GAS TURBINE BLADES INTERNAL COOLING: DESIGN, DEVELOPMENT AND VALIDATION OF A NEW RIG FOR HEAT TRANSFER MEASUREMENTS UNDER ROTATION

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ABSTRACT
The contribution describes part of the work carried out on a wider research project aimed to set up a new tool to study rotational effects on the heat transfer distribution inside realistic cooling passages for gas turbine blades.

Transient thermochromic liquid crystals (TLC) measurement technique is chosen in order to obtain spatially resolved heat transfer data. This obliges to perform the transient measurements with a cold temperature step on the coolant flow, in order to replicate correctly the buoyancy effects induced by rotation. This target is achieved by a new facility which components and working principle have been the subject of previous contributions. In the present paper, the progresses made in the development of the data processing methodology are described at first. Successively, a first step into the demanding rig and methodology validation process is commented by exploiting the results of a wide test campaign on a simple cooling channel geometry.

KEYWORDS
Internal cooling, rotation, liquid crystals, transient, gas turbine

NOMENCLATURE
Bo buoyancy parameter
\(c_{\text{mat}}\) Plexiglas specific heat capacity
\(D_h\) hydraulic diameter
\(h\) heat transfer coefficient
\(H\) channel height
\(K\) thermal conductivity
\(L\) channel length
\(N_u\) Nusselt number
\(N_u_0\) reference Nusselt
\(P\) rib pitch
\(R\) evaluation radius
\(Re\) Reynolds number
\(Ro\) rotation number
\(\Theta\) non-dimensional temperature
\(\Omega\) rotational speed
\(\rho\) air density
\(\mu\) air dynamic viscosity
\(T_0\) initial temperature
\(T_b\) bulk flow temperature
\(T_w\) wall temperature
\(U_b\) bulk flow velocity
\(W\) channel width
\(\text{mat}\) refers to material properties
\(\text{air}\) refers to air properties

INTRODUCTION
Performance augmentation of a gas turbine engine is mainly achieved by increasing the turbine inlet temperature. This choice reflects on higher thermal stresses on the first stages of the high pressure turbine, hence complex blade cooling systems are required. The design and development of these complex devices is entrusted to CFD models that, due to the complexity of the considered geometries, must be experimentally validated. Therefore, dedicated test rigs must be developed and they have to satisfy different requirements such as the possibility to accommodate large test sections and to replicate the real working conditions of the cooling system.
The performances of a blade cooling system can be mainly evaluated by the determination of the heat transfer coefficient (HTC) distribution on the cooling passage surfaces. This task can be achieved in different ways. Probably the simplest is to make use of thermocouples installed on the measurement surfaces. The main drawback of this technique is that the achievable spatial resolution is not sufficient to investigate in detail the HTC distribution generated inside the passage [1].

To overcome this limitation, high-resolution infrared camera can be used [2]. However, its application is limited to few examples on simple geometries due to the difficulties associated to the manufacturing of complex models optically transparent to infrared radiation.

One of the most widely used methods for surface heat transfer measurements is the liquid crystals thermography (LCT). It ensures high spatial resolution and accurate measurements on complex geometries, without requiring too expensive devices. Two different methodologies can be followed: steady or transient LCT. The former, well documented in [3], requires an accurate estimation of the heat transfer losses through the model surfaces. In particular, this estimation becomes more difficult for rotating experiments and can significantly affect the final accuracy. The transient LCT is more complex with respect to steady LCT in terms of experimental apparatus and post-processing software but it overcomes the problem of the heat losses estimation. Moreover, it requires much shorter testing time, making this technique very attractive for testing under rotation large and complex models.

The key point of transient LCT tests is to impose a temperature step to the coolant flow in order to activate the heat transfer process, hence to provide the boundary conditions used to compute the HTC distribution on the investigated surfaces [4-7]. Electric mesh heaters are widely used to generate a steep flow temperature rise. Unfortunately, this approach cannot be used under rotation where, conversely, a sudden temperature drop of the cooling flow is required in order to match the same buoyancy effects found in real working conditions. The main drawback of this requirement is that it increases the technical complexity of the experimental apparatus and methodology.

At the University of Udine a new rig has been developed to perform rotating and transient LCT measurements. The rig components, its working principle and the experimental approach have all been subject of previous publications [12]. The present contribution aims at describing the progresses made in the development of a more accurate and efficient processing algorithm and the efforts made in the difficult task to validate the results obtained by the complex experimental methodology. The results obtained on a very simple but documented internal passage geometry are used to demonstrate the correctness of the approach. Therefore, the focus of this paper won’t be on the analysis of the rotational effects inside the considered geometry (already documented in literature) but solely on the demonstration of the reliability of the data that can be obtained with the new experimental apparatus.

**EXPERIMENTAL APPARATUS**

**Channel geometry**

The test section has a square cross section of 50x50 mm² and a length L = 1000 mm. In the first 200 mm, the channel walls are smooth while on the remaining part 16 squared ribs are installed on one side of the passage and are arranged normal to the flow direction. The ribs height is equal to 5 mm resulting in a pitch-to-height ratio P/e = 10 and in a blockage ratio e/Dₕ = 0.1.

This geometry was selected because it can be considered as a good test case against which validate the proposed experimental rig and methodology, since its aero-thermal behavior is well documented in literature, at least for the stationary channel [8]. For the rotating channel case, data on a nearly similar geometry are also available [9, 10].

The test model is completely machined out of Plexiglas, with a minimum wall thickness of 20 mm. This value ensures a maximum allowable duration of the transient tests of about 240 s, in accordance to the relation given in [11].
Test facility

The design of the rotating facility is already documented in [12], hence just a brief description is here reported in order to ease the reading.

The test section is installed on one side of a rotating arm (Fig. 1), which can be spun around a vertical axis at the maximum velocity of about 400 rpm, thanks to a transmission belt connected to a 5 kW electric motor. The test model is installed in such a way that the rib edges are parallel to the rotation axis and is on the trailing side with respect to the direction of rotation. A sketch of the air circuit is provided in Fig. 2. Air enters from the top inside a heat exchangers/valve system and is routed through a sealed rotating bearing inside a mesh heater and finally, after a 90-degree bend, into the test section. At the end of the test section an U-bend diverts the flow into a return channel that is connected to a rotating fluidic joint and then to a fan. The mass flow rate is continuously measured by means of a calibrated orifice flow meter located between the rotating joint and the fan. The distinguishing feature of the air circuit is the heat exchanger/valve system above.

Figure 1: the rotating facility sketch (a) and installation (b)

Figure 2: air circuit sketch

Figure 3: air circuit detail: pre-test phase (a), test phase (b), temperature evolution (c)
mentioned and sketched in Fig. 3. In this apparatus, a set of fin and tube heat exchangers are fed by liquid N\textsubscript{2} allowing to cool the airflow temperature down to about -70 °C. Step temperature variation (cold step) is obtained by a set of valves which control the airflow supply to the rotor. In a pre-test phase (Fig. 3a), rotor and test section are fed with ambient air but the two circuits are isolated by closing the central valve (red valve in Fig. 3a). In this phase, the correct initial isothermal boundary condition are set for the test model and, meanwhile, the heat exchangers reach a stable operating temperature. The simultaneous and sudden switching of the valves unit allows connecting heat exchangers and test model air circuits, so delivering to the channel the cold flow that is passing through the heat exchangers (Fig. 3b). An example of the flow temperature evolution at the inlet of the test section is provided in Fig. 3c. For more details about design and operation of the flow cooling system, please refer to [12].

For the static tests only (mainly performed for validation purposes, see later on in the discussion) a mesh heater is used to generate a sudden warm up of the fluid (hot step).

A frame grabber (Basler acA1300-60gc) and a set of two LED lamps compose the vision system that is rotating integral with the test section. The choice of using LED lamps avoids issues related to radiative effects of the lights on the measurement surface. Flow temperature variation is measured by means of 10 K-type thermocouples installed along the channel centerline, entering the channel from both the side lateral walls (with respect to the ribbed surface) at every 200 mm from the channel inlet.

In addition, a mesh of 5 thermocouples are placed at the entry cross section of the channel in order to monitor the temperature distribution at the channel inlet. During the execution of the test, temperature differences below 1°C were observed among the 5 readings, confirming no distortion of the temperature field that could be a main issue in terms of data accuracy. Thermocouples signals are acquired by a NI-cRIO system, also installed on board of the rotating arm. A TTL signal generated by a clocking module (Ni-myDAQ) allows to synchronize camera and thermocouples acquisitions.

Reference test parameters, such as Reynolds and rotation numbers at the inlet of the test model, are computed in real time during the tests execution thanks to a set of dedicated measurements (i.e. mass flow rate, flow temperature and pressure and rig angular velocity). A feedback control loop allows to keep both Reynolds and rotation numbers constant throughout the test with a maximum uncertainty of 2% with respect to the target values [12].

MEASUREMENT TECHNIQUE AND DATA REDUCTION

Transient liquid crystal thermography was used in order to perform measurements of the convective HTC on the rib roughened surface. Several contributions well document the working principles of this technique [4-7]. The key point is to impose to the process fluid a step temperature variation in order to activate the heat transfer on the measurement area. The temporal evolution of both fluid and wall temperatures are the boundary conditions to solve the heat transfer equation on the surface. Adapting the Duhamel approach, the final equation that has to be solved for each point of the measurement surface is:

\[
T_w = T_0 + \sum_{i=1}^{n} (T_{b,i} - T_{b,i-1}) \times \left[1 - \exp \left( \frac{h^2(t-\tau)}{(\rho c k)_{mat}} \right) \right] \text{erfc} \left( \frac{h^2(t-\tau)}{(\rho c k)_{mat}} \right) \quad (1)
\]

Heat transfer coefficient \(h\) is evaluated in each point of the domain by knowing: the liquid crystal activation temperature from its calibration (which is already described in [12]), the liquid crystal activation time (maximum intensity of the green signal) and the bulk flow temperature distribution during the test duration. This latter is computed on the whole test geometry starting from the thermocouple readings and using the Laplacian diffusion equation method [5]. It is important to specific that eq. 1 is valid under the assumption of mono-dimensional energy diffusion inside the model walls. This hypothesis is satisfied by the large wall thickness and by the short duration of the tests, about 120 s, a value that is below the maximum allowable duration previously mentioned.
Data Processing

An in-house developed processing software is used to perform the heat transfer computation. The working principle of this software is already described in [12]. A number of improvements have been made in order to increase the accuracy and the reliability of the results and to reduce the computational time. The most important features of each step of the processing procedure are reported in the following.

Camera calibration

Camera calibration is needed to account for the optical distortion caused by the short focal distance of the adopted camera lenses and by the Plexiglas walls. An in-situ calibration procedure was developed. A dotted target (dots diameter d=1 mm arranged in a grid of 5x5 mm spacing) is placed inside the test section and in contact with the measurement surface. From an image of the installed target and with respect to a user-defined reference point, the software identifies the location of each dot in the distorted image (in pixel) and evaluates their real position in the CAD space (with dimension in mm). Starting from this information, the software computes the coefficients of the polynomials necessary to correlate the two spaces and that are used to de-warp the images.

Peak find procedure

The peak find procedure has the target to locate the time instant at which the color signal from the active liquid crystal reaches its maximum. Hence, the software has to investigate the red, green and blue (R, G, B) intensity signals of each pixel included in a user-defined domain. The peak is obtained by interpolating the raw signal on a stencil of points around the specific peak. Therefore, the main target of the peak finding procedure is to identify the location in time and amplitude of the stencil where to interpolate the signal.

As a first step of the procedure, a background signal computation and subtraction is performed to improve the data quality. The mean values of the R, G, and B channels over the first 25 frames (1 second of acquisition time) are computed and successively subtracted from the signals of each investigated pixel. The background value is computed at the beginning of the time series because the liquid crystals are obviously still not active and an almost black image is obtained.

The signals are successively filtered either with a Discrete Fourier Transform (DFT) or with Discrete Wavelet Transform (DWT) method. The choice of one method with respect to the other is related to which type of experiment is conducted. If a single liquid crystal is used, the DFT method is sufficient for the purpose. An auto-adaptive algorithm was developed in order to automatically set the correct cut frequency that allows to eliminate only the noise frequencies from the signal. The white noise content is first identified on the FFT spectra, and the rms of its module is computed. The cut frequency is substantially set as 2 to 3 times this value. Conversely, noise reduction in signals with multiple peaks (e.g. from a mixture of different liquid crystals) is more complex due to the different characteristics of the peaks (mainly height and aspect ratio). The adoption of a single cut-off frequency to perform the DFT analysis may lead to signal distortion. A better solution is to make use of a DWT, since, as known from the available literature [13], wavelets are functions defined in both time and frequency domain, i.e. they capture both frequency and location information (location in time). By selecting the waveform that best fits with the signal type it is possible to decompose the original signal in a finite number of levels in the wavelet domain. Each level of the decomposition has a specific frequency content that can be excluded in the reconstruction process. At the end of the procedure, the filtered signal is obtained without local distortion or peak shifting (in time).

Activation peak position is determined as the maximum of the polynomial curve that best fit the raw signal over a given stencil. This latter is defined in position and amplitude by an analysis of the filtered signal (obtained either via DFT or DWT) and of its first derivative. Control points are defined as: 1) first derivative local maxima (they correspond to the inflection point of the rising edge of each activation peak), point Q in Fig. 4, 2) the first derivative zero point that follow each local maximum (which corresponds to the local maximum of the filtered signal), point B’ in Fig. 4. The amplitude of the interpolation stencil (between points A and C in Fig. 4) is defined as the time interval where the
raw signal ranges from 80% to 100% with respect to its peak value (point B, which as the same location in time as point B'). This procedure is applied only for the peaks whose maximum raw value and first derivative are both above given thresholds, in order to look only for reliable peaks. By testing the procedure on different signals, reference values for the thresholds have been identified namely 25% and 20% of the peak values for raw signal and its first derivative, respectively.

Data validation is the last step of the procedure. A hierarchical algorithm was developed in order to identify and classify pixels not in compliance with a “well done experiment” criteria; as an example, pixels where the R, G, B activation order is not respected or where one color peak is missing.

The results of this procedure are “n” validated activation time matrices (one for each liquid crystal) defined on the image space. Finally, thanks to the application of the dewarping polynomial law, it is possible to associate to each element of the matrix a point inside the real geometry with the corresponding flow temperature.

**EXPERIMENTAL CONDITIONS**

The measurement campaign had the goal to provide data useful for the rig and methodology validation. With this in mind, a wide test matrix was defined (see Tab. 1) where the variation of multiple experimental choices and parameters is considered. A first series of tests (Tab. 1(a)) were performed in static conditions, at Re=30000 and by warming up the fluid (hot step). Heat transfer data were acquired from tests characterized by different activation times of the liquid crystals (achieved with different temperature step evolutions imposed to the process fluid) and by different liquid crystals setup (single or mix of 3 liquid crystals with equal proportion in volume).

Successively, the Reynolds number was reduced to 10000, in order to be able to explore sufficiently high Rotation values (Ro=0-0.4) so highlighting the buoyancy effects that are varying between cold or hot step, see Tab. 1(b). Indeed, with the appropriate selection of a single liquid crystal, the same test was repeated imposing a cold or hot step. The static case condition was also repeated in order to verify for data consistency with the rig operated in cold or hot step modality.
Narrow banded liquid crystals have been used, namely Hallcrest R32C1W (LC1), R36C1W (LC2) and R40C1W (LC3) for the hot step tests, and Hallcrest R12C1W for the cold step ones. The liquid crystals were chosen according to the relation given in [7]:

$$\Theta = \frac{T_w - T_0}{T_b - T_0}$$  \hspace{1cm} (2)

<table>
<thead>
<tr>
<th>a)</th>
<th>Activation Time</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hallcrest R36C1W</td>
<td>20,\text{min} \quad 01 _ LC2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5,\text{min} \quad 02 _ LC2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40,\text{min} \quad 03 _ LC2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80,\text{min} \quad 04 _ LC2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,\text{min} \quad 05 _ LC2</td>
<td></td>
</tr>
<tr>
<td>Hallcrest R32C1W</td>
<td>20,\text{min} \quad 01 _ LC1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5,\text{min} \quad 02 _ LC1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50,\text{min} \quad 03 _ LC1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,\text{min} \quad 04 _ LC1</td>
<td></td>
</tr>
<tr>
<td>MIX (R32+R36 +R40)</td>
<td>10,\text{min} \quad 01 _ MIX</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,\text{min} \quad 02 _ MIX</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,\text{min} \quad 03 _ MIX</td>
<td></td>
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</table>

<table>
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<tr>
<th>b)</th>
<th>Re</th>
<th>Ro</th>
<th>Bo_{obs}</th>
<th>Note</th>
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<tr>
<td>Hallcrest R36C1W</td>
<td>0.1</td>
<td>0.016</td>
<td>0.4</td>
<td>HOT STEP</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>0.2</td>
<td>0.063</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>0.141</td>
<td></td>
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<td></td>
<td></td>
<td>0.4</td>
<td>0.251</td>
<td></td>
</tr>
<tr>
<td>Hallcrest R12C1W</td>
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<td>0.019</td>
<td>0.4</td>
<td>COLD STEP</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>0.2</td>
<td>0.077</td>
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</tr>
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<td></td>
<td>0.3</td>
<td>0.172</td>
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<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>0.306</td>
<td></td>
</tr>
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Table 1: test matrices: static tests - hot step (a); static/rotating tests cold/hot step comparison (b).

This relation ensures that the data uncertainty on the HTC measurement can be minimized if, during the experiments, the non-dimensional temperature parameter is maintained within the range 0.3<\Theta<0.7.

Reynolds and rotation numbers are defined with the well-known equations in correspondence of the test section inlet (Re = \(U_b \, D_h \, \rho)/\mu \) and Ro = \((\Omega \, D_h)/U_b\). Buoyancy parameter is evaluated with the following equation:

$$Bo = \frac{T_w - T_b}{T_b} \, \text{Ro}^2 \, \frac{R}{D_h}$$  \hspace{1cm} (3)

where R is the radius (with respect to the rotation axis) of the point considered for the evaluation. For the Bo data provided as reference in Tab. 1(b) (absolute values), T_w and T_b are evaluated at the activation time of the liquid crystals and along the channel centerline, and R is set at 915mm which correspond to the middle radius of the investigated inter-rib pitch (see in the following). It should be noted that although the absolute value of the Bo parameter is about the same for similar tests with hot or cold step, they actually pertain to opposite buoyancy effects, not realistic for the hot step case (hotter fluid with respect to the wall).

Heat transfer data will be presented in terms of Nusselt number (\(Nu = (h \, D_h)/k_{air}\)) or enhancement factor (\(Nu/Nu_0\)) where the reference Nusselt number is computed according to the Dittus-Boelter correlation for smooth tubes.

Heat transfer data were acquired in correspondence of the inter-rib area between the 11th and the 12th ribs (between x/D_h=14-15 from the test section inlet).

RESULTS

Validation tests

Figure 5 reports the results obtained with LC2 for tests with different flow temperature steps (see Tab.1(a)), which evolution is shown in Fig. 5(a). Nusselt profiles are extracted in correspondence of the channel centerline and reported in Fig. 5(b). The typical features of the heat transfer field inside
a rib roughened channel flow are detected [8] namely: a region of high heat transfer located just downstream of the flow reattachment (X/e about 4), the consequent decrease of Nu because of new boundary layer development, and the further peak of Nu upstream of the following rib due to the new flow separation. However, the scope of the present work is to validate the rig and methodology, which is actually confirmed by the satisfactory comparison between the Nu profiles in Fig. 5(b). Indeed, Nu values from different tests are within ±5% of Nu AVG, which is the ensemble average of all data. These data also highlight the effect of the Θ parameter choice on the data accuracy. As reported in [7], when Θ approaches the limits of its possible range of variation, the data uncertainty can rise up very quickly. Indeed, data from tests 02_LC2 and 04_LC2 differ about 2-3% from the others, which conversely are characterized by a Θ value in the middle of the suggested range and provide almost identical results.

The same considerations can be made by looking at the Nu profiles obtained from tests carried out with the use of a different and colder liquid crystal (LC1), Fig. 6. Also in this case all the profiles fall in the ±5% range with respect to their averaged value, while the effect of Θ is less evident. The comparison with the data obtained with LC2, which averaged value is also reported in Fig. 6(b), confirms once again the robustness of the developed methodology.

Figure 7 reports the results obtained with the three liquid crystals used in mix. Data comparison, here not reported for brevity, shows that also in these cases the variation of the step profile has a minor impact on the final values. For this reason, only the averaged data from the different tests are...
reported in Fig. 7. The indications provided by the three liquid crystals used in mix are in good accordance to each other. A maximum difference of about 4% can be found in the region of high heat transfer/flow reattachment downstream the rib. The comparison between the indication of LC1 and LC2 used as single liquid crystals or in mix are also very well in agreement. This confirms that the developed image processing tools are well suited to handle the unavoidable loss of signal intensity that occurs with mix of multiple liquid crystals. As a final remark, it can be noticed that the indications with the lowest Θ parameter (LC1 data in Fig. 7(a)) are the only data that provides higher Nu values which are not in perfect agreement with all the other indications.

The results above commented can be also used to provide an estimation about the data uncertainty. Indeed, the test matrix in Tab. 1(a) covers a wide range of variation of multiple experimental parameters. Indeed, by applying it to the same experiment it allows to highlight the measurement errors that can be generated by uncertainties on the measurement of \(T_b\), \(T_w\) and on the identification of the activation time. With this in mind, and in view of the results of above, the overall uncertainty can be estimated below 10%.

As a final verification, a comparison with the available literature is made in Fig. 8. The data are compared in terms of Nu/Nu₀ values, span-wise averaged on the inter rib surface. The selected references are for geometries not identical to the present one but with minor differences that do not affect the comparison (0.9 aspect ratio for [10], 12.5% of rib blockage for [1]). The present data are in good agreement with the literature, the differences fall within the expected uncertainty for heat transfer measurements.
Rotating tests

Before going into the details of the rotating data, a first comparison between data obtained with cold or hot step is made in static conditions in order to assess methodology relatability. The comparison is provided in Fig. 9(b) (Nu values along the channel centerline), which shows that there is no effect on the aerothermal behavior by changing the test modality. Differences below 5% are observed on the Nu distribution if the data are compared in terms of local ratio, as in the map of Fig. 9(a) (blanked data are regions where the liquid crystals did not activate and therefore HTC values cannot be computed, the same comments also applies to the data in Fig. 10).

In Fig. 10 Nu maps at the investigated conditions are shown. As a general comment, an augmentation of Nu values is observed at increasing Ro, as expected in view of the rotational effects and the location at the trailing side of the ribbed wall [9, 14]. The increasing trend is not monotonic, consistently with the literature where a plateau in the enhancement factor is observed for Ro>0.2 [10]. However, the behavior is much different if realistic or opposite buoyancy effects (cold or hot step, respectively) are applied to the flow. From the maps in Fig. 10, it can be appreciated how the area of high heat transfer widens much more at increasing Ro for the cold step cases. Also, much lower heat transfer is found upstream of the second rib in the hot step data. A better comparison can be made by looking at the plots in Fig. 11, where Nu profiles along the channel centerline are compared. In order to better highlight the effects here introduced, each curve is normalized with respect to its Nu maximum value. For the cold step case, the Nu profiles remain self-similar, an indication that the mean flow path does not change dramatically with rotation. In particular, the location of the heat

Figure 10: Nu/Nu₀ maps for cold (top) and hot (bottom) steps

Figure 11: Nu/Nu_MAX comparison for Re = 10000, different Ro: cold step (a), hot step (b)
transfer peak does not change significantly with rotation and the Nu distribution (and hence the flow field) remains almost identical once rotation is set above a certain level (Ro>0.2). This is in agreement with the de-stabilizing effect of rotation on the separated shear layer at the trailing side commented by Coletti et al. [9]. By looking at the flow field behavior, they see an almost stable or slightly shorter reattachment length at increasing both Ro and Bo, associated to higher turbulence intensity that explains the increased Nu. A much different behavior is found if the fluid is warmer than the wall (hot step, opposite buoyancy forces with respect to the real application). The heat transfer data suggest that rotation determines a dramatic change in the flow path. Indeed, Nu peaks move more and more upstream as Ro is increased which means an upstream motion of the reattachment points. Consistently with a more upstream reattachment location, a lower and lower heat transfer region is found where the new boundary layer develops. Local heat transfer can drop down to 50% of the peak value, conversely to the cold step condition where, consistently with the literature [10], 20% to 30% lower heat transfer is measured.

**CONCLUSIONS**

The contribution reports the progresses made at the University of Udine in the development and validation of a new rig for heat transfer measurements in rotation inside gas turbine blade cooling channels. The main feature that characterizes the approach is the application of the transient liquid crystal technique also in rotation, which poses many technical issues that have been solved and described in previous contributions.

In this paper, a new algorithm to process the acquired data (liquid crystals images/activation peak detection) is presented. It allows a more efficient, accurate, and automatic detection of the activation time even in presence of mix of multiple liquid crystals.

The rig and the methodology have been successfully validated with a wide tests campaign on a simplified internal cooling geometry. In particular, rotating tests have been performed at different Ro and Bo values, repeating the same experiment also by imposing opposite buoyancy forces with respect to the real application, i.e. by warming the fluid as usually done with the transient liquid crystal approach. The reported results confirm the need to go for the presented methodology in order to achieve meaningful heat transfer data, even at the relatively low values of Ro and Bo here considered. However, these results represent only the first steps into the validation process of such complex methodology. One of the crucial point that remains open is the effect on the final accuracy of the buoyancy forces that are actually changing during the test, which is associated to the wall and flow temperature variation required by the transient approach. Further testing and analysis are ongoing in order to clarify this aspect and will be the subject of a future publication.

**REFERENCES**


