2 The thin film gauges

2.1 Introduction

Existing theory and work about the thin film gauges are compared to other already existing convective heat transfer measurement techniques, in the following paragraphs. Then, the idea of the new two-layer thin film gauge technique is introduced by summarizing previous work at MIT and Oxford University and the VKI contribution is underlined.

2.2 An overview of heat transfer measurement techniques

2.2.1 The thin film sensor

The thin film sensor is a highly conductive film whose resistance changes are related to its temperature fluctuations (resistance thermometer). In the range of the temperatures considered here, the relationship between the thin film resistance and its temperature can be expressed as a linear approximation, which is demonstrated in Eq. (1). A second form of this linearity is shown in Eq. (2), where the coefficient a_T is a property of the thin film material and depends on its temperature:

$$R = a_{\Delta T} T + b_{\Delta T} \ , \tag{1}$$

$$R = R_0 \left[1 + a_T \left(T - T_0\right)\right] \quad \Leftrightarrow \quad \begin{cases} R_0 = b_{\Delta T} + a_{\Delta T} T_0 \\ a_T = a_{\Delta T} / R_0 \end{cases} . \tag{2}$$

The sensor placed on a substrate (wall) is connected to a Wheatstone Bridge (W/B) that operates either under constant current mode (type I) or under constant temperature mode (type II) (Olivari and Carbonaro, 1994, and Sieverding et al., 2000). (Simple schematics of the two above circuits are shown in the appendix 18.1.)

The circuit of type I is used for wall heat transfer measurements and is called thin film gauge. The W/B output is proportional to the wall temperature changes in time. When it is coupled with an appropriate analytical model, and if the wall thermal properties are known, the wall temperature history can lead to the calculation of the wall heat flux history. The thin film gauge operation is transient and thus, it is widely used in short duration facilities (paragraph 1.5). The measurement techniques and their applications that are described in the next paragraphs of this work are all based on type I operation of the thin film.

The circuit of type II is used for shear stress measurements that provide information on the onset, development and end of boundary layer transition and is named hot film gauge. The W/B output of the hot film gauge additionally passes through a control circuit that interferes with the supply voltage of the W/B, such as to maintain the film temperature constant. The latter is a function of the flow geometry: the increase/decrease of the dissipated heat flux in the thin film sensor from the supply current is proportional to the convection on the sensors substrate which is influenced by the flow velocity. The hot film gauge operation is continuous and it is mainly used in continuous facilities.

2.2.2 The single layer thin film gauge for heat transfer measurements

The thin film sensor is deposited on an insulating substrate such as quartz or ceramic (Macor). Quartz and Macor are selected because their thermal properties variation with temperature is less than other insulators (e.g. Pyrex) [Miller, 1981]. In addition, the thermal properties of quartz are well documented and Macor can be machined with metal-working tools. At VKI, since Macor substrates can be fabricated inside the workshop, Macor is widely used not only for turbomachinery applications but also for high speed and high temperature experiments in aeronautics.

The fabrication of the thin film sensor on the substrate is made in several steps, at VKI. First a very thin film of platinum is hand-painted on a well polished Macor surface. Then, the whole Macor substrate is introduced in an oven at about *870K* for a few hours. A second layer of thin film is then painted on the top of the first one and the substrate is put back into the oven. The procedure continues till the desirable resistance is obtained for the final thin film sensor (between *30Ω* and *100Ω*). The gold connections between the thin film sensor and the cables leading to the W/B are applied in a similar way.

At VKI, the final thickness of the thin film sensor is a fraction of a μm and its length and width can be as small as *2mm* x *0.5mm*. Due to its small thickness and high thermal conductivity, its frequency response is as high as *50kHz* (Denos, 1996). In addition, many gauges can be deposited on a small area of the same substrate. Furthermore, the high sensitivity of the thin film gauge (*10K* of wall temperature change corresponds to around *1 Ohm* of resistance change for the VKI applications) allows the same gauge to be used for a wide range of wall heat transfer rates (Miller, 1981). The wall heat flux history during an experiment is determined from the wall temperature history by using the unsteady heat conduction equation applied inside the gauge substrate (paragraph 2.2.4)

2.2.3 Convective heat transfer measurement techniques

The slug calorimeter consists of a slug of a large thermal conductivity material that is embedded inside the insulator substrate (Schultz and Jones, 1973 and Diller, 1993). The slug absorbs the wall heat flux on its free front surface and increases its temperature. A thermocouple on the back surface of the slug measures this temperature rise as a function of time, which is approximately proportional to the wall heat flux. The technique is based on a very simple concept; however, the frequency response of the calorimeter is very low and it is mainly used for steady state measurements.

A direct heat flux gauge whose output voltage is proportional to the wall heat flux diminishes the effects of electrical noise on heat flux compared to the thin film gauge. The heat flux sensor consists of two temperature measurements on either side of a thermal resistance layer (high conductivity material); the wall heat flux is proportional to the above temperature difference (Fourier law). To increase the sensitivity of this gauge, hundreds of thermocouple pairs are arranged as a differential thermopile circuit (in series) (see Figure 2-1); the output voltage is then multiplied by the number of the pairs (Diller, 1993). The heat flux gauge used by Holmberg et al. (1994) reached a frequency response of the order of *100kHz*, however, the size of the sensor was quite large (*4mm* x *6mm*) compared to the thin film gauge.

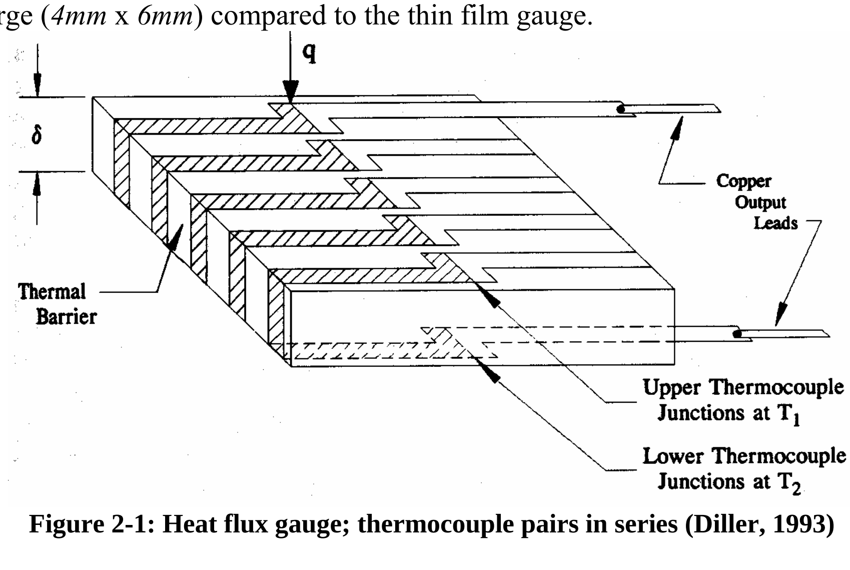

Figure 2-1: Heat flux gauge; thermocouple pairs in series (Diller, 1993)

A steady or transient liquid crystal thermography technique can also be employed for heat transfer measurements (Ekkad and Han, 2000). More specifically, some liquid crystal materials exhibit colors within the visible spectrum when they are heated to specific temperature ranges. They are attached or painted on the surface whose temperature spatial distribution has to be evaluated as a function of time. For heat transfer measurements, this surface should have a low conductivity (e.g. Plexiglas). During the transient operation of the liquid crystals, the solution of the unsteady one dimensional heat conduction equation applied on the substrate for a step in gas temperature is employed for the determination of the convective heat transfer coefficient. During the steady state operation, either the temperature difference across the substrate of known thickness and conductivity is needed (Fourier law) (Ireland and Jones, 2000), or the wall heat flux is supposed to be equal to the electrical heating of the liquid crystals sheet, once the latter is well isolated (VKI technique – Cakan and Arts, 1997 – Casarsa et al., 2002). Although the advantage of the liquid crystals is that they cover the complete surface allowing global temperature distributions to be measured, their frequency response is limited to a few hundreds of Hertz. They also require the use of a camera to record the reflected colors during the test as well as a suitable image processing tool.

The infrared thermography technique captures the thermal radiation emitted by a hot black body and transforms this part of the radiative emitted heat flux into an electrical signal, related to the surface body temperature (Buchlin, 2004). More into detail, the power of the total emitted heat flux depends on the body temperature and the wavelength spectrum. The infrared camera detects and records the emitted heat flux in a wavelength band where the atmosphere is transparent to radiation ($3.5\mu m$ to $12\mu m$) that is inside the infrared spectrum limits. The final relationship between the emitted heat flux and the surface body temperature is obtained from a suitable calibration. Recording the wall temperature history and using the solution of the unsteady one dimensional heat conduction equation applied on the model's substrate (a selected insulator) for a step in gas temperature or for a constant convective wall heat flux, the convective heat transfer can be determined.

The naphthalene sublimation technique determines the local mass transfer coefficient by using a heat and mass transfer analogy (Papa et al., 2003, Rhee et al., 2001). More specifically, the model is covered with a layer of naphthalene that is exposed to the flow. The depth of the layer is measured before and after the experiment to determine the mass loss; the latter, divided by the naphthalene saturated vapor density, provides the mass transfer coefficient. This technique can only provide time-averaged measurements and it is highly sensitive to natural convection losses of naphthalene before and after the experiment.

A brief comparison between the thin film gauges and the other techniques shows the superiority of the thin film sensor for turbomachinery applications. While other techniques offer greater spatial resolution (e.g. liquid crystals), the thin films are valuable in their sensitivity, accuracy and speed. They also require no camera and thus no transparent window between the test section and the camera. Nevertheless, their application in continuous facilities is limited, since the operation of the thin film gauge is transient.

2.2.4 From wall temperature measurements to wall heat flux determination

A general unified theoretical treatment of most of the above heat transfer techniques reveals that once the wall temperature is measured, the wall heat flux can also be determined either by unsteady solutions of the heat conduction inside the substrate or by steady state solutions of the same equation. The unsteady solutions are used for transient measurements and imply an insulator substrate. Either solutions that correspond to constant wall heat flux or constant flow temperature are used to analytically derive the wall heat flux from the wall temperature; or the heat conduction is solved for every time step (inversely proportional to the sampling frequency of the experiment) everywhere inside the substrate and the wall heat flux is

computed by the Fourier law. The thin film gauges utilize the second approach as more general case that can be applied to the complicated turbomachinery flows. In practice, the wall heat flux is either:
a) calculated numerically using the Crank-Nicholson scheme to discretize the heat conduction equation in time and space;
b) measured during the experiment when the W/B is further connected to an electrical analogue circuit of resistors and capacitors;
c) first the measured wall temperature is transformed in series (by using Fast Fourier Transform) in the frequency domain where the wall heat flux is calculated and then the latter is transformed to the time domain. Additional details are given in the following paragraphs.

Semi-infinite condition: the semi-infinite principle implies that during the transient operation of the thin film gauge, the temperature on the back side of the gauge substrate remains equal to its initial value prior to the experiment. Thus, the thickness of the substrate should be large enough, so that the conductive heat transfer does not penetrates till its back side. Schultz and Jones (1973) propose that the penetration depth at which the temperature and the heat flux inside the substrate are 1% of their wall values are $3.16(\alpha t)^{0.5}$ and $3.74(\alpha t)^{0.5}$ respectively for a constant wall heat flux (α stands for the thermal diffusivity of the substrate and t for the experimental time).

Numerical solution: the temperature profile inside the substrate can be computed at each time step by solving the unsteady one dimensional conduction equation with the Crank Nicholson scheme (Denos, 1996 – Buttsworth, 1997). This scheme leads to a tri-diagonal matrix which can efficiently be solved with algorithms found in numerical libraries. The wall heat flux is calculated from the slope of the temperature profile at the wall using the two grid points near the wall (Fourier law).

Electrical analogy: in this technique, a resistance-capacitance (*R-C*) transmission line, or electrical analogue, is used to convert the wall temperature signal into a signal proportional to the wall heat flux (Oldfield et al, 1982). The flow of current through a continuous *R-C* line is equivalent to the one dimensional flow of heat through the gauge substrate. By imposing the transfer function of the *R-C* line to be the same as the one dimensional heat conduction in the gauge substrate, the voltage across the first *R-C* is set equal to the thin film temperature (wall temperature) and the current is equal to the wall heat flux. The number of the *R-C* elements is chosen to verify the semi-infinite condition. More about the theory of the electrical analogue can be found in Meyers (1960).

Fast Fourier Transform (FFT): once the wall temperature is transformed in the frequency domain by using an FFT, a complex product is performed between the wall temperature and the transfer function of the wall heat flux in order to determine the latter in the frequency domain. An inverse FFT provides the wall heat flux in the time domain (Doorly, 1988).

2.3 Literature survey on the two-layer gauges

2.3.1 General aspects

The idea of using two substrates instead of one for the new two-layer thin film gauge, where the first layer is an insulator sheet (e.g. plastic) glued or mounted on a second material that the model is made of, seems to offer a number of advantages compared to the Macor single-layer thin film gauge. Not only the machinable glass (Macor) is expensive, but also mechanical strength limitations prevent its use for rotating turbine blades, where the stress levels increase enormously. Moreover, Macor inserts in metallic blades in a fully rotating turbine stage suffer from surface discontinuities in temperature and they are effectively limited within the space of the insert. This technique is also time-consuming because it requires the machining of pockets with a three axis-milling machine. Then, inserts have to be carefully fitted in the pocket to restitute the external blade shape. Finally, the instrumentation of one section requires that the gauges are spread over several blades in order to limit the weakening that results from the existence of pockets. On the other hand, the blade models can be instrumented simply with the two-layer gauges and relatively inexpensively, bringing the application of thin film instrumentation to a routine procedure, thus ease of manufacture. Besides, the two-layer gauges can be implemented on highly curved surfaces (providing that they can be developed in a plane area), such as three dimensional rotor blades and make use of the already existing metallic blades in a cost-effective and quick manner.

The development of the two-layer gauges measurement technique requires:

i) the establishment of the gauges geometry,
ii) a thorough material choice for substrates,
iii) the substrate thermal properties determination,
iv) the accurate characterization of the heat flux source used during the gauges calibration,
v) the most efficient operating principle of the gauges during the real measurements.

These five techniques, as well as the gauges applications, are mainly discussed in the next paragraphs dedicated to the work on the two-layer gauges performed outside VKI. The VKI choices are then summarized in paragraph 2.4, while the calibration procedure of the gauges is analytically described in chapter 3.

2.3.2 The MIT two-layer gauge

The two-layer thin film gauge technique was intensively developed at MIT, by Epstein et al. (1986). The gauge consisted of two temperature sensors (thin-films) on either side of the first insulating substrate (*25μm* polyimide sheet). This sheet was bonded to a test article. As the boundary conditions on each side of the instrumented sheet were known, only the thermal properties and the thickness of the first layer were required. The gauge response was separated according to the frequency of the applied wall heat flux. At high frequencies, the polyimide appears semi-infinite to the upper sensor and the unsteady one dimensional conduction equation was used to determine the heat flux. At low frequencies, the polyimide was acting as a thermal shunt: the temperature difference across the polyimide was a direct measure of the heat flux. The actual data during a test was reduced with an electrical analogy which reconstructed the entire frequency domain. In the electrical analogy, the voltage across the first and the last resistor-capacitor elements was set equal to the temperatures measured by the upper and the lower sensors respectively. For the calibration of the thermal properties and the thickness of the insulating layer, a step in radiative heating was applied to the top gauge surface twice, with the upper sensor both covered and uncovered by a reference fluid of known thermal properties. The semi-infinite one dimensional conduction solution for constant wall heat flux determined the first layer thermal properties; while extending the heating time to steady state conditions, the first layer thickness could be found.

The above described gauges were glued around the rotor blade of the turbine stage of the MIT blowdown turbine facility by Abhari et al. (1992) in order to examine the time-resolved heat transfer and to assess the impact of various modeling assumptions and numerical approximations on the heat transfer calculations. Steady and time-resolved heat transfer was also measured using the above two-layer gauges on the same rotor blades both cooled and uncooled by Abhari and Epstein (1992), in order to quantify the influence of three-dimensional and unsteady effects on the rotor film cooling process.

2.3.3 The Oxford two-layer gauge

2.3.3.1 Enamel coated blades

Remarkable effort on the development and the improvement of the two-layer thin film gauge technique was also carried out at Oxford University. Doorly and Oldfield (1986) proposed the possible use of metallic turbine blades which were completely coated with an electrical *200μm* thick insulator and which were subsequently instrumented with thin film sensors. The coating of vitreous enamel was fired onto mild steel cylinders models for stagnation point heat transfer measurements. They were tested in the working section of the Isentropic Light Piston (I.L.P.) Tunnel at Oxford and successfully compared to the single-layer gauges. The thermal properties of the mild steel (second layer) were considered well known, while the thermal properties of the coating were calibrated with an electrical discharge technique for short testing times (heat produced by ohmic dissipation is applied to the sensor). During the calibration, for short testing times, the response of the thin film sensor was approximated with a semi-infinite single-layer gauge consisting of only the coating substrate, thus a linear response as a function of square root of time for a step in wall heat flux; for longer times, the sensors response was approximated with a semi-infinite single-layer gauge consisting of only the mild steel substrate, thus a second linear response, with an offset to account for the presence of the insulator. The thickness of the first layer was determined by the intersection of the above two linear responses: the measured one for short times (from the electrical heating) and the fitted one for longer times (known thermal properties of the steel). The wall heat flux during the measurements in the I.L.P. Tunnel was determined with electrical analogue circuits which modeled the one layer case, together with a numerical correction to accommodate the second layer. Essentially, the electrical circuit served as an exact model for high frequency heat conduction in the first layer (semi-infinite for short times), whereas the numerical correction was applied to the low frequency conduction, to account for the second layer.

This numerical correction was further optimized by Doorly (1988), by considerably saving computational time. He also suggested to calculate numerically the wall heat flux directly from the digitally recorded wall temperature signal, using Fast Fourier Transform (FFT) techniques. Finally, the application of the two-layer gauges on a turbine blade in a cascade wind tunnel undergoing simulated engine unsteady flow was also successful. In addition, Doorly and Oldfield (1987) gathered the equations that characterize the one dimensional heat conduction in single and two-layer substrates and derived more analytically the equations concerning the numerical correction to obtain the wall heat flux for the multi-layer gauges by using the electrical analogy of single-layer gauge. The concept of two-layer finite backwall substrate was also introduced.

Furthermore, the manufacturing procedure of the thin film sensor on the coating, as well as the coating deposition on a three-dimensional turbine blade was described by Ainsworth et al. (1989). The sensor is applied by painting liquid platinum and firing it at high temperatures. It was also shown that at high frequencies the gauge sensitivity on wall heat flux decreased as the square root of frequency, thus, it was desirable to amplify the high frequency components of the signal. Hilditch and Ainsworth (1990) finally used seven two-layer gauges to measure the heat transfer at the mid-chord of a turbine rotor blade in the I.L.P. tunnel at Oxford. The thermal properties of the first layer (the enamel coating) were determined through the electrical discharge method over a short time so that the conduction remained one-dimensional. The properties of the second layer (metallic blade) and the thickness of the first layer were determined by the use of a thermal radiative wall heat flux. The wall heat flux during the measurements was resolved by employing the FFT techniques. However, the size of the sensor was considered too large for the heat transfer measurements at the mid-span of the blade by Allan et al. (2004) who suggested a higher spatial resolution gauge: thin film sensors and golden leads were developed, making use of a photo-etching technique and provided high density instrumentation. The golden gauges were successfully placed at mid-span, except in the regions of large curvature where hand-painted platinum gauges were mounted. The heat transfer measurements highlighted the role of the upstream nozzle guide vane wakes and shock features. A further application of these gauges on a nozzle vane of the second stator in the I.L.P. facility at QinetiQ was conducted by Chana et al. (2003): the gauge results were compared to two different numerical predictions; however, the stagnation point heat transfer was not measured, because it was not possible to instrument the stagnation point region, because of the high curvature.

Platinum thin-film sensors with gold connecting tracks were produced by Thorpe et al. (2000) rapidly, at precisely known locations. The size of the gauges was *1mm* x *0.08mm*. First, layers of metallo-organic platinum ink were fired on the blade coating. Then, a focused light beam from a pulsed laser cut or etched the gauges out from the continuous film. The control of the laser ablation technique was provided by a computer. The gold connections were next fired on the coating surface.

2.3.3.2 Upilex plastic sheet adhesively bonded to blades

A second design of the two-layer thin film gauge technique was proposed at Oxford University by Guo et al. (1995). The thin film sensors were instrumented onto flexible, Upilex sheets (*50μm* thick) which were easily bonded to nozzle metallic blades with double sided adhesive. The thickness of the glue was less than *20μm* and its thermal properties were similar to those of the Upilex sheet. In order to cope with the curvature of the surface, the sheets were cut into several pieces and glued separately onto the blade. The gaps between the sheets were far from the gauges and filled with a suitable filler. The wall heat flux was determined by the method suggested by Doorly and Oldfield (1987), exactly as for the enamel coated blades. The gauges were used for heat transfer measurements in an annular cascade consisting of nozzle vanes and compared with results obtained by means of a liquid crystal technique. Although the trends were identical for the two techniques, the liquid crystal measurements reported higher mean values. This was attributed to the roughness of the liquid crystal layer compared to the smooth polyamide film. However, no calibration of the thermal properties of the two layers and the thickness of the first one was performed as their values were claimed to be well known. A further application of the same configuration of gauges, glued on Perspex blades (whose thermal properties are similar to Upilex) was used for the heat transfer coefficient determination over the above nozzle vanes when being heavily film cooled (Guo et al., 1997, 1998). The gauge was considered as single-layer from a thermal point of view.

The instrumented Upilex sheet was further optimized with high density thin film gauge arrays at Oxford University by Anthony et al. (2004). On a flat plate model, 15 different arrays with 233 total thin film sensors were covering an instrumented area of *332mm* x *150mm*. The spatial resolution of the heat flux measurements was succeeded within *0.2mm*. Sensors within a single array are arranged in series and supplied with a constant current. This configuration highly reduced the number of the leads that transfer the voltage across the thin film sensors. The Upilex sheet was glued on a Perspex plate, whose thermal properties matched that of the Upilex sheet; thus, a single-layer semi-infinite heat transfer analysis was made. The gauges were used to investigate bypass transition induced by freestream turbulence on a flat plate wind tunnel model.

Piccini et al. (2000) proposed to place a thermocouple between the Upilex sheet and the metallic model, a configuration closer to the MIT gauge (paragraph 2.3.2). The wall heat flux was numerically calculated by solving the heat conduction equation for one layer with the boundary conditions on each side of the instrumented sheet known; thus, only the thermal properties and the thickness of the first layer were required (two parameters). During its calibration, the gauge was submitted to a sudden heating from a hot air jet. During such a test, it is the heat transfer coefficient that remained constant; a superposition technique was then applied to the measured wall temperature signal in order to construct a wall temperature that corresponded to a constant wall heat flux that was measured by a calorimeter. The constant wall heat flux solution of the heat conduction equation for a semi-infinite two-layer gauge was then fitted to the superimposed wall temperature to determine the thermal properties and the thickness of the Upilex sheet. An application of the above configuration of the gauges was carried out on nozzle guide vanes to investigate the influence of the surface roughness on heat transfer (Guo et al., 2000). The blades after being instrumented with the gauges for smooth surface tests, were then coated with liquid crystals for rough surface tests.

2.4 VKI contribution on the thin film gauges

Up to now, at VKI, platinum thin-film gauges fired onto a single-layer machinable glass ceramic (Macor) substrate (and/or quartz) are widely used. Their manufacturing procedure, their operating principles as well as the determination of the wall heat flux through electronic analogue circuits are analytically discussed by Ligrani et al. (1982). First, Consigny et al. (1979) used gauges on a cold flat plate made of quartz to determine the influence of the pressure gradient and the free stream turbulence on the heat transfer to the plate using the VKI I.L.P. facility, CT2. Then, the entire blade can be made of ceramic for cascade testing in the CT2 facility, e.g.:

a) Arts et al. (1990) studied the effect of freestream turbulence, Reynolds number and Mach number on the time-averaged heat transfer distribution at midspan of a nozzle guide vane;

b) Camci and Arts (1990) measured the time-averaged heat transfer at midspan of a film-cooled rotor blade.

More recently, measurements were successfully performed on the rotor blades of the one and a half stage turbine of the I.L.P. tunnel of VKI, CT3 by using ceramic inserts fitted into metallic blades, e.g.:

a) Denos (1996) studied the influence of the shock wave of the nozzle guide vanes on the Nusselt number distribution around the rotor blade midspan;

b) Didier et al. (2002) determined the time-averaged and time-resolved heat transfer coefficient at 15%, 50% and 85% span of the rotor blade as well as on the rotor tip and hub platform.

Coating a metal blade with enamel would require careful matching of metal with enamel and would involve heating the assembly. Also, the thickness of the enamel is difficult to control around the whole blade surface. The choice of a flexible plastic sheet avoids the above difficulties of the assembly, and provides a constant thickness around the blade. These reasons mainly influenced the VKI two-layer configuration of the thin film gauges.

The originality of the VKI two-layer gauges measurement technique compared to the existing ones at MIT and Oxford University is based on two ideas.

The first idea is based on a faster, simpler, more reliable and always repeatable calibration procedure of the two layers thermal properties and the thickness of the first layer (three parameters). The two-layer gauges are submitted under a convective heat flux source that is first calibrated by the use of a single-layer gauge with known thermal properties. Then, an iterative procedure selects the values of the three parameters in such a way that the measured wall temperature signal of the two-layer gauge matches the numerically reconstructed one by solving the one dimensional conduction in the gauge substrates under the boundary condition of known wall heat flux.

The second idea provides the determination of the wall heat flux from the wall temperature measurements by using a fast numerical data reduction technique that requires:

a) no approximations as far as the heat conduction phenomena in the gauge substrates is concerned (except the one dimensionality assumption);

b) the use of no complicated additional electrical circuit.

The discretized one dimensional conduction equation in space second order and in time second order Crank-Nicholson scheme is solved inside the substrates for every time step (determined by the sampling frequency during the measurement). The scheme ends up in a tri-diagonal matrix that can be quickly solved with already existing subroutines. The wall heat flux is then calculated by the Fourier law.

Since the two-layer gauges have been developed at VKI, their cost is moderate and their assembly and application is fast and simple. No additional electronics than those used for the single-layer gauges were designed or bought. In addition, the two-layer gauges facilitate the heat transfer measurements at VKI compared to the single-layer gauges and thus were already used on a blade tip for investigating the tip leakage flows in the I.L.P. facility, CT2. All the advantages described above make the two-layer gauges the most challenging future heat transfer measurement technique for turbomachinery applications.

2.5 References

Abhari R.S., Epstein A.H., 1992, *'An experimental study of film cooling in a rotating transonic turbine'*, ASME 92-GT-201, Cologne, Germany

Abhari R.S., Guenette G.R., Epstein A.H., Giles M.B, 1992, 'Comparison of Time-Resolved Turbine Rotor Blade Heat Transfer Measurements and Numerical Calculations', ASME J. of Turbomachinery, vol. 114, pp 818-827

Ainsworth R.W., Allen J.L., Davies M.R.D., Doorly J.E., Forth C.J.P, Hilditch M.A., Oldfield M.L.G., Sheard A.G., 1989, *'Developments in Instrumentation and Processing for Transient Heat Transfer Measurement in a full-Stage Model Turbine'*, J. of Turbomachinery, vol. 111, pp 20-27

Allan W., Ainsworth R., Thorpe S., 2004, *'Unsteady heat transfer measurements from transonic turbine blades at engine representative conditions in a transient facility'*, ASME GT2004-53835, Vienna, Austria

Anthony R.J., Jones T.V., LaGraff J.E., 2004, *'High frequency surface heat flux imaging of bypass transition'*, ASME GT2004-54162, Vienna, Austria

Arts T., Lambert de Rouvroit M., Rutherford A.W., 1990, *'Aero-thermal investigation of a highly loaded transonic linear turbine guide vane cascade (A test case for inviscid and viscous flow computations)'*, VKI TN 174.

Buchlin J.M, 2004, *'Infrared Thermography'*, Advanced measurement techniques for aero engines and stationary gas turbines, VKI LS 2004-04

Buttsworth D.R., 1997, *'A finite difference routine for the solution of transient one dimensional heat conduction problems with curvature and thermal-dependent thermal properties'*, University of Oxford, OUEL Report number 2130/97

Cakan M., Arts T., 1997, *'Effect of rib height on heat transfer enhancement in a cooling channel'*, Proc. Eurotherm Seminar 55, Heat transfer in single phase flows 5, Santorini, Greece

Camci C., Arts T., 1990, *'An experimental convective heat transfer investigation around a film-cooled gas turbine blade'*, J. of Turbomachinery, vol. 112, pp 497-503

Casarsa L., Cakan M., Arts T., 2002, *'Characterization of the velocity and heat transfer firlds in an internal cooling channel with high blockage ratio'*, ASME GT-2002-30207, Amsterdam, The Netherlands

Chana K.S., Povey T., Jones T.V., 2003, *'Heat transfer and aerodynamics of an intermediate pressure nozzle guide vane with and without inlet temperature non-uniformity'* ASME GT2003-38466, Atlanta, Georgia, USA

Consigny H., Chan C.K., Richards B.E., 1979, *'The effect of pressure gradient and external turbulence on heat transfer to a cold flat plate'*, VKI TN 128

Denos R., 1996, *'Aerothermal investigation of the unsteady flow in the rotor of a transonic turbine stage'*, Ph.D. thesis, University of Poitiers

Didier F., Denos R., Arts T., 2002, *'Unsteady rotor heat transfer in a transonic Turbine Stage'*, ASME 2002, Amsterdam, GT-2002-30195, J. of Turbomachinery, vol. 124(4), pp614-622

Diller T.E., 1993, *'Advances in heat flux measurements'*, Academic Press, Inc, ISBN 0-12-020023-6, Advances in heat transfer, vol. 23, pp 279-368

Doorly J.E., 1988, *'Procedures for determining surface heat flux using thin film gages on a coated metal model in a transient test facility'*, J. of Turbomachinery, vol. 110, pp 242-250

Doorly J.E., Oldfield M.L.G., 1986, *'New heat transfer gages for use on multilayered substrates'*, J. of Turbomachinery, vol. 108, pp 153-160

Doorly J.E., Oldfield M.L.G., 1987, *'The theory of advanced multi-layer thin film heat transfer gauges'*, J. of Heat Mass Transfer, vol. 30 (6), pp 1159-1168

Ekkad S.V., Han J.C., 2000, *'A transient liquid crystal thermography technique for gas turbine heat transfer measuremnts'*, J. of Meas. Sci. Technol., vol. 11, pp 957-968

Epstein A.H., Guenette G.R., Norton R.J.G., Yuzhang C., 1986, 'High-frequency response heat-flux gauge', Review of Scientific Instruments, vol. 57 (4), pp 639-649

Guo S.M., Jones T.V., Lock G.D., 1997, *'Gas turbine heat transfer measurements with engine simulated film cooling'*, 2nd European Conference on Turbomachinery – Fluid Dynamics and Thermodynamics, Antwerp, Belgium

Guo S.M., Lai C.C., Jones T.V., Oldfield M.L.G., Lock G.D., Rawlinson A.J., 2000, *'Influence of surface roughness on heat transfer and effectiveness for a fully film cooled nozzle guide vane measures by wide band liquid crystals and direct heat flux gauges'* J. of Turbomachinery, vol. 122, pp 709-716

Guo S.M., Lai C.C., Jones T.V., Oldfield M.L.G., Lock G.D., Rawlinson A.J., 1998, *'The application of thin-film technology to measure turbine-vane heat transfer and effectiveness in a film-cooled, engine-simulated environment'*, Int. J. of Heat and Fluid Flow, vol. 19, pp 594-600

Guo S.M., Spencer M.C., Lock G. D., Jones T.V., Harvey N. W., 1995, *'The applications of thin film gauges on Flexible Plastic Substrates to the gas Turbine Situation'*, ASME paper 95-GT-357, Houston, Texas, USA

Hilditch M.A., Ainsworth R.W., 1990, *'Unsteady heat transfer measurements on a rotating gas turbine blade'*, ASME 90-GT-175, Brussels, Belgium

Holmberg D.G., Mukkamala Y.S., Diller T.E., 1994, *'Shock tunnel evaluation of heat flux sensors'*, AIAA-94-0730, Reno, NV, USA

Ireland P.T., Jones T.V., 2000, *'Liquid crystal measurements of heat transfer and surface shear stress'*, J. of Meas. Sci. Technol., vol. 11, pp 969-986

Ligrani P.M., Camci C., Grady M.S., 1982, *'Thin film heat transfer gage construction and measurement details'*, VKI TM 33

Meyers R.F., 1960, *A heat-flux-meter for use with thin film surface thermometers'*, Aeronautical Report LR-279, National Research Council of Canada, Ottawa

Miller C.G., 1981, *'Comparison of thin-film resistance heat transfer gauges with thin-skin transient calorimeter gages in conventional hypersonic wind tunnels'*, NASA Technical Memorandum 83197

Oldfield M.L.G., Burd H.J., Doe N.G., 1982, *'Design of wide-bandwidth analogue circuits of heat transfer instrumentation in transient tunnels'*, 16th Symposium of the International Center of Heat and Mass Transfer, Dubrovnik, Croatia

Olivary D., Carbonaro M., 1994, *'Hot wire measurements'*, Measurement techniques in fluid dynamics, VKI LS 1994-01, pp 193-228

Papa M., Goldstein R.J., Gori F., 2003, *'Effects of tip geometry and tip clearance on the mass/heat transfer from a large-scale gas turbine blade'*, J. of Turbomachinery, vol. 125, pp 90-96

Piccini E., Guo S.M., Jones T.V., 2000, *'The development of a new direct-heat-flux gauge for heat-transfer facilities'*, J. of Measurement Science and Technology, vol. 11, pp 342-349.

Rhee D.H., Choi J.H., Cho H.H., 2001, *'Effect of blade tip clearance on turbine shroud heat/mass transfer'*, ASME 2001-GT-0158, New Orleans, Louisiana

Schultz D.L., Jones T.V., 1973, *'Heat Transfer Measurements in Short Duration Facilities'*, AGARDograph no 165

Sieverding C.H., Arts T., Denos R., Brouckaert J.F., 2000, *'Measurement techniques for unsteady flows in turbomachines'*, J. of Experiments in Fluids, vol. 28, pp 285-321

Thorpe S.J., Yoshino S., Ainsworth R.W., 2000, *'Fabrication and calibration techniques for turbine rotor tip heat transfer gauges'*, Proceedings of the XV Symposium on Measuring Techniques for Transonic and Supersonic Flows in Cascades and Turbomachines, Florence, Italy