface	arbitrary surface of finite surface area

7. REFERENCES

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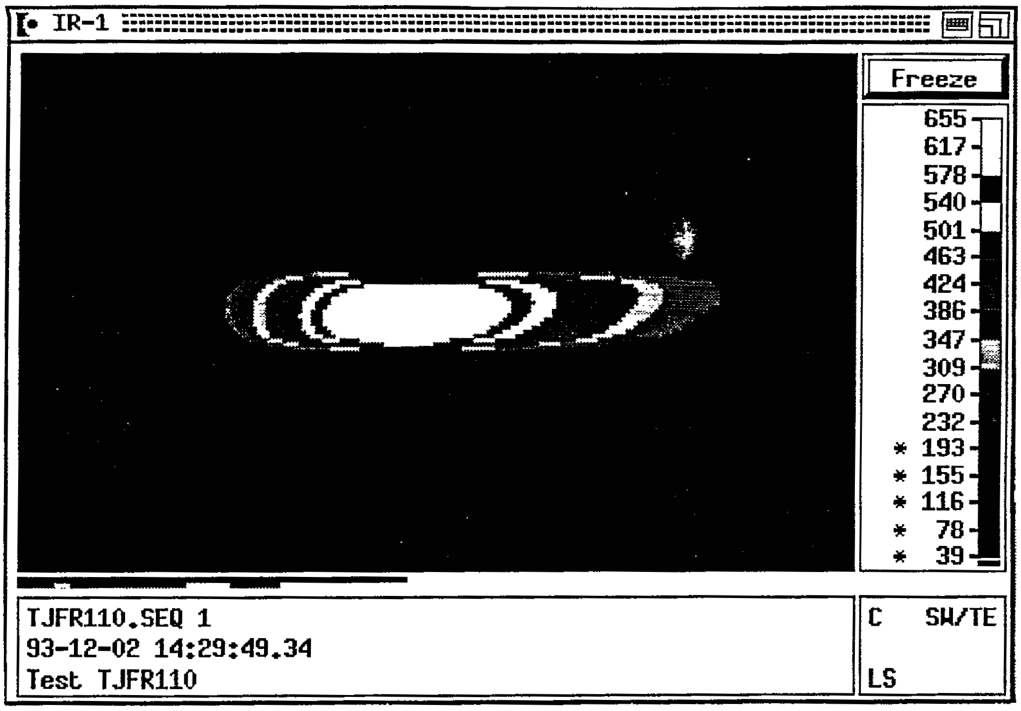

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Plate 1, False colour temperature profile of steel pipe immediately after jet fire impingement

Plate 2, Photograph of steel tubular immediately after jet fire impingement