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THE AMMONIA AND DIAZZO SURFACE COATING TECHNIQUE FOR MEASURING ADIABATIC FILM COOLING EFFECTIVENESS

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ABSTRACT

A technique for taking quantitative measurements of adiabatic film cooling effectiveness has been developed. It is based on an established surface-flow visualisation technique. It makes use of the analogy between heat and mass transfer and relies on measurements of surface concentration. The surface of the test piece is coated with chemicals that react with the coolant flow which has been seeded with gaseous ammonia and water vapour. The result of the reaction is a visible trace of varying intensity, dependent on the local concentration of coolant. An on-line calibration is performed during the experiment, giving the correlation between the darkness of the trace and the concentration of the coolant, and thus the adiabatic film cooling effectiveness.

Cooling effectiveness results from the ammonia and diazo technique are compared to ones obtained by a gas sampling technique and are in excellent agreement. A significant advantage of the ammonia and diazo technique is that it provides a complete representation of the film cooling effectiveness distribution. Furthermore, the technique is low-cost and easy to use.

NOMENCLATURE

$C_{coolant}$	coolant concentration
$C_{free\ stream}$	free stream concentration
$C_{adiabatic\ wall}$	impermeable wall concentration
h	heat transfer coefficient
$M = \frac{\rho_{jet} \cdot V_{jet}}{\rho_\infty \cdot V_\infty}$	blowing ratio
ρ_{jet}	coolant jet density
ρ_∞	free stream density
q''	wall heat flux
$T_{coolant}$	coolant stagnation temperature
$T_{free\ stream}$	free stream stagnation temperature
T_{wall}	actual wall temperature
$T_{adiabatic\ wall}$	adiabatic wall temperature
η	film cooling effectiveness
η_{iw}	impermeable wall effectiveness
V_{jet}	coolant jet velocity
V_∞	free stream velocity

INTRODUCTION

An increase in the cycle efficiency of gas turbines can be achieved through higher turbine entry temperatures. In turn, this requires the development of materials and efficient cooling methods. One cooling method that has gained increasing importance is film cooling, where coolant air is discharged through discrete holes forming a protective layer between the hot mainstream gas and the surface that is to be protected.

The temperature that an adiabatic wall would assume under the influence of the injected coolant is of interest to film cooling research. The adiabatic wall temperature drives the wall heat flux q", which in film cooling is usually defined using an analogy to convective heat transfer:

$$q'' = h \cdot \left(T_{wall} - T_{adiabatic\ wall} \right) \tag{1}$$

A first order approximation for the heat transfer coefficient h relates it to the value of the coefficient occurring in natural convection without injection. The adiabatic wall temperature is usually expressed as a dimensionless temperature, or adiabatic film cooling effectiveness η.

$$\eta = \frac{T_{adiabatic\ wall} - T_{free\ stream}}{T_{coolant} - T_{free\ stream}} \tag{2}$$

An isothermal film cooling effectiveness can be defined based on isothermal wall arguments. This is an alternative to the adiabatic film cooling effectiveness and is used in temperature based experimental studies with isothermal wall conditions.

Techniques for the experimental determination of adiabatic film cooling effectiveness can be classed into two groups. In the first group the coolant is injected at a temperature different to the mainstream and the adiabatic wall temperature is measured directly. Thermocouples, thermochromic liquid crystals or infra-red cameras may be used to measure the surface temperature. In these experiments it is often difficult to achieve an adiabatic wall, so corrections are applied to allow for conduction in the wall. The second group of techniques relies on the analogy that exists between heat and mass transfer. Coolant air at the same temperature as the free stream is seeded with a tracer gas, and surface concentrations of the tracer gas are measured. Analogous to the adiabatic film cooling effectiveness η, an impermeable wall effectiveness based on concentration measurements can be defined:

$$\eta_{iw} = \frac{C_{impermeable\ wall} - C_{free\ stream}}{C_{coolant} - C_{free\ stream}} \tag{3}$$

If the temperature field above an adiabatic surface is similar to the concentration field above an impermeable surface, the two effectiveness parameters are equal, so that

$$\eta_{iw} = \eta \tag{4}$$

To date, surface concentration measurements have been performed by analysing gas samples taken through tappings in the wall. This paper describes an alternative technique for performing surface concentration measurements; the ammonia and diazo surface coating technique.

The ammonia and diazo surface coating technique for measuring adiabatic film cooling effectiveness is based on an established surface-flow visualisation technique. In investigations such as those reported by Joslyn and Dring (1983) and Hodson and Addison (1988), the surface of the test piece is coated with Diazo paper. Pure ammonia gas is then either passed slowly through wall tappings or is injected from an upstream probe. The ammonia gas leaves a trace on the paper as it is transported over the surface by the flow under investigation. Dring et al. (1980) and Jabbari et al. (1994) used the same basic technique to visualise coolant flow in film cooling investigations. The coolant air was seeded with ammonia gas and was passed over a surface covered with diazo paper, leaving traces of varying darkness. The first suggestion of the use of the ammonia and diazo technique for quantitative effectiveness measurements seems to have been by Soechting et al. (1987). To simulate a realistic density ratio they used CO_2 as coolant, demonstrating the use of the basic technique with other coolant gases than air. They did not develop a quantitative ammonia and diazo technique, as they concluded that extensive calibrations were necessary to correlate the darkness of the trace to the coolant concentration.

In both the temperature and concentration based experiments, different techniques are capable of different degrees of resolution of film cooling effectiveness. Jabbari et al. (1994), for example, encountered difficulties with their gas sampling technique. As experimental conditions were varied, the coolant trajectories moved relative to the fixed gas sampling tappings. In practice, thermocouple and gas sampling techniques are only able to measure at predetermined locations. The thermochromic liquid crystal, infra-red camera or the ammonia and diazo techniques cover a large area of the surface and provide a complete representation of the film cooling effectiveness.

EXPERIMENTAL SETUP

A flat plate with a single row of five discrete film cooling holes has been used in the development of the measurement technique. It was first used by Burch (1994) and is shown in Fig. 1. The five holes inject cooling air at an angle of 35° to the surface. The holes with a diameter of 10 mm have a length to diameter ratio of 3.5 and a spacing to diameter ratio of 3.0. The test section is used in a low speed wind tunnel, and is operated at a free stream velocity of 20 m/s. The coolant air is injected at a blowing ratio M = 0.5, which at the unity density ratio used results in a jet to free stream velocity ratio of 0.5.

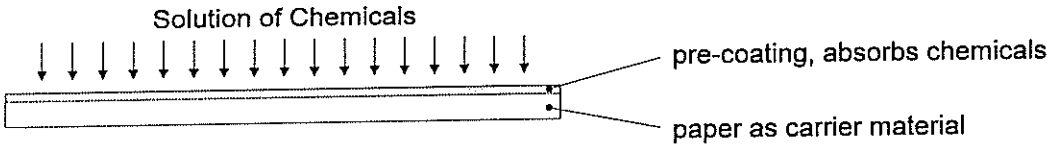
THE MEASUREMENT TECHNIQUE

In the ammonia and diazo surface coating technique the test piece is coated with chemicals that react with the coolant flow which has been seeded with gaseous ammonia and water vapour. The result of the reaction is a trace of varying darkness. The relationship between the darkness of the trace and the concentration of the coolant is determined. Using this relationship, the distribution of adiabatic film cooling effectiveness may be calculated.

Diazo Paper and Film

The "Ozalid paper" or "blueprint paper" described here is correctly termed "diazo paper for ammonia development". It is manufactured in the UK by OZALID (UK) Ltd., Loughton. The original use for diazo paper lies in the reproduction of technical drawings. The transparency that is to be copied is laid over the diazo paper, which is then exposed to light from either a fluorescent or a mercury vapour lamp for approximately one minute. In the areas not covered by lines of the technical drawing, the light sensitive chemicals are 'burnt' away, and the diazo paper is desensitised to ammonia. After exposure, the paper is developed. It is passed through an atmosphere of water vapour and ammonia. The remaining chemicals react with the ammonia and water vapour to colour the paper. The result is that the areas which had not been exposed to the light are coloured, giving a reproduction of the original drawing.

Diazo paper is made from pure, non-recycled, pulp. The paper is first covered with a pre-coating layer containing silica-gel. This absorbs a water solution of chemicals that is then applied. The paper is finally dried to between 3% to 5% water content. The chemicals applied to the paper determine the colour of the final image and the required exposure time to light. They consist of ten to fifteen different components, mainly diazos, couplers, and additives. The diazos are light sensitive and react with ammonia and water to form radicals. The couplers react with the radicals to form the dyes colouring the paper. The additives may include stabilisers, contrast enhancers, and ethylene glycol to absorb moisture.



Polyester film is an alternative carrier material to paper. "Ozafilm" consists of a 0.050 mm polyester film covered with chemicals embedded in resin, and was preferred in the experiments described below. It has a smoother surface, is easier to remove after the experiment after being fixed with double-sided-adhesive tape, and does not contain residual moisture. Although paper and polyester film are very convenient carrier materials, it may not always be possible to fix them satisfactorily to the surface. However, the solution of chemicals may be applied directly to the experimental surface. This is useful in the study of very complex three-dimensional geometries.

Experimental Procedure and Processing

Prior to the experiment, diazo film is fixed to the experimental surface with double-sided-adhesive tape. The wind tunnel is started, and conditions are allowed to stabilise. The cooling air is then seeded with ammonia gas (~0.5%) and water vapour (~90% rel. humidity) for between one and two minutes, depending on the desired darkness of the traces. After the experiment the image is fixed by exposure to light. An example of the resulting image is shown in Fig. 3. A visual inspection directly reveals coolant trajectories, but processing is necessary to determine the cooling effectiveness. The technique relies on the principle that the darkness of the traces on the diazo surface coating is dependent on the surface concentration of the coolant gas.

A standard for comparison is required to relate the darkness to surface concentration. For this reason, a calibration strip such as the one shown in Fig. 4 is produced on-line for every experiment by mixing the coolant gas mixture with free stream air from the wind tunnel in known ratios. To create this calibration strip, a mixing box has been designed (see Fig. 2). It provides eleven sampling tubes with coolant to mainstream mixtures of 0% to 100%, in 10% steps. Each of the sampling tubes is fed by a total of ten holes. The 0% tube is fed from ten holes ejecting mainstream air, the 10% tube is fed from nine mainstream holes and one coolant gas hole, and so on. The air in each of the sampling holes is passed over a strip of diazo paper or film, creating the calibration strip. The function of the mixing box was checked and found to be satisfactory by analysing gas samples from each of the sampling tubes.

As only the coolant is seeded with ammonia and water vapour, the free stream concentration corresponds to a value of zero percent. With the mixing box defining the coolant concentration as 100%, the measured relative concentration values are equivalent to the adiabatic film cooling effectiveness η. Equations (3) and (4) therefore become:

$$\eta = \eta_{iw} = \frac{C_{\text{impermeable wall}}}{C_{\text{coolant}}} = C_{\text{relative}} \tag{5}$$

In order to quantify the darkness distribution, both the image and the corresponding calibration strip are digitised simultaneously using an optical scanner. The analysis of the calibration strip gives the relationship between the darkness of the trace and the relative concentration of the coolant. This results in calibration curves such as the one shown in Fig. 5. By applying the calibration using interpolation between the calibration points, the relative concentration of each measurement point is determined.

For the results presented here, the images were scanned using 256 greyscales at a resolution of 75 dots per inch, giving approximately three measurement points per millimetre. Fig. 3 shows such a scanned image of an ammonia trace. The best scanner settings have to be determined experimentally. For a paper with blue traces it was found that the 8-bit blue content of a 24-bit RGB colour image gave the best variation, whereas the polyester film with black traces gave best results when 8-bit greyscales were analysed. The scanning resolution was found to be sufficient with 75 dpi, but could be increased if necessary as the scanner used has an optical resolution of 400 dpi.

VALIDATION OF THE AMMONIA AND DIAZO TECHNIQUE

A gas sampling technique for determining film cooling effectiveness was used in the validation of the ammonia and diazo surface coating technique. The cooling air was seeded with ethylene gas and samples were taken from surface tappings at fixed locations downstream of injection. Using an infra-red gas-analyser, the concentration of the tracer gas in the samples of the surface flow was determined.

The gas sampling technique is not problem free, as the samples should be taken without disturbing the flow. For example, suction rates that are too high could result in samples that are no longer representative of the surface flow, or could result in a change of the flow structure of the coolant jet. A suction velocity of 0.1 of the free stream velocity was used in the experiment. For similar experimental dimensions and conditions, Pedersen (1972) found that the flow structures of a coolant jet at a blowing ratio of $M = 0.5$ were not influenced by suction. He found that a suction velocity of about 0.1 of the free stream velocity gives a representative sample of the surface flow. To verify that suction does not change the cooling effectiveness at the measurement points, an ammonia and diazo trace was produced while simultaneously sucking through the sampling tappings. A comparison of the cooling effectiveness downstream of the centreline of a cooling hole measured using the ammonia and diazo technique with and without suction is shown in Fig. 7. A change in the measured surface concentrations due to suction is not visible.

Fig. 8 shows the comparison between the results of the gas sampling technique and averaged results from the ammonia and diazo technique. The results are in good agreement.

DISCUSSION

A result obtained using the ammonia and diazo technique on the flat plate used in this investigation is shown in Fig. 6. This shows the distribution of film cooling effectiveness over the surface downstream of the central hole. The lateral spreading of the jets as they mix with the main stream and the reduction in centreline effectiveness can be seen. The jets merge after about 20 hole diameters downstream of injection, where the cooling effectiveness between the jet cores is between 5% and 10%.

Fig. 9 shows a result obtained in the vicinity of the central cooling hole on the flat plate. Details such as the influence of the horseshoe vortex can easily be seen. The horseshoe vortex forms as the boundary layer of the main flow encounters the blockage presented by the jet. It rolls up and wraps itself around the jet, in this case staying on the surface and being entrained into the counter rotating vortex structure of the jet as it develops downstream. The level of detail shown in this figure and in Fig. 6 would have been difficult to obtain using discrete measurement points, as would have been the case when using gas sampling or thermocouples.

The concentration of ammonia and the time of exposure to the mixture can be varied to achieve certain experimental goals. The calibration curve shown in Fig. 5 illustrates the non-linearity of the relationship between darkness and concentration. Clearly saturation occurs above certain levels of ammonia concentration. In experiments where the cooling effectiveness far downstream is of interest, higher concentrations and exposure times are used. These result in a darker trace, increasing the resolution at low concentrations. The results shown in Fig. 7 are from experiments having calibration curves similar in character to the one in Fig. 5. The region of saturation and therefore low resolution lies above 50% to 60% cooling effectiveness. Small changes in colour result in large changes in effectiveness, illustrated by the large steps in the upper regions of the curves in Fig. 7. The repeatability of the results is excellent in the regions of high resolution and deteriorates slightly in the upper regions. The average of the curves is shown in Fig 8., illustrating that the accuracy in the experiments performed, even in the regions of low resolution, is better than 5%.

For studying the vicinity of injection a lighter trace is required. By producing a lighter trace, the resolution in regions of high cooling effectiveness is increased. The result shown in Fig. 9 was taken from such an experiment. The corresponding calibration curve is shown in Fig. 10. The resulting poor resolution at low cooling effectiveness results in the noise seen upstream of the hole in Fig. 9.

It has already been noted that the darkness of the trace left by the coolant mixture is dependent on several factors. For the chemical reaction to take place, ammonia and water have to be present. It is therefore not surprising that higher concentrations of ammonia result in a darker trace. Humidity has an equally strong effect. Without the addition of water vapour, even pure ammonia will not produce a trace on the polyester film. On paper, the residual moisture from the manufacturing process is

sufficient to allow the chemical reaction to take place, but again the addition of moisture will significantly darken the resulting trace. In high speed experiments where the supply of coolant at 90% relative humidity can cause problems due to condensation, the use of paper is an alternative. Exposure time to ammonia and water vapour also affects the darkness of the trace, with a longer exposure resulting in a darker trace.

Experiments were performed to determine if the flow Reynolds number or if ammonia or water vapour depletion have an influence on the darkness of the trace. For the depletion experiment, a mixture of ammonia and water vapour was passed through a two metre long tube, the inside of which was coated with diazo film. For the Reynolds number experiment, a mixture of fixed concentration was passed over a series of diazo film strips at different flow velocities, covering the range of Reynolds number found in the experiment. Neither the Reynolds number nor ammonia or water vapour depletion had a detectable effect on the darkness.

In performing the on-line calibration, the above mentioned dependencies are automatically taken account of. The calibration strip is exposed to the same ammonia and water vapour concentrations for the same amount of time as the experimental surface, thus eliminating these influences.

The influence of temperature is initially surprising, as a higher temperature gives a lighter trace. In the present experiment, the temperature influence has been taken account of by having the free stream, the coolant air, and the calibration box at the same temperature. To illustrate the influence of temperature, flows of fixed concentrations were cooled, with diazo film strips being placed upstream and downstream of the cooling device. The resulting differences in darkness are shown in Fig. 11. Even a temperature difference of 3°C changes the darkness by about 20%. This difference will change the interpreted value of cooling effectiveness according to the local slope of the calibration curve. By careful insulation of the mixing box and its feed lines, the on-line calibration should be able to take account of a coolant temperature that is different from the main stream, as the calibration strip is exposed to representative samples of both.

ammonia concentration	strong influence	higher concentration -> darker trace
humidity	strong influence	higher humidity -> darker trace
time	strong influence for first 30 sec.	longer exposure -> darker trace
temperature	strong influence	higher temperature -> lighter trace
Reynolds number	no influence visible	-
ammonia / water vapour depletion	no influence visible	-

Table 1 Dependencies of the Ammonia and Diazo Reaction

Under certain circumstances it may not be possible to produce a valid calibration strip such as the one shown in Fig. 4. An alternative method of calibration is proposed by Haslinger and Hennecke (1994). For a specific experimental condition, a gas sampling technique such as the one used for validation here may be used to determine concentrations at discrete locations on the surface. An ammonia and diazo trace is produced for the same condition. By comparing the measured surface concentrations to the darkness values of the trace at the same locations, a calibration curve can be derived. Initial ammonia and diazo traces could be used to determine which locations will give a sensible distribution of darkness values. However, the appropriate locations can vary with experimental conditions as the coolant trajectories change (see Jabbari et al. (1994)). By using this alternative method of calibration the above mentioned dependencies of the reaction are also taken account of, and the advantages inherent in the ammonia and diazo technique remain.

CONCLUSIONS

A usable technique for the quantitative measurement of adiabatic film cooling effectiveness has been developed. It is based on the established ammonia and diazo surface-flow visualisation technique. The experimental procedure consists of three steps. Firstly, the surface under investigation is coated with chemicals that react with ammonia gas and water vapour, forming a trace of varying intensity. Secondly, the experiment is run with the coolant gas being seeded with gaseous ammonia and water vapour. Finally, the image is fixed through exposure to light. The resulting image directly reveals coolant trajectories.

In order to make concentration measurements and therefore determine the film cooling effectiveness, three processing steps are necessary. Firstly, the image is digitised using a optical scanner. Secondly, by evaluating the on-line calibration, the relationship between the darkness of the trace and the coolant concentration is determined and applied to the scanned image. Finally, the 2D-array of data is presented in form of axial or lateral variations, or as an area contour or surface plot of adiabatic film cooling effectiveness.

A comparison between results from the ammonia and diazo technique and results from a gas sampling technique has shown good agreement. The repeatability of the results over separate experimental sessions was shown and found to be good. The measurement technique is non-intrusive, low-cost, easy to use, fast, and gives a complete overview of the cooling effectiveness

distribution. The full area coverage ability is very important in film cooling investigations in which the coolant trajectories vary strongly with experimental conditions, such as in platform film cooling.

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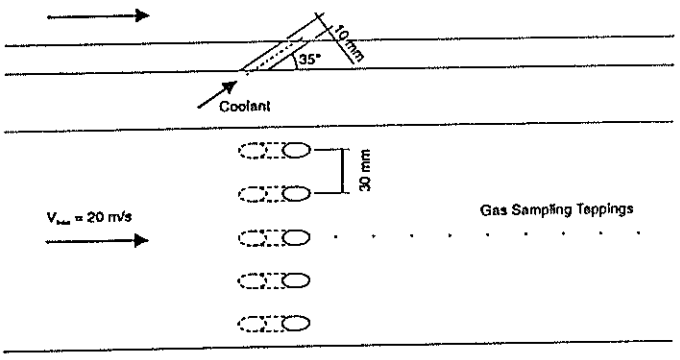

Figure 1 Experimental Setup

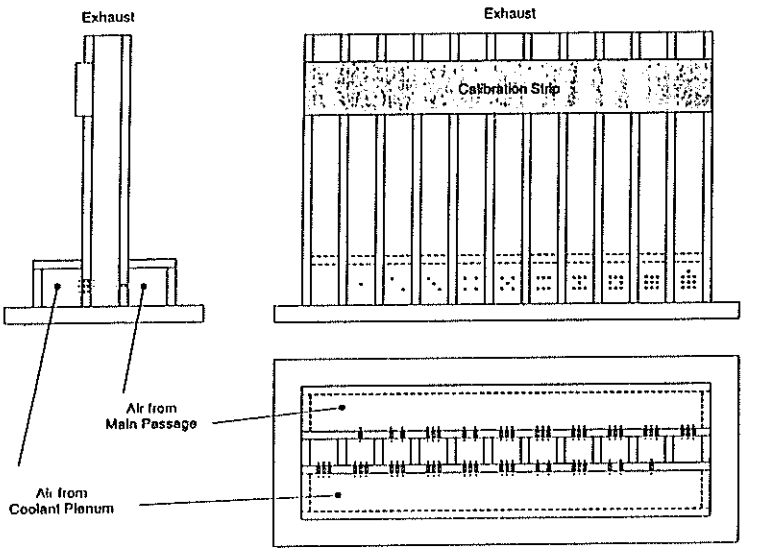

Figure 2 Mixing Box for On-Line Calibration

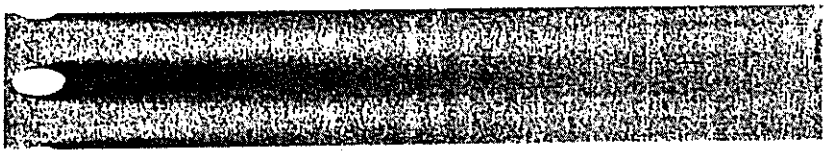

Figure 3 The Scanned Trace of a Film Cooling Jet Injected at 35°

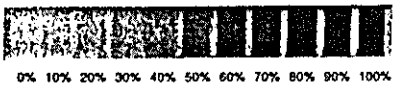

Figure 4 Calibration Strip Produced for the Trace in Fig. 3

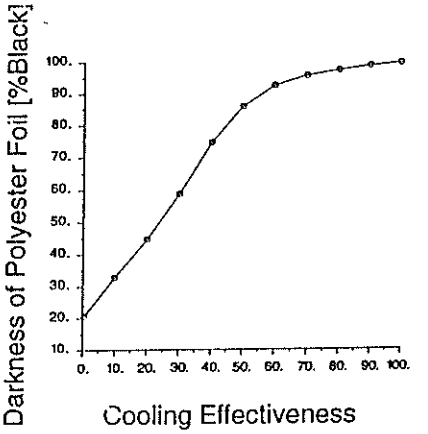

Figure 5 Calibration Curve Derived from Fig. 4

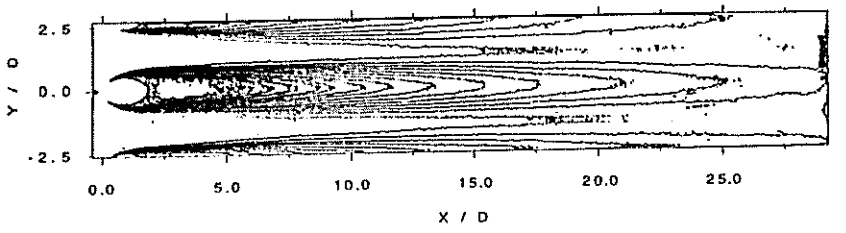

Figure 6 Contours of Adiabatic Film Cooling Effectiveness; Contour Interval 5%

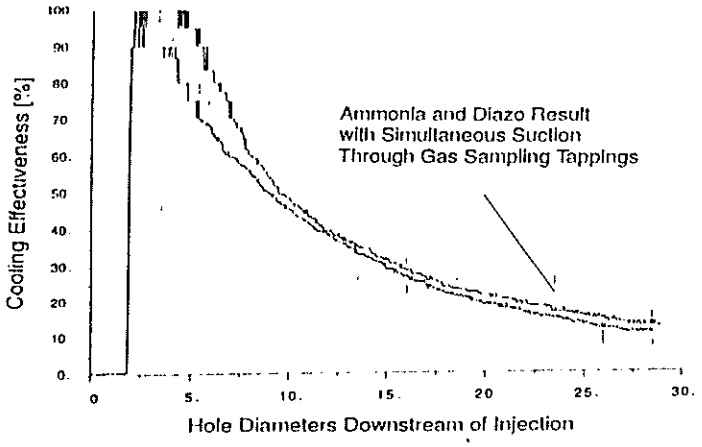

Figure 7 Cooling Effectiveness Along the Centreline Downstream of Injection Comparison of Various Ammonia and Diazo Results With and Without Suction

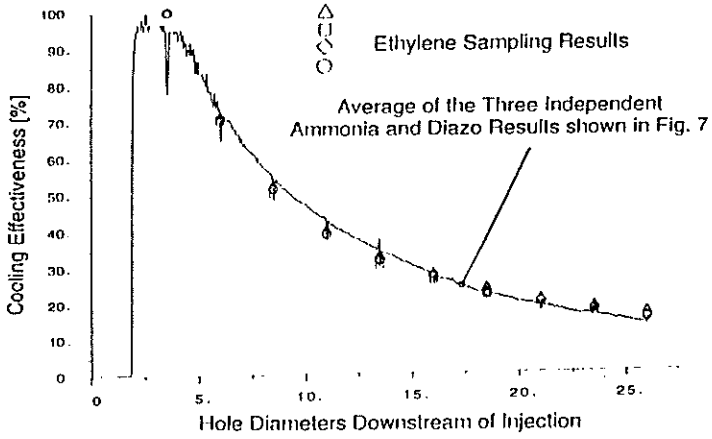

Figure 8 Cooling Effectiveness Along the Centreline Downstream of Injection Comparison of Averaged Ammonia and Diazo Results and Gas Sampling Results

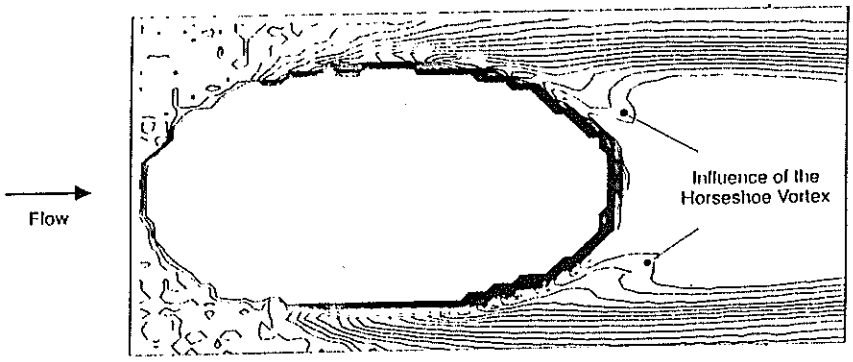

Figure 9 Contours of Film Cooling Effectiveness in the Vicinity of the Hole; Contour Interval 5%

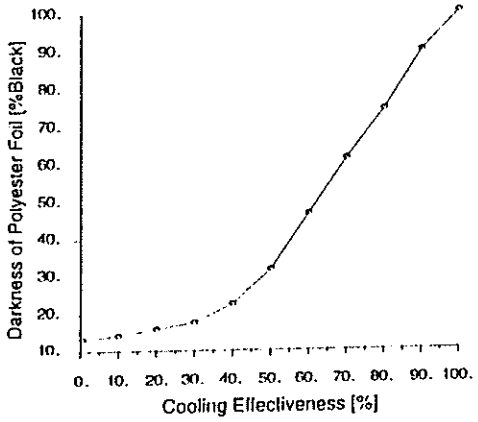

Figure 10 Calibration Curve Used for Figure 9

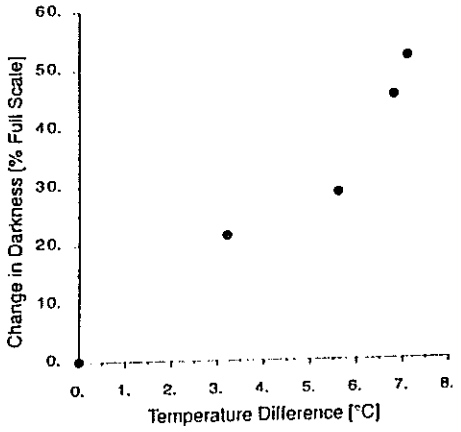

Figure 11 Change of Darkness Due to a Change in Temperature