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Mapping Temperature Distributions in Hot Gas Plumes

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Abstract

A novel measurement technique that uses the infrared imagery of a radiating mesh to map a flow field temperature distribution has been extended beyond its initial capability of < 100°C. The application of this technique to higher temperature flow fields (up to 650°C) is described. A range of suitable mesh materials and coatings have been examined and tested. Selecting materials with high and uniform emissivity values is the key to optimising this method. Successful validation tests performed on a fine stainless steel mesh coated with a high emissivity, high temperature paint are described. It is established that an approximation of the effective emissivity of the porous mesh is simply a function of the porosity and filament emissivity.

Introduction

Infrared thermography can be used to measure the temperature of a body via the measurement of the net radiative flux to a detector. The use of IR thermography is generally confined to the measurement of surface temperatures of solids or liquids as these tend to have high emissivity. Gases generally have very low emissivity and thus are poor emitters making it hard to measure their temperature via thermography. Direct measurement of gas temperatures via IR thermography is limited to gases at high temperature where there are significant concentrations of species such as CO_2 and H_2O, which will radiate significantly in the infrared such as in some non-luminous flames or in combustion product plumes. If a hydrocarbon flame is run rich, carbon soot may form which will act as a significant emitter at close to the flame temperature making thermography more straightforward in these luminous flames. However accurate measurement of the gas temperature via IR thermography also requires an accurate knowledge of the gas emissivity at all locations in the flow field, which is very complex to either measure or predict.

If we introduce a fine mesh of highly uniform emissivity into the heated flow field it will sit at a temperature close to the gas temperature and we can deduce the gas temperature via measurement of the radiation emitted from the mesh [6]. The mesh must be carefully selected to simultaneously satisfy a number of criteria. Its filaments or wires must be fine enough such that they approach the gas temperature, the mesh weave must be fine enough to provide a uniform view to each pixel of the IR camera and the mesh must be sufficiently porous so as to minimise the upstream interference with the flow [7]. The mesh material should also have high emissivity in the IR range (ideally > 0.9) and thus low reflectivity to both ensure a strong signal and to minimise error due to reflection. This emissivity must be uniform across the mesh. A fine mesh placed in a heated flow will reach an equilibrium temperature defined by the local balance of the incoming convective heat flux and the outgoing radiative heat flux. While this technique has been proven at temperatures below 100°C [6] it is desirable to extend it to higher temperatures for a range of applications including the characterisation of engine exhaust flows [5].

Initial testing [6] at high temperature highlighted issues of mesh robustness and non-uniformity of the emissivity on the mesh surface. At these temperatures the mesh will sit at a lower fraction of the gas temperature due to radiative loss but care must be taken to select a filament diameter that maintains the mesh temperature safely below the failure temperature of the mesh material. The mesh filament diameter can be deliberately increased in size to reduce the mesh temperature if necessary, although this will reduce both the spatial and temporal resolution of the mesh, and then the appropriate correction factor applied in post-processing to recover the gas temperature field accurately.

Properties of the Mesh

Mesh Material

The original mesh studies [6] were performed using a fine nylon mesh in flows with temperatures up to 80°C. Nylon proved to be particularly suitable given its availability in fine woven meshes, its high emissivity and its low thermal conductivity. At temperatures above about 200°C nylon is no longer practical. Metal meshes are therefore required for use in the high temperature flows described in this paper. It is noted that the use of other non-metallic fibres such as ceramics may be possible but they are neither readily available in mesh form nor are they likely to be of high enough ductility.

Fine aluminium and stainless steel meshes were selected for this study due to their ready commercial availability in suitable geometries. The fly screen aluminium alloy used has a melting point of approximately 660°C but has degraded mechanical properties at significantly lower temperatures. In contrast stainless steel will maintain high stiffness and strength to significantly higher temperatures than the aluminium.

Conduction Loss

The small diameter (~0.1 mm) and the low thermal conductivity of the nylon mesh material used in the original experiments precluded any significant conduction loss of heat away from the heated zone along the mesh filaments. The use of the larger diameter metal filaments described in this paper presents the potential for significant conduction loss, especially at the much higher mesh temperatures and therefore required investigation.

A numerical study of the smearing of the measured temperature footprint on the mesh was performed along a single filament using a finite element approach. A forced convective input and a radiative heat loss were defined as boundary conditions on the surface of the filament (Figure 1). The convective heat input was modelled as cross flow over a cylinder using the relation in equ. 1 [3].

$$\mathrm{Nu} = 0.3 + \frac{0.62\,\mathrm{Re}_d^{\,1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{3/4}}\left[1+\left(\frac{\mathrm{Re}_d}{282000}\right)^{5/8}\right]^{4/5}$$

for $10^2 < \mathbf{Re}_d < 10^7$ (1)

To investigate the worst case smearing the flow temperature was applied to only a section of the cylindrical filament. The resulting temperature distribution in the filament was calculated and compared with the gas temperature step to ascertain the level of conductive smearing. These calculations were performed for a range of filament diameters, materials and emissivities.

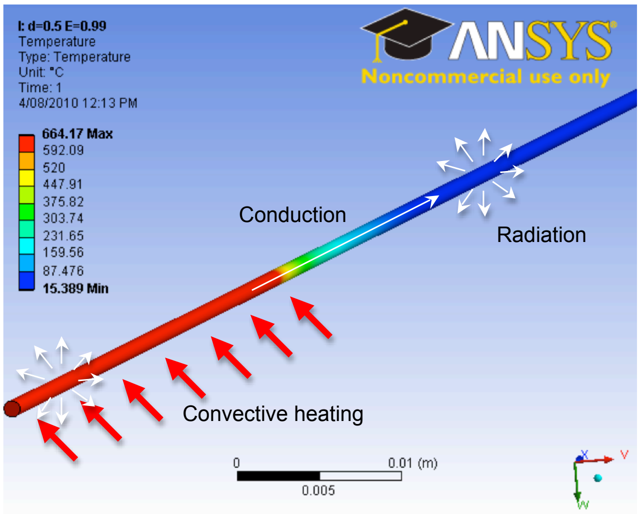

Figure 1. FEM prediction of temperature distribution along the mesh filament when immersed in a zone of high temperature flow.

The level of smearing was defined as the length of unheated filament required for the temperature to drop by 95% of the temperature difference between the heated and unheated sections. The influence of filament diameter was assessed for a range of emissivities from ε = 0.99, 0.5 and 0.1. The case of a high practical emissivity was achievable via the high temperature paint coating discussed in the next section. The influence of emissivity was similarly assessed across a range of filament diameters from 0.1 to 0.5 mm. A 0.22 mm diameter was used in the experimental study, as it was commercially available as stainless steel mesh. The relative conductive smearing for each of these cases is evident from the temperature distributions plotted in Figure 2.

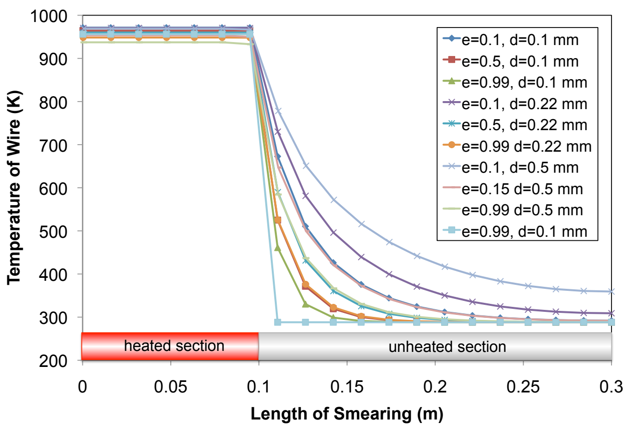

Figure 2. Temperature distribution along stainless steel filaments showing level of conductive smearing for a range of mesh diameters, materials and emissivities.

The dependence of the conductive smearing on emissivity and diameter is more clearly shown in Figure 3. It can be readily seen that either increasing the filament diameter or decreasing the emissivity of the mesh will increase the smearing. This is because a large filament diameter will enlarge the conduction path. The filament diameter will also influence the convective transfer of heat to the mesh. The heat transfer coefficient to the filament in the heated zone is reduced as the diameter is increased although this is outweighed by the improved conduction path. A lower emissivity means that the conducted heat is not rejected as efficiently from the unheated part of the mesh filament increasing the smearing. If a mesh with a small filament diameter and a high emissivity is used the thermal smearing will be minimised.

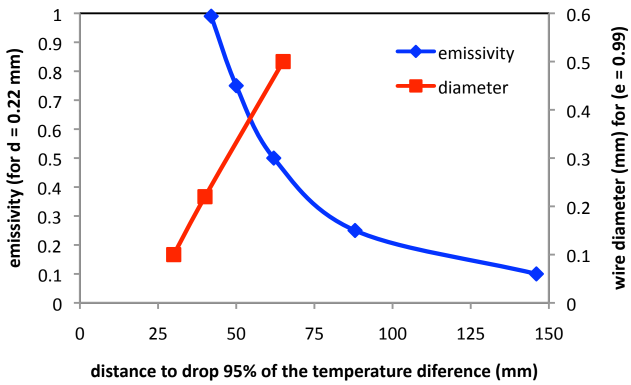

Figure 3. Temperature smearing as a function of emissivity and wire diameter.

It is noted that the conditions modelled assume a worst case driving temperature difference for the conduction loss down the filament and do not account for any potential convective heat removal from the unheated section of the filament, which may result from shear driven dilution at the edge of a free jet passing through the mesh. A measure of the best case (ε = 0.99, d = 0.1 mm) was assessed by applying a convective flow to the unheated section at matching velocity but at ambient temperature. The minimal conductive smearing that results is plotted as the final data set in Figure 2 for comparison.

Mesh Emissivity

The commercial aluminium fly screen used as a mesh came supplied with a matt black powder-coating. The commercial stainless steel meshes were procured bare with a polished finish. Effective and accurate measurements of gas temperature require a uniform and high emissivity [6].

Numerous studies have shown that for steels with uniform surface finish, emissivity is not a strong function of temperature [4, 8, 9]. Earlier testing [6] had confirmed the well-known fact that steel will permanently discolour when heated due to surface oxidation [1, 10]. This could potentially cause a nonuniform emmisivity across the surface with an added dependence on the heating history. Calibration experiments were performed to both measure the change in emissivity resulting from the oxidation of polished stainless plates when heated to high temperature and the ability of preheating to produce an oxide coating of uniform emissivity. It was found that although a uniform oxide coating could be produced by preheating of the whole sample or mesh, the variation of emissivity caused by the oxide formation was small and not sufficient to raise the emissivity significantly (Figure 4).

Instead, a commercially available high temperature paint (VHT FlameProof™ SP102 Flat Black) was used to coat the stainless steel mesh. This paint is rated for use up to 1093°C when cured correctly. Solid plate samples coated with the paint were heated to a range of known temperatures on a variable hot plate to measure the temperature dependence of the emissivity. The surface was viewed by a NEC 7102WV Thermo Tracer long wave IR (8-14 μm) thermographic camera.

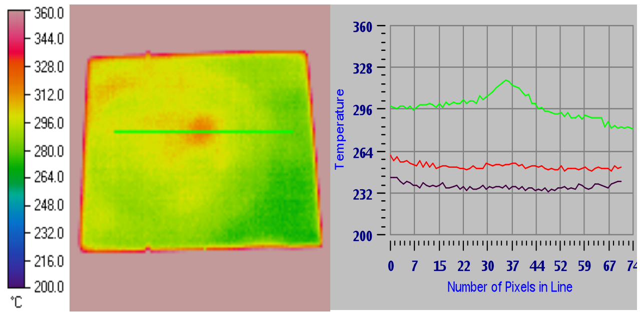

Figure 4. Influence of surface oxidation on the emissivity of a bare stainless steel sample heated uniformly on a hot plate.

A high emissivity is also necessary to reduce the influence of thermal reflection from the mesh, especially of the heat source, which could corrupt the measurement. The high emissivity coating has the additional benefit of reducing the influence of any deposition on the mesh from the flow. Even if soot or other products of incomplete combustion are deposited on the mesh they can do little to locally enhance the already high emissivity whereas on a bare stainless steel or aluminium mesh with lower emissivity they may significantly alter the value and thus the uniformity of emissivity across the mesh.

The coatings were tested for robustness at temperatures up to 700°C. While the high temperature paint on the stainless steel mesh was seemingly unaffected by the high temperatures that it was subjected to, the powder coating on the aluminium mesh deteriorated at approximately 250°C.

Correction Factors

Although the raw IR data provides useful qualitative information about the relative distribution of temperature, two levels of correction must be applied to the measurements to ensure quantitative accuracy. Firstly the temperature reported by the thermographic camera must be corrected using an effective emissivity that is a function of the mesh porosity due to the camera's combined view of the mesh and the background visible through the mesh [6].

radiation received = mesh radiation + background radiation

$$\sigma\varepsilon'\left(T_{ind}^4 - T_{cam}^4\right) = \sigma\Lambda\varepsilon_{mesh}\left(T_{mesh}^4 - T_{cam}^4\right) + \sigma(1-\Lambda)\varepsilon_b\left(T_b^4 - T_{cam}^4\right)$$

$$\varepsilon' = \Lambda\varepsilon_{mesh}\frac{\left(T_{mesh}^4 - T_{cam}^4\right)}{\left(T_{ind}^4 - T_{cam}^4\right)} + (1-\Lambda)\varepsilon_b\frac{\left(T_b^4 - T_{cam}^4\right)}{\left(T_{ind}^4 - T_{cam}^4\right)}$$

$$\varepsilon' = \Lambda\varepsilon_{mesh} \qquad (2)$$

This relation can be rearranged to establish the functional dependence of the effective emissivity (ε') on the other parameters. For the uncooled camera used in these experiments the detector temperature (T_{cam}) is nominally equal to the ambient background temperature (T_b) and thus the right hand term in equ. (2) cancels. If the effective emissivity is now adjusted until the temperature indicated by the camera (T_{ind}) is equal to the mesh temperature (T_{mesh}) then the effective emissivity should only be a function of the emissivity of the mesh material (ε_{mesh}) and the view fraction of the mesh (Λ), which is the complement of the mesh porosity.

Additionally the mesh will sit at a temperature below the actual gas temperature due to the balance of convective input and radiative loss [6]. This is the same as for any thermocouple placed in the flow and is a function of the flow velocity, mesh filament diameter, filament emissivity and the local gas temperature. Thus to recover the true gas temperature a thermocouple correction must be applied to the measured temperature [2]. Careful selection of the mesh geometry can reduce the need for this correction as explained in the previous section and detailed in [6].

Calibration of the Mesh at High Temperature

The prepared metal meshes were tested using a variable power Bosch PHG 630 DCE hot air gun as the source of hot flow. The continuously variable 2kW hot air gun was able to produce a flow of up to 500 l/min at temperatures of up to 630°C.

A 450x450mm sample of stainless steel mesh was mounted in an aluminium frame. This mesh was then painted with the high temperature paint. Five K-type thermocouples were woven into the mesh to produce an array along the vertical centreline of the mesh. The first thermocouple was located at the centre of the mesh with the others spaced out below it. The plume from the hot air gun was played on the centre of the mesh and the mesh was visualised using the IR camera.

The experimental set up is shown in Figure 5 and an example thermographic image is shown in Figure 6. Visible on the infrared image is the strong emission from the thermocouples for which the applied value of effective emissivity is under-representative.

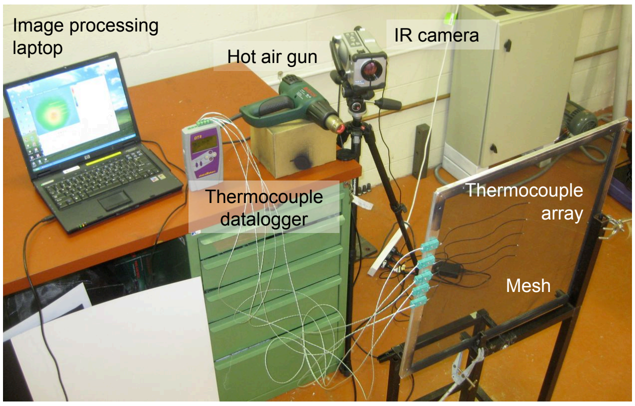

Figure 5. Experimental set up showing the hot air gun heating the painted stainless steel mesh which is viewed by the IR camera.

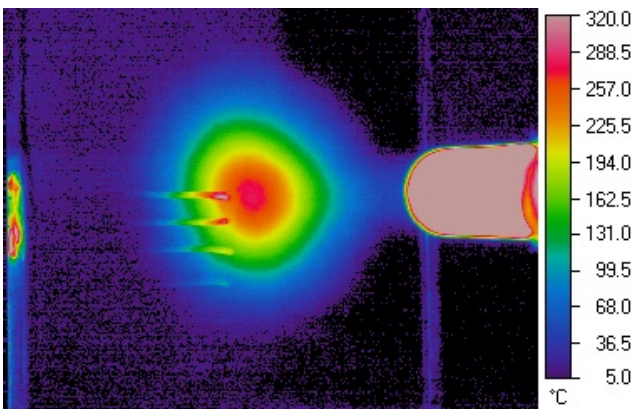

Figure 6. Transverse gas temperature distributions imaged on a fine stainless steel mesh using an IR camera in a 600°C flow of air exiting from a heat source, visible on the right. The imbedded thermocouple array is clearly visible.

As a measure of the validity of the derivation of equ. (2) and the assumption of the dependence of the effective emissivity only on the mesh porosity and filament emissivity, the temperatures measured by the thermocouple array were compared with those deduced from the IR measurements using a fixed emissivity of 0.25. This comparison is plotted in Figure 7 for two different core flow temperatures with the mesh positioned at two downstream locations (1 & 2).

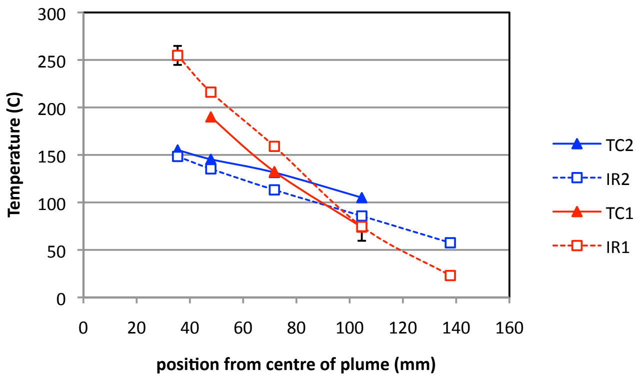

Figure 7. Comparison of local temperatures measured by thermocouple (TC) and IR camera (IR) for two different flow conditions.

When the mesh was positioned closer to the heat source (position 1) it was observed that, as expected, the temperature fell more rapidly away from the plume centreline. For both cases the agreement was reasonable although the measurements were prone to a large spatial error. These measurements confirm that effective emissivity is nominally constant for a given mesh geometry and camera view and it is not a strong function of either the local gas temperature or the local flow velocity which both vary to a large degree across the mesh and the thermocouple array due to the dilution and mixing of the hot jet in the colder ambient air.

Conclusions

The use of a highly porous and emissive mesh to map temperature distributions in a flow has been successfully demonstrated in heated flows at temperatures of up to 650 °C. The dependence of the measurements on mesh geometry, material and surface coating has been examined. It has been shown that the smearing of the temperature measurements due to conduction loss can be minimised by the use of a fine stainless steel mesh. It is beneficial to maximise the value and uniformity of the mesh emissivity via the application of a high-temperature paint. These coated meshes have been shown to remain robust under the high-temperature flows considered. The use of an effective emissivity nominally based solely on the view fraction of visible mesh seen by each camera pixel and the filament emissivity has been validated by the experiments, even at these elevated temperatures. This simplifies the post processing required for the measurements.

Acknowledgments

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