A comparison of postprocessing methods for hot film sensors for the heat transfer analysis of impinging jet flows

Paula Murphy\textsuperscript{1,2}, Tim Persoons\textsuperscript{1}, Seamus O'Shaughnessy\textsuperscript{1} and Darina Murray\textsuperscript{1}
\textsuperscript{1}Dept. of Mechanical and Manufacturing Engineering, Trinity College Dublin, Ireland
\textsuperscript{2}murphp32@tcd.ie

Abstract. The aim of this investigation is to optimise the data post-processing techniques associated with hot film sensors when intended to be used as a means of accurate, high-resolution heat flux measurement. More specifically, this project focuses on the performance of hot film sensors operated in a constant temperature anemometer bridge, used in conjunction with impinging jet air flows. The characteristic heat transfer behaviour in this impinging jet flow provides the reference against which the heat flux data attained using the hot film sensor is compared. As part of this investigation, three hot film calibration methods are examined for a range of sensor overheat values: (A) a wall shear correction method, (B) a physical quasi 1-D conduction model and (C) a physical quasi 2-D fin conduction model. The results show that the method C, when used in conjunction with a 5 K sensor overheat, best replicated that of the reference heat flux sensor for the jet configurations investigated.

1. Introduction
The current approach in experimental heat transfer studies is based on either direct heat flux measurement, such as that provided by a reference thermopile sensor, or on a local surface temperature measurement. In general, the methods available for direct heat flux measurement do not provide the required accuracy for the development of advanced cooling technologies, as the results tend to be spatially averaged and the associated response rates are relatively slow compared to the heat transfer fluctuations. This has led to discrepancies in much of the published literature which highlights the need for improvement. The use of a hot film sensor could offer a solution in this regard as it is small and fast-responding, which should allow for accurate, repeatable heat flux measurements and enable a better cross-comparison between different investigations [1].

The hot film sensor used in this study consists of a nickel sensor element and two copper leads on a polyimide substrate. The sensor element has a thickness of \(<0.2\ \mu m\) and a frequency response rate in the region of 100 kHz [1, 2]. When used in conjunction with a constant temperature anemometer (CTA), the nickel element is heated to a specified temperature above that of the surface of interest, \(i.e.,\) the sensor overheat (\(\Delta T\)), and the heat flux is determined from the power required to maintain \(\Delta T\), which is hence proportional to the square of the voltage, \(E\) [1]. Thus, the heat flux for a given sensor overheat can be inferred if the specific temperature-resistance relationship for the hot film sensor (\(R_f\)) is known. However, this method introduces a bias to the data, as conduction into the surface arising from the sensor overheat cannot be distinguished from the heat flux and the localised temperature elevation can cause a further overestimation, as shown by O’Donovan et al. [1-3].

This bias can be reduced by appropriate post processing and through the optimisation of the sensor overheat value, such that the sensor overheat is sufficiently large to generate a measurable signal without...
significantly interfering with the uniform wall temperature (UWT) boundary condition. This investigation focused on three primary hot film post processing techniques, namely the wall shear correction method (A), a physical quasi 1-D conduction model (B) and a physical quasi 2-D fin conduction model (C), and aimed to further optimise $\Delta T$ when used in conjunction with impinging air jet flows.

2. Hot Film Sensor Data Post Processing Techniques

2.1. The Wall Shear Correction Method
O’Donovan et al. [1] suggested that, to eliminate the induced bias, the heat flux data acquired for the surface under unheated or adiabatic conditions (subscript a) can be subtracted from that for heated conditions (subscript h) for the same sensor overheat, i.e.,

$$q'' = E_R^h R_{f,h} \left[ A_{eff,h} \left( R_{probe,h} + R_1 \right)^2 \right]^{-1} - E_R^a R_{f,a} \left[ A_{eff,a} \left( R_{probe,a} + R_1 \right)^2 \right]^{-1}$$

where $R_{probe} = R_f + R_{wires}$ and $R_1$ is the resistor connected in series with $R_{probe}$ in the CTA Wheatstone bridge setup. The effective area, $A_{eff}$, generated by the sensor overheat can be calculated using Equation 2, where $h_{ref}$ is a reference heat transfer coefficient. This term refers to the stagnation point of the impinging jet and is determined using the Lytle and Webb correlation [4].

$$A_{eff} = E_f^2 R_f \times \left[ h_{ref} \left( R_{probe} + R_1 \right)^2 \left( T_f - T_{jet} \right) \right]^{-1}$$

2.2. The Physical 1-D Conduction Model
Developed by Persoons [5], this method takes an energy balance approach to equate the measured heat dissipation to the sum of the heat convected to the cooling fluid and the heat conducted into the impinging plate, normal to the surface, such that

$$q'' = h \left( T_f - T_{jet} \right) = E_f^2 R_f \times \left[ A_{eff} \left( R_{probe} + R_1 \right)^2 \right]^{-1} - (k/t) \Delta T$$

This calibration procedure takes an iterative approach, where the equivalent conduction coefficient $(k/t)$ is systematically estimated. This is achieved through calculating $A_{eff}$ for a range of surface temperatures using Equation 4 and fitting a second order polynomial to the acquired results. Thus, by rearranging Equation 3, the hot film voltage can be estimated and compared to the experimental findings. The equivalent conduction coefficient can therefore be adjusted accordingly. Similar to the previous method, $h_{ref}$ is calculated based on the Lytle and Webb [4] correlation and, in the case of zero flow, the McAdams [6] natural convection correlation is used.

$$A_{eff,t_s} = E_f^2 R_{f,T_s} \times \left[ \left( R_{probe,T_s} + R_1 \right)^2 \left( h_{ref,T} \left( T_f - T_{jet} \right) + (k/t) \Delta T \right) \right]^{-1}$$

2.3. The Physical 2-D Fin Conduction Model
Persoons [5] proposes a 2-D fin conduction model which accounts for heat conducted both laterally along and normal to the surface. As per section 2.2., the heat flux dissipated is determined using Equation 3, however the effective area formula differs, such that

$$A_{eff} = A_{geo} \left[ 1 + \frac{2}{w} \sqrt{k t / (h + k t)} \right]$$

where $(k/t)$ and $(k t)$ lump the effect of normal and transverse conduction respectively and $A_{geo}$ is the geometric area of the hot film sensor element, i.e., $A_{geo} = l \times w$. The values of $(k/t)$ and $(k t)$ are optimised in an iterative manner until the predicted hot film voltage values for both flow and zero flow conditions are in good agreement with their respective experimental values for a range of surface temperatures. Once optimised, the heat flux is determined by further iterations, such that

$$q'' = E_f^2 R_f \left( A_{eff} \left( R_{probe} + R_1 \right)^2 \right)^{-1} - (k/t) \Delta T$$
This iterative definition of \( q \) usually converges after approximately three iterations. For each iteration, \( A_{eff}^{(i)} \) is determined using Equation (5), where \( h = q''^{(i-1)} \times \left( T_f - T_{jet} \right)^{-1} \) and \( q''^{(1)} = 0 \).

3. Methodology

The experimental apparatus, shown in Figure 1, consisted of a circular jet (diameter \( d = 13 \text{ mm} \)) located perpendicular to a copper impingement surface, onto which a series of sensors were mounted. The impingement surface had the ability to traverse with respect to the jet nozzle by means of a stepper motor. An uncoated Sfenlex® SF9902 Single Element heat flux sensor was mounted flush with the impingement surface alongside a Rdf Micro-Foil® heat flux sensor, which was used to benchmark the hot film sensor’s performance due to its general consistency with the published literature. The initial jet configuration investigated was for a Reynolds number of \( Re = 5000 \) and a \( H/d \) value of 1. Data was collected for sensor overheat values of \( \Delta T = 3 \text{ K}, 5 \text{ K}, 7 \text{ K} \) and \( 10 \text{ K} \). A constant plate temperature of \( 65^\circ\text{C} \) was used throughout and the hot film data acquisition frequency was fixed at 10 kHz. Further data was collected at \( Re = 12000 \) for \( \Delta T = 3 \text{ K} \) and \( 5 \text{ K} \) and all other parameters remained constant.

4. Results and Discussion

From the results acquired, selected hot film \( Nu \) profiles are presented in Figure 2, along with a Micro-Foil sensor profile; the values predicted at the stagnation point using the Lytle and Webb [4] correlation are also shown. For both \( Re \) investigated, the hot film \( Nu \) data corresponding to \( \Delta T = 3 \text{ K} \) and \( \Delta T = 5 \text{ K} \) best agree with that of the Micro-Foil, regardless of the post processing method used, hence the data corresponding to \( \Delta T = 7 \text{ K} \) and \( \Delta T = 10 \text{ K} \) is excluded. In both Figure 2 (a) and Figure 2 (b), the trends associated with hot film \( Nu \) profiles are in good agreement with those found in the published literature regarding impinging jets, where the \( Nu \) is greater towards the stagnation point and generally decreases with increasing radial distance [6]. In addition, each plot indicates a strong secondary peak at approximately \( 1.5d \), which is in keeping with that typically expected for low \( H/d \) values [2]. This behaviour is also consistent with the results acquired using the Micro-Foil, where the radial averaging induced due to the Micro-Foil sensor’s low spatial resolution is also evident.

Based on the results shown in Figure 2, the hot film post processing method C provides the best representation of the \( Nu \) profile for both \( Re \) values, as the curves produced are the most closely aligned with that of the Micro-Foil overall. For method A, the results suggest a slight overestimation of the \( Nu \) in regions of low heat flux, whereas the method B tends to underestimate \( Nu \) values in these regions and to approach 0 at higher radial distances. Conversely, method C provides the best evaluation of the \( Nu \) across all regions and levels off as expected at higher radial values. In general, method C seems relatively unaffected by the sensor overheat value unless the heat flux is very high, such as that at the stagnation point for \( Re = 12000 \); however the estimated uncertainty for method C using \( \Delta T = 5 \text{ K} \) can be seen to encapsulate this value. A higher \( \Delta T \) may thus be required when measuring larger \( q'' \) values.

To investigate this finding further, the effective areas for each of the post processing methods, as well as the equivalent conduction coefficient values if applicable, were examined with respect to the sensor overheat, as shown in Figure 3, where both parameters were found to be relatively independent of the Reynolds number. With regard to the effective area, very opposing trends can be seen in Figure 3.
(a), where the $A_{\text{eff}}$ values associated with method C lie distinctly between that of the A and B methods, which could provide some explanation as to why method C best fits the Micro-Foil data.

Figure 2. Comparison between the Micro-Foil and hot film sensor radial $Nu$ profiles for $\Delta T = 3\, K$ and $5\, K$, where $H/d = 1$ and $Re = (a) 5000$ and (b) $12000$. Uncertainty is shown for method C for $\Delta T = 5\, K$ only for clarity.

The calculated equivalent conduction coefficient values for the B and C methods are shown in Figure 3 (b) and compared to that of the adhesive layer between the sensor overheat and the plate thermocouple. For each sensor overheat, the $(k/t)$ values associated with method C are less than that of method B, which could explain why the $Nu$ curve for method B tended to approach zero. It is also interesting to note that the sensor overheat and data post-processing method combination which best calculated the correct $Nu$ curve as per Figure 2, i.e., method C with a sensor overheat of 5 K, also had values for both $(k/t)$ and $(kt)$ that were closest to that of the adhesive.

Figure 3. Relationship between the sensor overheat and (a) $A_{\text{eff}}$ and (b) $(k/t)$ and $(kt)$. The values for $(k/t)$ and $(kt)$ are compared to that of the adhesive layer beneath the hot film sensor, where $k_{\text{adh}} \approx 0.11\, W/m^2K$ [7] and $t_{\text{adh}} \approx 0.25\, mm$.

5. Conclusions
This investigation explored the data post-processing methods associated with hot film sensors when used for high resolution heat flux measurement, with a view to elimination of the bias induced as a result of the sensor overheat. The study was conducted for impinging jet flows. For the jet configuration investigated, the results suggested that method C with $\Delta T = 5\, K$ provided the most accurate radial $Nu$ curve when compared to that of the Micro-Foil sensor; this may be linked to the close alignment between $(k/t)$ and $(kt)$ with that of the adhesive layer beneath the hot film sensor.

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