Simultaneous kHz-rate temperature and velocity field measurements in the flow emanating from angled and trenched film cooling holes

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A B S T R A C T
To design more efficient film cooling geometries for gas turbines, non-intrusive measurements of the flow temperature, velocity and derived quantities like the turbulent heat flux are needed in well-defined, generic flow configurations. With this aim we have applied thermographic particle image velocimetry (thermographic PIV) to investigate the flow emanating from angled and trenched cooling holes in a closed-loop optically-accessible wind tunnel facility. BAM:Eu2+ thermographic phosphor particles were seeded into the flow as a tracer. A pulsed high-speed UV laser was used to excite the particles and the luminescence was detected using two high-speed cameras to determine the temperature field by a two-colour ratiometric approach. The velocity field was measured using ordinary high-speed PIV. The simultaneously measured fields were sampled at a rate of 6 kHz in a vertical plane through the centreline of the symmetrical single-row cooling holes. The flowrate and temperature of the cooling air and heated main flow were chosen to achieve density and momentum flux ratios of 1.6 and 8 respectively. For these conditions the average and RMS temperature fields show that for ordinary angled holes the jet is detached from the surface. In contrast, the trenched geometry leads to a cooling film attached to the surface. However, time-resolved image sequences show instances where hot air breaks through the cooling film and almost reaches the surface. Similar image sequences for the angled holes show that the detached coolant jet becomes unstable downstream and pockets of cold air are ejected into the main flow. This intermittency may in part explain the observation that the measured turbulent heat flux is oriented towards the cold core, but deviates from the direction of the mean temperature gradient, thereby contradicting the simple gradient diffusion hypothesis commonly used in RANS simulations.

1. Introduction

Film cooling is a key technology for modern gas turbine engines [1]. A protective layer of cooling air is applied to the surface to isolate it from hot gas and to remove heat from it. The most common way to form a cooling film is by ejecting coolant through an array of inclined holes. These holes can either be cylindrical or shaped. Fan-shaped holes with a diffuser outlet are used to improve the lateral distribution of cooling air and reduce the penetration of hot air into the boundary layer [2]. Another recent development are trenched cooling holes [3]. Here, the cylindrical holes are placed in a shallow slot, i.e. a trench, which is intended to promote the lateral distribution of coolant. Previous studies [4–7] have shown that the trench also prevents the cooling air from completely lifting off the surface. Hence, a high cooling effectiveness can be achieved even when the cooling air velocity and density is very high.

To illustrate the complex flow topology, a sketch of the average flow field in the vicinity of a trench is shown in Fig. 1. After leaving the hole, the coolant jet impinges on the downstream trench wall where it is deflected upwards and sidewards. The fanned out jet shields the wall from the main flow downstream of the ejection, which leads to a recirculation zone with two counter-rotating vortices. The laterally deflected coolant moves along the trench and mixes with hot gas that “falls” into the groove. Between two neighbouring holes, two opposing streams meet. A counterflow region with recirculation and increased mixing forms. Furthermore, excess air is deflected vertically out of the trench.

New low NOx emission combustor concepts with leaner combustion need most of the available air for fuel preparation and combustion control. Then, less air is available for cooling the
walls and so more efficient cooling geometries like the trench are required. One of the major challenges during the design of new film cooling geometries is the correct prediction of the turbulent mixing between cooling air and hot gas. The widely used Reynolds-averaged Navier–Stokes (RANS) simulations with two-equation turbulence models tend to underpredict the lateral distribution of coolant [8]. Acharya et al. conclude that more sophisticated Large Eddy Simulations (LES) are needed to reproduce the highly anisotropic flow and the turbulent transport caused by large scale fluctuations. However, due to their low computational cost, several attempts were made to improve the modelling of scalar fluxes within the RANS models. A recent study by Ling et al. [9] compares RANS simulations with different algebraic closures for the turbulent fluxes to LES results. In RANS models the scalar flux is commonly calculated with the gradient diffusion hypothesis:

\[
\overline{\rho u_i T} = -\chi T \frac{\partial T}{\partial x_i}
\]

(1)

The scalar flux is assumed to be proportional to the gradient of the time-averaged scalar field. The turbulent diffusivity can be assessed with the Reynolds analogy \( \chi_t = v_t / Pr_t \). The turbulent Prandtl number is usually set to a constant value of \( Pr_t = 0.85 \), often used in a flat plate boundary layer. Ling et al. show that more sophisticated approaches including spatial variations of \( Pr_t \) are able to produce better predictions of the film cooling flow.

To improve computationally inexpensive RANS simulations with more precise models for \( Pr_t \), measurements of the turbulent transport in film cooling flows are needed. Therefore, velocity and a scalar have to be measured simultaneously, which requires – from the practical point of view – two separate, non-interfering experimental techniques that can be applied at the same time. Kohli and Bogard [10] combined cold wire and Laser Doppler Velocimetry (LDV) measurements to acquire pointwise temperature–velocity data in the flow downstream of a cylindrical hole. The results showed that the highest turbulent transport occurs in the regions with the strongest mean velocity gradients. The turbulent Prandtl number varied between 0.5 and 2, which clearly deviates from the constant value of \( Pr_t = 0.85 \) commonly assumed in RANS simulations.

Su and Mungal [11] used particle image velocimetry (PIV) and planar acetone Laser Induced Fluorescence (LIF) to measure the velocity and concentration fields to assess the turbulent scalar transport in a cross-flowing jet. Their measurements indicate a sign change of the scalar flux component perpendicular to the jet axis. The values at the windward side of the jet are negative, while the turbulent flux in the shear layer downstream is less significant and positive. The turbulent flux parallel to the jet axis was always positive and exceeds the other component. The authors attribute the sign of the turbulent transport to the fact that fluid parcels with excess velocity in the direction of the jet are likely to feature higher scalar concentrations, while slower fluid from the unseeded main flow would produce values of \( \overline{wC} < 0 \).

Muppidi and Mahesh [12] investigated the scalar transport of a round turbulent jet in a laminar cross-flow by means of Direct Numerical Simulation (DNS). The numerical results support the findings of Su and Mungal. Again, the component of the turbulent transport which is oriented in the direction of the jet axis shows no change of sign between the leading and the trailing edge of the jet. The authors classify this effect as counter gradient diffusion and attribute it to the asymmetric pressure distribution in the vicinity of the jet. Counter gradient diffusion describes turbulent transport against the gradient of the mean scalar field and is known from premixed combustion (e.g. [13]).
While these experimental and modelling efforts reveal some of the limitations of conventional RANS models, further measurements are needed in representative film cooling geometries. Measurements of the turbulent transport provide valuable information to guide the development of turbulence models in RANS simulations and subgrid models in LES, which resolve the energy-containing turbulent scales and are better able to predict counter gradient diffusion. In general, time-resolved planar measurements would provide further insight into the unsteady behaviour of film cooling flows, as well as additional spectral information which can be compared to that extracted from LES.

A technique that allows simultaneous single-shot planar measurements of flow temperature and velocity at kHz sampling rates was recently demonstrated [14]. This thermographic PIV technique is based on thermographic phosphors, which are solid materials with temperature-dependent luminescence properties. Phosphor particles are seeded into the flow under investigation. A laser is used to excite the particles in the measurement plane, and their temperature-sensitive luminescence emission is recorded to determine the particle temperature using a two-colour intensity ratio method. Simultaneously, visible laser light scattered by particles in the same plane is recorded to determine the velocity field using a conventional PIV approach. For particles on the order of 1 μm, it can be shown that the particle temperature and velocity match that of the surrounding gas sufficiently fast to trace many turbulent flows of practical interest [15]. Prior to the aforementioned demonstration study [14], at low repetition rates of a few Hz this technique has been used for time-averaged [16] and single-shot simultaneous temperature and velocity measurements [15,17], besides several demonstrations of the thermometry technique alone [18–21]. A similar concept named thermographic LDV has also been demonstrated for simultaneous kHz-rate point measurements with a higher spatial resolution [22].

Besides the advantage that only a single tracer is seeded into the flow, thermographic PIV requires relatively simple instrumentation. Thermographic phosphors generally possess broad excitation spectra and therefore can be excited with solid state (Nd:YAG) lasers, producing sufficient signal levels even in oxygen-containing environments. The luminescence can be detected using lasers, producing sufficient signal levels even in oxygen-containing environments. The luminescence can be detected using the frequency-tripled output of diode-pumped Nd:YAG lasers, which are then interpreted in the context of the turbulent mixing.

In this study thermographic PIV is used to simultaneously measure the temperature and velocity fields in the flow emanating from single-row angled and trenched film cooling holes in a closed-loop wind tunnel facility. Using an electrically-heated main flow and liquid nitrogen-cooled cooling air, the density and momentum ratios are adjusted to conditions representative of those in an aero gas turbine combustor. Measurement sequences acquired at a sampling rate of 6 kHz are used to analyse the mean and Root Mean Square (RMS) temperature and velocity fields and to calculate the turbulent diffusion terms. Time-resolved measurement sequences are used to provide insight into the nature of the fluctuations in both the cylindrical and trenched film cooling flows, which are then interpreted in the context of the turbulent mixing.

2. Experimental

2.1. Test facility

The experiments were performed in a heated, closed-loop wind tunnel. The nominal mainstream velocity was \( u_0 = 10 \text{ m/s} \) and the temperature was \( T_0 = 373 \text{ K} \). The Reynolds number based on the main stream flow and hole diameter of \( Re_D = 2600 \) is representative for aircraft gas turbine engines [29]. The flow is driven by a radial blower, that is followed by a 18 kW electrical heater, a settling chamber containing honeycombs and screens, and a 5:1 contraction nozzle, which reduces the turbulence intensity to \( u' / u \approx 1 \% \) to create well-defined boundary conditions to study these film cooling flows. It should be noted that the turbulence level in the wind tunnel is lower than in a gas turbine combustor, where turbulence levels in excess of 25% were measured [30]. The power supply to the heater is regulated by a PID controller through which the mainstream temperature, that is measured at the inlet of the test section, is adjusted. The test section has a cross-section of \( 400 \times 150 \text{ mm} \) and is shown in Fig. 2.

The first segment of the test plate has a sharp leading edge with boundary layer suction and a trip wire 140 mm upstream of the cooling air holes to create a well-defined turbulent boundary layer profile. LDV measurements at the cooling holes yielded a momentum thickness Reynolds number of \( Re_D = 805 \), a ratio of boundary layer thickness to hole diameter of \( \delta / D = 1.83 \) and a shape factor, i.e. ratio of displacement to momentum thickness, of \( H = 1.6 \).

The upstream portion of the wall was heated to avoid conduction losses and guarantee a uniform temperature profile normal to the wall, which was verified with cold wire measurements. Two exchangeable film cooling segments featuring three cooling holes each with an inclination of 30° relative to the main flow direction were investigated. The cooling hole geometries and their main dimensions are shown in Fig. 3. The cylindrical holes were designed with pipe inserts that extended beyond the lower plate surface. The pipes had an inner diameter of \( D = 6 \text{ mm} \) and a length \( L / D = 10 \). This design was chosen to improve the seeding distribution in the coolant jet, because the extended protruding pipe inlets promote an axisymmetric inflow and a parabolic flow profile at the pipe exit. The trenched holes did not require extensions since the strong deflection and mixing within the trench produce a rather uniform seeding distribution. The film cooling inserts were made of Obomodulan, a foamed plastic with a low thermal conductivity. The test plate downstream had a stainless steel surface which was painted with matte black paint to reduce stray light reflections.

The cooling air is supplied by a rectangular plenum, which is mounted at a 45° angle to the lower part of the test section (see
The amount of coolant, coming from a pressurised air reservoir, is regulated and monitored using a mass flow controller. The density ratio is adjusted using the cooling air temperature by mixing ambient air with air that is cooled by liquid nitrogen. The mixing ratio is set by a mass flow controller in the bypass of the heat exchanger and constantly adjusted to stabilise the cooling air temperature down to 233 K. The temperature of the coolant is measured with a 0.1 mm type K thermocouple located in the centre of the outlet of one of the cooling holes. The thermocouple was placed within the core region of the jet, where a uniform temperature distribution was previously measured with a traversable cold wire probe. The origin of the coordinate system, which is used throughout the paper, is located at the trailing edge of the central cooling hole with the axes oriented as indicated in Fig. 2.

During the thermographic PIV measurements, the main flow as well as the cooling air were independently seeded with BAM:Eu phosphor particles (KEMK63/UF-P1, Phosphor Technology, median diameter (based on volume) of a volume-equivalent sphere: 2.4 \( \mu \)m). Rather than being perfect spheres, these particles have flat hexagonal disc-like shapes (see Ref. [25]). Following the analysis of Wadewitz and Specht [31], the temperature response times were calculated for volume-equivalent oblate spheroids in air at 300 K. The 95% response times range between 99 and 143 \( \mu \)s for aspect ratios between 0.1 (a flat disc-shaped particle) and 1 (a perfect sphere) respectively. For the same conditions, the velocity response time for 2.4 \( \mu \)m diameter spherical particles was calculated to be 192 \( \mu \)s. However, non-spherical particles will tend to align so the long axis of the particle is perpendicular to the flow, increasing the drag force and improving the response time. The morphology of these particles improves both the temperature and velocity response times compared with volume-equivalent spheres. Specifically for this application, these response times are sufficiently fast to reproduce the amplitude of turbulent fluctuations up to the maximum measurement sampling rate of 6 kHz, and are appropriate for tracing in the flows considered here.

The particles were introduced into the main flow by injecting air through a reverse cyclone seeder and into the wind tunnel. The seeded air was introduced just downstream of the test section to guarantee sufficient mixing during the passage through the blower and the settling chamber. This method produced an adequate particle number density to measure for at least 20 s, which was sufficient for the short duration high-speed recordings. To seed the cooling air, during the measurements part of the ambient air coolant mass flow was diverted through a bypass into a seeder containing a magnetic-stirrer bar to continuously agitate the particles within. This seeded flow was then mixed with the liquid nitrogen-cooled air inside the plenum.

2.2. Laser diagnostics

2.2.1. Thermometry

The experimental setup is shown in Fig. 4. The phosphor particles were excited with a frequency-tripled diode-pumped Nd:YAG laser at 355 nm (Hawk HP-355-20-M). Operated at a 6 kHz repetition rate, the laser produced 25 W (4 mJ/pulse). The laser beam was expanded with a telescope and reflected into a beam homogeniser (Bayerisches Laserzentrum) consisting of a microlens array and Fourier lens (see Ref. [32] for a description) and through sheet optics (-30 and + 80 mm cylindrical lenses). This produced a light sheet where both the vertical intensity distribution and beam waist were uniform. The beam height was 25 mm, and the Full Width at Half Maximum (FWHM) of the beam waist was 900 \( \mu \)m, determined from a Gaussian fit through the differentiated laser intensity profile measured using a powermeter and a razor blade translated through the light sheet. Because BAM:Eu saturates, the low intensity regions at the side of the Gaussian light...
sheet can contribute more significantly to the total signal, decreasing the spatial resolution in the out-of-plane direction. However, based on the measured values the laser fluence is 17 mj/cm², only just in the saturation regime of BAM:Eu [25]. The out-of-plane luminescence signal profile was simulated using the light sheet profile and saturation data from [25], finding that the effective FWHM is increased by approximately 10% to 1 mm. Therefore in this case the saturation effect has little effect on the out-of-plane spatial resolution.

Initially the 355 nm laser was introduced through the top of the test section, but this was found to produce a luminescence signal from particles deposited on the test plate downstream of the cooling holes which was so strong that it prevented measurements near the test plate. Therefore the laser beam was introduced through a separate downstream access using a periscope and reflected to make the laser sheet parallel to the test plate (see Fig. 4). The periscope was purged with pressurised air to avoid contamination with phosphor particles. A preceding RANS simulation showed that for the flow boundary conditions in this study the difference in the flowfield with and without the periscope installed was negligible, with a maximum difference in the streamwise velocity $u_x$ of 3.5% at $x/D = 9$. Therefore, the film cooling flow upstream of the periscope is hardly influenced, and with the lower edge of the sheet adjusted to 3 mm above the test plate, this setup effectively removed the interfering signal from deposited particles.

The luminescence was detected with two high-speed CMOS cameras (Photron SA4, 1024×1024 pixels). At a framerate of 6 kHz, the cameras read out a region of 1024×640 pixels. The exposure time was set to 5.6 μs. However it should be noted that the actual measurement duration is determined by the luminescence decay time of BAM:Eu (1/e decay time = 1 μs at room temperature). The cameras were fitted with 85 mm f/1.4 Zeiss lenses. For the two-colour measurement of the spectral change in the luminescence emission, the signal was separated and filtered using a longpass dichroic beamsplitter with a cutoff at 445 nm (445LP, Chroma Technology) and two bandpass interference filters at 466–40 and 425–50 nm (86363 and 86561 respectively, Edmund Optics. The nomenclature is central wavelength, FWHM).

The luminescence emission of BAM:Eu exhibits a blue-shift and spectral broadening of the emission line with increasing temperature, from room temperature up to at least 1100 K [25]. Because of the sub-zero temperatures used in this study, an experiment was conducted to verify that the inverse spectral behaviour occurs with decreasing temperature. For this purpose BAM:Eu particles were pressed between a small heat exchanger and a fused silica window. Liquid nitrogen-cooled ethanol was run through the heat exchanger and the temperature of the phosphor was measured using a thermocouple. The phosphor was excited using a high power continuous-wave LED at 365 nm and the luminescence was detected using a spectrometer (Solar MS350) and an intensified CCD (Princeton Instruments PI-MAX). Fig. 5 shows spectra recorded between 313 K and 217 K, confirming that the emission is temperature dependent over the whole range of temperatures used in this study. The intensity ratio calibration procedure is described in Section 2.3.2.

2.2.2. Particle image velocimetry

A double-pulse frequency-doubled diode-pumped Nd:YAG laser at 532 nm (Lee LDP-100 MQG) was used for PIV. The laser was operated at a frequency of 6 kHz with a pulse separation of 21 μs. A light sheet was formed using cylindrical $f = 125$ mm and spherical $f = 700$ mm lenses and was adjusted to have a similar thickness as the UV sheet. The laser light was introduced into the test section through an optical access directly above the region of interest. 532 nm light scattering from the test plate did not interfere with the thermometry or PIV measurements. Mie scattering images were recorded with a Phantom v710 high speed CMOS camera (1280×800 pixels). The camera was operated at 12 kHz to achieve double-frame acquisition at 6 kHz, with a readout region of 1280×480 pixels. Due to the viewing angle of approximately 70°, the 100 mm f/2 Zeiss lens was mounted with a Scheimpflug adapter to eliminate off-axis defocusing across the field of view. The region where the 355 nm and 532 nm light sheets were superimposed extended from $-3 < x/D < 9$ in the streamwise direction and from $0.5 < z/D < 4$ normal to the wall. The field of view was chosen based on previous PIV measurements and CFD simulations [7], which had shown that, at a momentum ratio of $I = 8$, the jet from cylindrical holes clearly lifts off the surface. In case of the trench, the cooling film stays attached to the wall. The interaction with the hot main flow is expected to occur in a single shear layer, which is well above the surface. Therefore a distance of $x/D = 0.5$ between the wall and the lower bound of the field of view is considered acceptable.

2.2.3. Timing

The appropriate repetition rate of the diagnostics was determined using an approximation based on the Strouhal number $St$ for the Kelvin–Helmholtz instabilities in the shear layer. The LES film cooling flow study of Kalghatgi and Acharya [33] determined that $St = 0.125$. Presuming a similar value for $St$ and using the relevant parameters (momentum thickness and freestream velocity) for the flows studied here, the shear layer fluctuations are predicted to have a frequency of 2.6 kHz. Therefore we used a 6 kHz repetition rate to satisfy the Nyquist sampling theorem.

The lasers and cameras were synchronised using a timing clock (TSI LaserPulse Synchroniser #610036). The UV laser pulse was timed during the simultaneous exposure (5.6 μs) of the thermometry cameras, which was temporally positioned in the middle of the PIV camera interframe time (13 μs). The two PIV laser pulses were temporally spaced symmetrically before and after the UV laser pulse, at the end of one PIV camera frame and the start of the following frame, to produce dual-frame image pairs for PIV at the desired 6 kHz rate.

The cameras were controlled using software provided by the camera manufacturers (FastCam Viewer 350, Photron and Phantom Camera Control 2.14, Vision Research). Synchronised...
recordings were achieved by commanding the start of acquisition for the Phantom camera using a software trigger signal. A signal from the Phantom camera was then used to directly trigger acquisition for both thermometry cameras simultaneously. The onboard memories of the thermometry and PIV cameras were 16 Gb and 32 Gb respectively, allowing the acquisition of nearly 18,000 temperature and velocity fields for each 3 s measurement run.

2.3. Image processing and data reduction

2.3.1. Image processing

The recorded images were imported into DaVis 8.1 (LaVision) for initial processing. Background images were recorded before each measurement run, averaged, and subtracted from the luminescence and Mie scattering images. Images of a calibration target positioned in the measurement plane were used to generate a spatial calibration function based on a camera pinhole model. This was then used to remove distortion from the PIV images and map all images onto a common coordinate system.

To facilitate simpler data handling, the luminescence images were binned (4 × 4). In Matlab, a cutoff filter at 20 counts and 3 × 3 linear smoothing were applied. Image pairs were then divided, and an average intensity ratio image recorded in a uniform temperature flow (295 K) was used to correct the single shot intensity ratio images for spatial non-uniformity in light collection efficiency. After processing, the in-plane spatial resolution of the temperature measurements was 800 μm (FWHM of a Gaussian curve fitted through a recorded image of a razor blade positioned in the measurement plane).

2.3.2. Temperature calibration

An in situ temperature calibration was performed by recording images using the two-camera thermometry system and evaluating the intensity ratio in two regions of the flow known to be at uniform temperature: the heated main flow at 373 K and from the jet core of the cooling flow at 232 K (see Fig. 6). For all the measurements presented here, a simple linear relationship intersecting these points was used to convert the intensity ratio images to temperature.

The validity of this linear calibration approach was checked by digitizing the luminescence emission spectra from Fig. 5 and data from Ref. [25] using the filter and beamsplitter transmission functions provided by the respective manufacturers. The quantum efficiency of the CMOS cameras and lens transmission were also accounted for. The integrated signals in each detection channel were divided to produce intensity ratio data, also displayed in Fig. 6. A linear fit through these points (R² = 0.9846) is also shown, which indicates that the two-point calibration performed in the flow is reasonable for this narrow range of temperatures.

An in situ calibration is required because the absolute value of the intensity ratio is not accurately predicted by digitally integrating the emission spectrum. Possible reasons are that the filter transmission curves are provided for light at normal incidence and therefore are not exactly valid for this imaging configuration, or that the gain function is different between the two cameras. Furthermore, there may be a difference between the emission spectra of aggregated particles and dispersed particles, due to amplified spontaneous emission, re-absorption or laser-induced heating/damage, as discussed in Ref. [24]. In principle, due to the reasonably constant particle number density during the 3 s measurement sequences, and between different measurement sequences, the in situ calibration approach can also compensate for a possible influence of the multiple scattering of luminescence emitted by particles at the main flow temperature on the intensity ratio measured in the jet core. The results in Section 3 indicate that using the in situ calibration curve to convert the intensity ratio images to temperature produces the correct main flow and coolant temperatures.

2.3.3. PIV processing

First an average background image was subtracted from the individual PIV image pairs. The velocity field was calculated using an adaptive multi-pass cross-correlation algorithm (DaVis 8.1, LaVision), with a starting window size of 64 × 64 pixels and 50% overlap, and a final window size of 16 × 16 pixels, corresponding to a vector spacing of 650 μm.

2.3.4. Data reduction

First the temperature field was interpolated onto the velocity vector grid, resulting in a field consisting of 113 × 40 measurements. The average and RMS temperature and velocity fields, the turbulent shear stress, and the streamwise and wall-normal turbulent heat fluxes were all calculated from 6000 consecutive images (corresponding to 1 s recording duration). A non-dimensional temperature θh was determined from the fluid temperature Tfl and the main flow Tm and cooling air Tc temperatures according to:

\[ θ_h = \frac{T_m - T_{fl}}{T_m - T_c} \]  

2.4. Measurement uncertainty

The precision of the temperature measurements was evaluated from the single shot standard deviation of temperatures in a homogeneous region in the main flow at 373 K, upstream of the cooling jet. This was calculated from an area comprising of 20 × 20 binned
pixels (i.e. approximately 45 simultaneously sampled, independent temperature measurements), and then averaged over 200 uncorrelated shots. The single-shot spatial standard deviation was 18.4 K (4.9%). The temporal standard deviation of the single-shot mean temperature was 4.9 K.

3. Results

The following sections describe the thermographic PIV results for a jet in a crossflow emanating from an angled cylindrical hole or a trench, respectively. For these experiments the nominal main flow velocity was 10 m/s and the density ratio was $DR = 1.6$. The cooling air was ejected with a momentum flux ratio of $I = (u_c^2 \rho_c)/(u_m^2 \rho_m) = 8$.

3.1. Mean flowfield

The distribution of the average absolute velocity and the fluid temperature for the cylindrical hole are depicted in Fig. 7. The dash dotted line shows a streamline originating at the centre of the hole exit to provide a reference indicating the jet trajectory. The core of the jet, marked with a contour line, was defined based on the RMS velocity. The RMS velocity and temperature are shown in Fig. 8.

The average distributions clearly indicate a detached cooling air jet around which the hot main stream flows. There is very little coolant close to the wall downstream of the hole. Compared to the maximum velocities in the jet, the minimum temperatures are shifted downstream. Cold wire measurements by Kröss and Pfitzner [6] that were conducted in the same facility, as well as planar LIF/PIV data by Su and Mungal [11], show a similar behaviour.

The RMS velocity and temperature fields depicted in Fig. 8 illustrate the extent of the shear mixing layer. The jet core with low fluctuations extends to about $x/D = 2$. Further downstream the growing mixing layers from the jet leading and trailing edges start to merge. The highest fluctuations are visible in the region $3 \leq x/D \leq 6$.

The average velocity and temperature fields of the trench are shown in Fig. 9. The corresponding RMS values are provided in Fig. 10.

In contrast to the cylindrical hole, the average distributions measured around the trench indicate an attached cooling film with a thickness of about 2D. The observation is supported by the RMS plots, which show only one mixing layer between the coolant and the main flow. The decay of the film temperature in the streamwise direction is moderate. At a streamwise location $x/D = 8$ near the wall, $\theta_f = 0.5$. This can be compared to the results for the cylindrical hole, where for the same streamwise position the main stream temperature ($\theta_m = 0$) is already reached. The temperature fluctuations below the jet trajectory are low, indicating that the trenched hole configuration produces a stable cooling film at the desired low temperature.

This finding is consistent with previous surface temperature and heat transfer measurements [34] using a technique based on infrared thermography and frequency domain phosphor thermometry [35]. For the same flow conditions in the same facility, using trenched holes an improved cooling effectiveness can be maintained far downstream of the cooling hole.

3.2. Instantaneous measurements

Time resolved measurements provide additional information about flow structures that cannot be seen in the averaged flow field. Fig. 11 shows a sequence of consecutive images for the cylindrical hole with 166 µs between images.

The images illustrate how the jet becomes unstable and starts to release pockets of cold air that mix with the hot main flow. In the wake of the jet, vertical structures with a non-dimensional temperature of $\theta_f \approx 0.5$ that travel downstream with a velocity of approximately $5–6\frac{m}{s}$ are apparent. These cold streaks are sup-
posedly caused by tornado-like vortices that are shed from the mixing layer around the coolant jet. Similar wake vortices have been observed in a previous study by Fric and Roshko [36].

A sequence for the trenched holes is shown in Fig. 12. The measurements provide an example of the intermittency of the cooling film emanating from the trench. The thickness of the cooling air layer fluctuates considerably. This particular sequence was chosen to illustrate an instance, where hot gas, which penetrates into the film, almost reaches the surface. Full video sequences for the cylindrical and trenched holes are provided with the online version of this article.
3.3 Turbulent flux

The measured velocity and temperature fluctuations were used to calculate the turbulent diffusion terms in the measurement plane. The results for the cylindrical hole and the trench are provided in Figs. 13 and 14, respectively. The upper diagram shows the turbulent shear stress. For both geometries, the maximum stresses occur in the windward shear layer and are positive. That means fluctuations of the $x$- and $z$-velocity component are likely to have the same sign. This might be interpreted as high velocity coolant that propagates into the main flow and slow main flow air that is mixed into the cooling jet. In case of the cylindrical hole, a second shear layer is visible at the trailing edge of the jet. The sign change of the turbulent stress at about $x/D \approx 3$ is supposedly caused by the deflection of the coolant. The cooling film emanating from the trench shows a pronounced shear layer above the trajectory. The negative stresses at $x/D \approx 2$ might be caused by a recirculation downstream of the deflected jet, which is typical for the trench flow field (see [7]).

The two diagrams at the bottom of Fig. 13 show the streamwise and wall-normal components of the turbulent heat flux. In each case the largest absolute values are visible starting from $x/D > 2$. The sign change of the $\overline{u'w'}$ flux indicates the transport of hot gas towards the jet axis and of cooling air into the main flow. In contrast, $\overline{u'T}$ is negative in both mixing layers. That means colder air tends to move with a velocity above the local average. This
observation contradicts the gradient diffusion hypothesis (1), which would predict a positive turbulent flux in the upper shear layer. The results are consistent with the findings of Su and Mungal [11] and Muppidi and Mahesh [12], which were discussed in the introduction.

For the trench, the components of the turbulent heat flux shown in Fig. 14 indicate a single mixing layer above the jet trajectory. Compared to the cylindrical hole case, the magnitude of the turbulent transport is smaller. Both components are negative, while the wall-normal component clearly dominates. Again, $\overline{u'\theta'} < 0$ indicates turbulent transport against the streamwise gradient of the mean temperature. However, the effect is less pronounced than for the cylindrical hole case.

To further investigate the direction of the turbulent transport, for the cylindrical hole flow the flux vectors and temperature contours are plotted in Fig. 15. The turbulent flux vectors are tilted in the upstream direction from the hot main flow towards the cold jet core. If the gradient diffusion hypothesis would fully apply to this flow field, the vectors should be normal to the temperature contours. In the present case, a deviation from the direction of the temperature gradient is clearly visible. One possible explanation might be the unsteady behaviour of the coolant jet, which is apparent in Fig. 11.

The meandering motion of the jet resembles a laminar instability and leads to a continuous release of lumps of coolant. Due to the excess velocity of the jet, these pockets of cold air travel faster than the main flow. In contrast, hot gas tends to move slower. That means that the mixing of cooling air and main flow might not only be caused by the fluctuations in two separate shear layers. The intermittency of the coolant jet might contribute substantially.

4. Conclusions

The flow emanating from angled and trenched cooling holes in a closed-loop optically-accessible wind tunnel facility was investigated using high-speed thermographic PIV. The 2D flow temperature and velocity was measured in a vertical plane intersecting the centreline of the single row cooling holes. High-speed lasers and cameras were used to acquire time-resolved data at a repetition rate of 6 kHz. The facility is run with liquid nitrogen-cooled cooling air and so in a preceding spectral-resolved study it was verified that the luminescence emission of BAM:Eu is sensitive to temperature down to 217 K. To avoid issues with particle deposition on the test plate, the UV laser beam was introduced through a periscope far downstream of the region of interest to allow the laser sheet to propagate horizontally above the test plate. This enabled measurements down to a distance of 3 mm above the test plate and, with optimisation, could be even closer.

Measurements were made for $DR = 1.6$ and $l = 8$. For these conditions the average and RMS temperature fields confirm that for ordinary angled cylindrical holes the jet lifts off quickly and detaches from the surface. In contrast the trenched geometry leads to a cooling film attached to the surface. However, time-resolved image sequences show instances where hot air breaks through the cooling film and almost reaches the surface, revealing that instantaneously the gas temperature adjacent to the wall may be significantly higher than one might judge from the average temperature field alone. Similar time-resolved image sequences for the angled cylindrical holes show that the detached coolant jet becomes unstable downstream and that pockets of cold air are ejected into the main flow. This intermittency may in part explain the observation that the streamwise turbulent heat flux term $\overline{u'\theta'}$ is negative in both mixing layers, thereby contradicting the gradient diffusion hypothesis. This produces the effect that, while the turbulent heat flux is oriented towards the cold core, it deviates significantly from a direction normal to the constant temperature contours.

Indeed one of the aims of this work is to provide experimental data in support of the development of CFD models which can aid the design of film cooling geometries in future gas turbines. The measurements are well-able to show that the gradient diffusion
hypothesis is not strictly valid in this flow. This assumption is commonly used in RANS simulations and so this kind of turbulent flux data can for example guide the development of more sophisticated RANS models. The measurement technique is able to deliver simultaneous measurements of temperature and velocity and especially at high repetition rates, where the tracer luminescence properties are most advantageous. Full-length 18,000-image sequences of the flow in both hole configurations are provided with the online version of this article. Future research will focus on using these to extract frequency spectra of the amplitude of the velocity and temperature fluctuations in the shear layer, which can be compared to LES. Also, zinc oxide (ZnO) particles have previously been used as a thermographic phosphor for thermographic PIV measurements with increased temperature sensitivity [37]. The use of ZnO in similar flows would improve the precision of the data, which would be especially useful for the turbulent heat flux measurements. Furthermore, of particular interest is the interaction of large scale turbulent structures, common for gas turbine combustors, and the cooling film itself. Now that the technique has been successfully demonstrated in this test facility, future work will focus on the generation of increased turbulence levels in the main flow to study these interactions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.092.

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