

16 Conclusion

16.1 Design, applications and necessity

The consequence of the continuous demand of aeroengines with less fuel consumption is the constant increase of the turbine entry temperatures (up to $2000K$); the need of advanced blade cooling techniques is a major issue for keeping the material temperatures at acceptable levels. An accurate determination of the heat transfer on the turbine blades and of the flow temperature facilitates the blade cooling control, and also enables the understanding of complicated turbomachinery flows (such as stator-rotor interactions, rotor blade tip leakage and secondary flows) and their catastrophic effects. Simulated aeroengine conditions (Mach and Reynolds numbers, free-stream to wall and wall to coolant flow temperature ratios) in the VKI Isentropic Light Piston (I.L.P.) facilities allow exhaustive heat transfer and flow temperature measurements (as well as pressure and velocity measurements) in a fast and accurate way combined with a low cost (compared to continuous facilities).

Two high frequency response measurement techniques, the two-layer thin film gauges for surface heat transfer measurements and the dual thin film probe for flow total temperature measurements, are the two main subjects of the present work. The main objectives focus on the design concepts of both techniques, the establishment of their calibration procedures, the development of their data reduction techniques and their successful application in high speed turbomachinery flows. Both techniques are optimized to operate in the I.L.P. facilities (CT2 and CT3) that are characterized by running times of the order of $0.5s$, blade passing events of $6.9kHz$ (in CT3), high temperature peaks (up to $80K$) during a very short time (few ms), different flow conditions (e.g. subsonic and supersonic Mach numbers).

Major achievements on the two-layer thin film gauge technique were already performed at MIT and at Oxford University and the dual thin film probe is already widely used at Oxford University, at NRC in Canada and at QinetiQ. The necessity of the VKI independent development of the above measurement techniques has to be underlined: not only knowledge and experience on this new techniques were gained but mainly their design was better controlled and finally adopted in the requirements of the VKI facilities in a cost effective way.

The two-layer gauges were validated at 50% span of the second stator blade of the VKI one and a half stage turbine (in the VKI I.L.P. CT3 facility) and they were applied on a blade tip (in the VKI I.L.P. CT2 facility). The rotor stator interactions were recorded and new aspects of the tip leakage flows were revealed. The dual thin film probe was validated behind a cascade (in the CT2 facility), as well as behind the rotor and the second stator of the CT3 facility. The results demonstrated the superiority of the probe compared to thermocouples and cold wires.

16.2 Achievements on the two-layer gauges

The thin film sensors for surface heat transfer measurements are installed onto a flexible, Upilex, plastic sheet ($50\mu m$ thick), which is glued to the blades with a two-sided adhesive sheet ($75\mu m$ thick). The assembly procedure is simple on geometries that can be developed in flat surfaces such as the two dimensional stator blade surfaces and the rotor blade tips. The difficulty of gluing the sheet on highly curved three dimensional blade surfaces can be overcome by cutting the sheets into several pieces and gluing them separately onto the blades. The major advantages of this technique are:

- a) high frequency response (higher than $50kHz$),
- b) small size ($1.9 \times 0.25mm^2$, and a fraction of μm thickness),
- c) no need of additional expensive equipment such as a high frequency infrared camera,
- d) high sensitivity and accuracy.

The thin film sensor operation is transient and the sensor is connected to a Wheatstone bridge operated in a constant current mode.

The thin film sensors measure the temperature of the wall on which they are deposited (temperature-resistance thermometers), while the corresponding wall heat flux is numerically reconstructed after the test. The one dimensional heat conduction equation across the gauge substrate is solved for every time step (discretized time step determined from the experiment). The Crank-Nicholson scheme is used for the discretization of the above equation, leading to the solution of a tri-diagonal matrix; the latter can easily and quickly be solved by existing subroutines. Finally the wall heat flux is calculated by the Fourier law. The advantage of solving the one dimensional conduction together with the Crank-Nicholson scheme has to be emphasized, because, not only the wall heat flux is based on the general solution with no additional approximations on the heat conduction, but also its determination is very fast (few seconds) even for high sampling frequencies such as tenths of kHz.

An original calibration procedure of the two thermal products:

- a) of the ensemble Upilex sheet and glue,
- b) of the blade material,

as well as of the thickness of the top layer (Upilex and glue) were proposed. The two-layer gauge is submitted to a known convective heat flux, previously calibrated by means of a single-layer gauge with known thermal properties. The electrical discharge method was utilized for the thermal product calibration of the single-layer gauge. Then the values of the three above parameters that characterize the two-layer gauge can be determined by an iterative procedure. The measured wall temperature matches with the numerically reconstructed one by solving the heat conduction inside the two-layer gauge substrates based on the selection of the three parameters and the known wall heat flux from the single-layer gauge. The accurate, repeatable and fast experimental determination of the thermal properties and the first layer thickness of the gauge substrates should be underlined. For the first time, all the three parameters can be determined simultaneously during the same test.

The heat transfer distribution under the form of Nusselt number at 50% of the blade height of the second stator (of the VKI turbine) was firstly determined by a row of 24 single-layer gauges. These gauges are fired onto a ceramic insert substrate (Macor). Their operating principle is similar to the two-layer gauges, however, their calibration procedure is much simpler, as it is only the thermal product of Macor that has to be determined. The single-layer gauge measurement technique is widely used at VKI and at other universities and institutes during the last decades. Nevertheless, the implementation of the Macor inserts in the metallic blades limits the blade mechanical strength, preventing the use of the Macor inserts in high speed rotating turbine blades, where the two-layer gauges seem to be the only solution. In our case, the Nusselt number results of the single-layer gauges are compared with the results of the two-layer gauges at the same positions for the same test conditions in order to validate the new two-layer gauge results.

Time-averaged and time-resolved Nusselt number results are recorded. Because of the resolution of the data acquisition system (limited to 12 bits) combined with the fact that the heat flux fluctuations of given amplitude are caused by smaller wall temperature fluctuations at high frequency, the signal is modulated in such a way that the voltage signal of the Wheatstone bridges has a constant amplification up to 100Hz and is then amplified by $\sqrt{j\omega}$ between 100Hz and 20kHz . The time-averaged results are low pass filtered at 100Hz and sampled at 1.2kHz , while the time-resolved results are high pass filtered at 750Hz and sampled at 300kHz . Also, the time-resolved quantities are phase locked averaged for three rotor revolutions (192 blade passing events).

Both time-averaged and time-resolved results of the two above techniques compared successfully. The repeatability of the time-averaged results for the two-layer gauges was found

$\pm 4.4\%$ and for the single-layer gauges $\pm 8.2\%$. The better repeatability for the two-layer gauges is attributed to the larger wall temperature increase. Since the computation of the Nusselt number requires the evaluation of the temperatures T_{GAS} , T_W and thus the heat flux Q_W , the uncertainty on each of these quantities will affect the repeatability of the Nusselt number. The effect of the higher wall temperature increase is the result of the higher surface insulation of the substrate of the two-layer model in comparison to the single-layer model.

The observed Nusselt number fluctuations on the time-resolved signals indicate a periodic phenomenon, which is probably of potential nature. As the rotor operates in the transonic regime, instantaneous rotor trailing edge shocks create steep gradients on the static flow pressure and temperature fluctuations that generate steep gradients on their corresponding total conditions in the absolute frame, since the absolute exit rotor Mach number is only 0.42. Thus, the steep gradient on the Nusselt number fluctuations can be generated by the steep gradients of the total flow conditions.

The only comparison between the two-layer and the single-layer gauges that showed a very high difference of 50% on the time-averaged results was between the two gauges that were located at the stagnation point of the blade profile. However, the difference was even slightly increased when the curvature effects in this region were also taken into account in the data reduction procedure for the wall heat flux determination. The Nusselt number decrease due to the curvature for the single-layer gauge was -15%, where the same decrease for the two-layer gauge was -6.7%. Empirical correlations established for cylinders in cross flow (that could approximate the blade stagnation region) suggest Nusselt number values at the stagnation point closer to the ones calculated by the single-layer gauge. Moreover, the thermal properties calibration of the two-layer stagnation gauge revealed no difference with the rest of the two-layer gauges from which Nusselt number values were successfully compared to the single-layer ones. Also the possibility of a misplacement of the two-layer gauge on the blade stagnation area combined with high changes in the flow incidence angle for the tests in the CT3 facility (that could move the stagnation point on the blade) was excluded. Although all the different possibilities that could explain the reason of this 50% Nusselt number difference were thoroughly investigated, this subject still remains open for future discussion.

The application of the two-layer gauges technique on flat and squealer rotor blades tips emphasized their ability to characterize very complex, three dimensional flows, such as the tip leakage flows, through surface heat transfer measurements. Two different exit Reynolds numbers, two exit Mach numbers (subsonic and supersonic conditions) and two levels of free stream turbulence intensity studied the flow development for different combinations of flow parameters in a four bladed linear cascade in the CT2 facility. Increasing the Reynolds number resulted in an increase of the heat transfer rates. Higher turbulence intensities influenced the boundary layer character resulting in higher Nusselt numbers. Increasing the exit Mach number decreased the heat transfer at the rear part of the blade.

16.3 Achievements on the dual thin film probe

When two thin film sensors are combined, total gas temperature measurements are possible with the dual thin film probe. Each sensor is located at the stagnation point of the hemispherical head of two Macor (ceramic) cylinders. A resistance placed inside of one of the two cylinders allows its heating before the test. Since the two gauges are nominally identical, when they operate at two different temperatures, the total gas temperature can be determined. The two major advantages of this probe are:

a) its higher frequency response than the other already existing techniques for flow temperature measurements (higher than 50kHz),

b) its ability to measure high temperature peaks (of the order of $100K$) during very short times (few ms).

It is also independent from gas composition and flow parameters such as Mach and Reynolds numbers, it can be applied in unsteady compressible and/or high free stream turbulence flows and its calibration and operation procedures are simple and fast.

The two wall heat flux calculations from the two wall temperature measurements also take into account the curvature effects on the one dimensional conduction inside the heads. The most significant difficulty associated with the operation of this probe is that the noise on the wall heat flux calculations (and inevitably on the gas temperature) increases with increased sampling frequency and/or with the ratio of the two wall heat fluxes approaching the value of 1. Therefore, during the measurements:

- a) the sampling frequency is chosen not higher than the needed one for the correct resolution of the signal,
- b) one of the two initial wall temperatures approaches the gas temperature (thus the corresponding wall heat flux is brought close to zero), or the difference between the two initial wall temperatures is chosen high enough (more than $30\text{-}40\text{ K}$) (so that the value of the wall heat flux ratio is “far” from 1).

Once the design of the two ceramic cylinders is decided according to the heating element dimensions, special care is given on the design of the support of these cylindrical heads. Plexiglas and Vespel are chosen as the most suitable materials for this support because they are electrical and thermal insulators, they can withstand high temperatures (at least $350\text{-}370K$) and their dilatation coefficient is close to the one of the ceramic heads. Both Plexiglas and Vespel support probes were tested behind a cascade in the CT2 facility. As the sampling frequency for the tests with the Plexiglas support probe was high ($10kHz$), the wall temperature signals were strongly low pass filtered at $10Hz$ in order to eliminate the important noise on the gas temperature calculations. Due to this strong filtering, although the mean calculated gas temperature with the probe was successfully compared to the results of a thermocouple placed upstream the cascade, the beginning of the test was lost. Thus, the next series of tests were performed at $1kHz$ sampling frequency. In addition, because the Plexiglas support could not withstand high heating of the hot head, Vespel was selected as the material of the new support. The new low pass filtering frequency was $100Hz$ and the new tests revealed the high gas temperature peak (30 K) at the beginning of the test. The Vespel support probe was also successfully tested for different exit Reynolds and Mach numbers as well as for different heating conditions (different initial wall temperatures).

The Plexiglas and Ertalon support probes were also applied to low frequency periodic flow ($33Hz$) at ambient static conditions, while two other Vespel support probes were specially redesigned to fit into the available space behind the rotor and behind the second stator of the one and a half stage turbine in the CT3 facility. The average gas temperature value measured by the probe was successfully compared to the results of thermocouples, while the probe showed its superiority by measuring gas temperature peaks up to 80 K at the beginning of the tests. A phase locked average on the wall temperature signals of 192 periods, drastically reduced the noise on the wall heat flux calculations (although the sampling frequency was $300kHz$) and smoothed out any high three dimensional component of the flow that the two heads can feel. The calculated total gas temperature fluctuations from the probe behind the rotor reached 24 K , were successfully compared to earlier fast response cold wire results and were found to most probably be an image/trace of the static temperature fluctuations originated by the rotor trailing edge shocks in the relative frame. The calculated gas temperature fluctuations from the probe behind the second stator were found no more than 6 K that indicated the high mixing of the flow when passing through the stator. The high repeatability on the time-averaged and time-resolved gas temperature components measured by the dual thin film probe should also be underlined for the tests performed in both facilities (CT2 and CT3) and in ambient conditions.

16.4 Recommendations

A future two dimensional approach on the heat conduction inside the blade substrates could probably give more information about the Nusselt number difference at the stagnation point of the second stator blade in the CT3 facility between the two-layer gauge and the single-layer gauge and could quantify the possible errors coming from the one dimensional semi-infinite assumption on very high curved surfaces such as the blade stagnation area. The one dimensional semi-infinite assumption could also be questioned at places where the blade thickness is limited to few millimeters, such as the blade trailing edge region, where a two dimensional approach could also clarify the limitations of the one dimensional approach. Note that no two-layer gauges close to the blade trailing edge were tested during the present work.

An application of the two-layer gauges on rotor blades could demonstrate the superiority of these gauges to withstand higher centrifugal forces compared to the single-layer ones. As the rotor blade geometries are usually three dimensional (such as the rotor blades in the CT3 facility), the instrumented Upilex sheet can be cut into several pieces and glued separately onto the rotor blade surfaces. Special care should be taken during the gluing procedure. No air bubbles should be accumulated between the Upilex sheet and the glue because:

- a)* the geometry of the blade profile is influenced,
 - b)* the air thermal properties are different than the Upilex and the glue.
- In addition, air bubbles close to the sheet edges reduce the strength of the glue to keep the sheet bonded on the blade surfaces during the tests and of course should also be avoided.

The dual thin film probe is optimized for the gas temperature range that is found in the VKI facilities. Before the probe starts to be used in real turbomachines, new materials for the support (and possibly for the heads) have to be chosen that can mainly withstand much higher temperatures. Although the gas temperature in real turbomachines can reach 2000K, because the probe operates in a transient regime, the new materials do not have to reach such high temperatures. On the other hand, the mechanism that will introduce the probe into the flow of a turbomachine for only one second is probably the most difficult future challenge. Thus, the probe dimensions should firstly been reduced without deteriorating its high accuracy. In addition, the wall heat flux calculations should also take into account lateral conduction effects, natural convection losses, as well as possible radiative heat fluxes.