

1 Introduction

1.1 Foreword

One of the most delicate engineering tasks is the design and the application of measurement techniques in gas turbine environments. First, an efficient design of instrumentation demands good knowledge of the aerodynamics of the gas flow in the machine and a good idea of the limits of the flow parameters mainly temperature and pressure. Also, a less intrusion from the gas flow instrumentation needs thorough investigation on the probe dimensions and on the probe operation principle. In addition, the material choice of the instrumentation is of great importance for the robustness and the cost of the probes. Moreover, a correct application of the instrumentation requires additional choices such as probe positioning, probe stability, reduction of vibrations and advanced support mechanisms. The effort gets even harder when measurements must be taken in the complex three dimensional environment of turbomachines, characterized by high frequency periodic unsteadiness, tens of kHz, by viscous and compressible phenomena, e.g. wakes, shock waves and by high free stream turbulence.

Achievements in new heat transfer and gas temperature measurement techniques in turbomachines are the main subject of the following work. Two new instrumentation techniques based on the thin film sensor are proposed: the two-layer thin film gauge and the dual thin film probe. Applications of the first technique on wall heat transfer measurements on the second stator blade of the VKI one and a half stage turbine, as well as on a rotor blade tip of a cascade validated the applicability of the technique. Applications of the dual thin film probe on total temperature measurements were also successful downstream of a cascade, and downstream of the rotor and the second stator of the VKI one and a half stage turbine. During the introduction, a brief description of a turbomachine is given, then the two new measurement techniques are briefly presented. The flow complexity and the necessity of measurements as well as the applicability of the above two techniques are underlined. Also, the different kinds of experimental facilities where these techniques can be applied and are applied at VKI are pointed out. The introduction ends with the scope of the following work.

1.2 Main principles in turbomachines

Turbomachines are widely used for power generation, e.g. electricity, on ground, for marine propulsion and for aircrafts. Steam turbines are mainly used for ground applications, while the aircraft engine operates with air. The turbomachinery part of an aircraft engine consists of two main components that are in a sequence of fixed and rotating parts, a compressor and a turbine, and a combustion chamber. An exhaust nozzle follows to complete the engine. The air from the atmosphere is drawn, compressed and heated in the turbomachinery part; this energy and momentum forces the air out of the nozzle at a very high momentum. Due to reaction Newton's third law, the jet engine moves to the opposite direction.

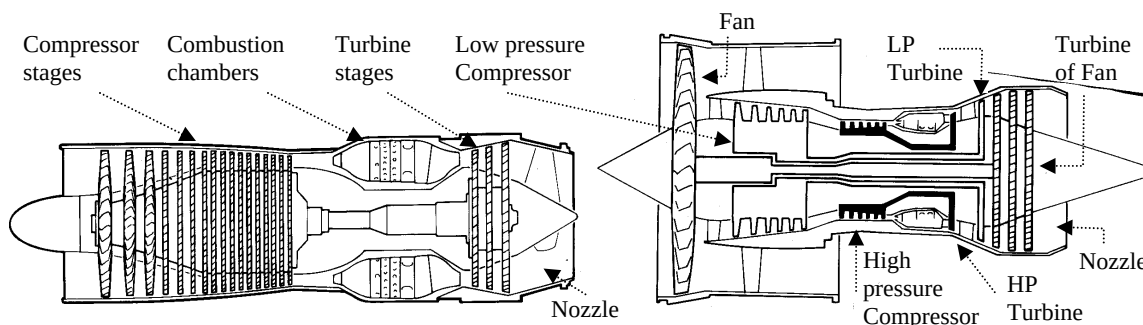


Figure 1-1: Mechanical arrangement of a single-spool axial flow turbojet (left) and a triple-spool front fan turbojet (right) (Rolls-Royce, 1986)

Part of the energy and momentum of the air during its expansion in the turbine is used to drive the compressor. The turbine gives power to the compressor either with a single shaft (left in Figure 1-1), or with two or three shafts (right in Figure 1-1) (Rolls-Royce, 1986). Every shaft is connected on one side to a turbine with at least one stage (one stationary and one rotating part, indicated as single line) and on the other side to several compressor stages (for the high and low pressure compressor) or to a fan.

The high momentum exhaust air can be generated either by a small mass of air at large velocity or by a large mass of air and small velocity. The engine on the right has a second stream of air that is exhausted immediately after being only compressed by the fan (by pass air) without passing through the rest of the components of the engine. This engine is mainly used in civil planes at subsonic travel speeds. The military planes that can reach Mach 3 are powered by a turbojet (left in Figure 1-1).

The turbine extracts energy from the hot pressurized gases delivered by the combustion chamber by expanding them to lower pressure and temperature. High stresses, high rotational speeds (tens of thousands RPM), and high turbine inlet temperature (up to $2000K$) are involved in this process. Thus, the different engine elements should be accurately designed and maintained while the machine stays on ground, and the flow parameters should be continuously controlled during the engine operation. The continuous optimization of old measurement techniques as well as the development of new ones that measure mainly pressure and temperature demonstrate the importance of an accurate knowledge of the turbine signature during engine operation. The turbine has to be tested for several flight conditions as the inlet air flow parameters drastically change during the flight time. An example of the atmospheric properties with the flight altitude is given in Table 1-1. The exit Reynolds number of the turbine (that is directly influenced by the inlet air pressure) can change by a factor 2 or 3 during flight, while the turbine can operate in both transonic and subsonic regimes depending upon the work extraction demand.

Altitude [m]	Temperature [K]	Pressure [Pa]	Speed of sound [m/s]
0	288.2	1.01325×10^5	340.3
4500	258.9	5.775×10^4	322.6
10000	223.3	2.650×10^4	299.5

Table 1-1: Representative values of the atmosphere properties (Kays and Crawford, 1980)

However, measurements in real engines are very difficult to perform as the instrumentation should be able to deal with all these different flow parameters and engine characteristics, while being resistive enough to high flow unsteadiness. This is one of the main reasons for the development of test rigs that provide full similarity with modern aeroengine operating conditions but in lower gas temperatures. In addition measuring in test rigs is much less expensive, compared to measurements in real engine environment, without sacrificing any of the accuracy.

This thesis is focused on heat transfer and temperature measurement techniques applied on and next to the turbine blades of turbine test rigs in short duration facilities. The two main instrumentation techniques are firstly introduced in a brief and compact way in the following paragraph, so that their applicability on the flow measurements can be sufficiently demonstrated.

1.3 New designs of instrumentation techniques in turbine stages

The thin film sensor has been used for the last four decades to measure heat flux rates in transient operation and is a thin and small conductive layer of platinum or nickel deposited on a thick material of low conductivity. Any temperature change of the thin film is proportional to its resistance change that is measured by a Wheatstone bridge operated in constant current mode.

Also, the thin film thickness is considered negligible and thus the conduction takes place only inside the substrate. The substrate consists either of a single-layer, or of two different materials. A two-layer substrate gauge is shown in Figure 1-2. The high frequency response of these gauges (due to the small dimensions of the thin film sensor) makes their operation in short duration measurements suitable and necessary. The heat flux can be determined with a suitable procedure, once the thermal properties of the substrate are known. The evolution from single-layer to two-layer gauges and the application of the latter in real turbomachinery flows is one of the two main parts of this thesis. The main advantage of the two-layer gauge is its easy implementation on blade surfaces, without any need of additional blade machining (which is the case for the single-layer gauges).

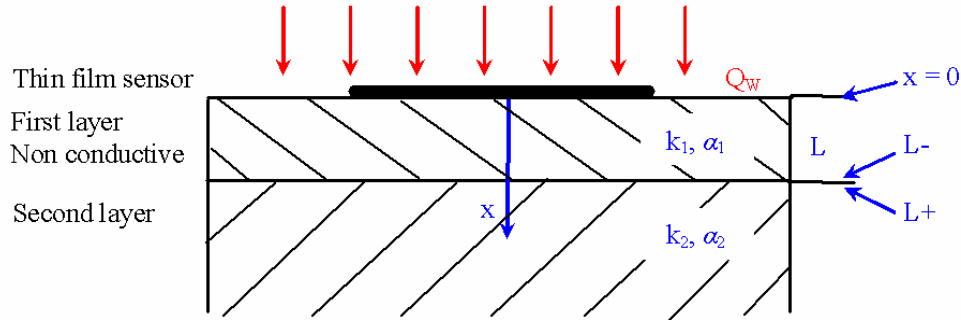
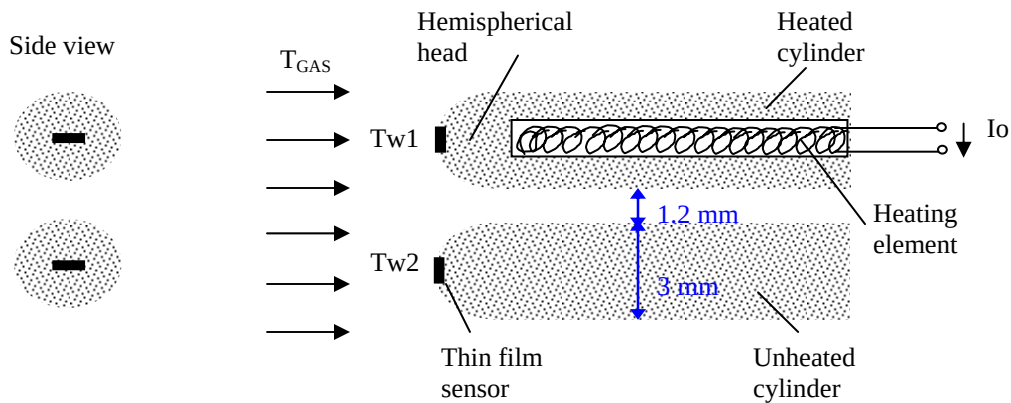


Figure 1-2: The two-layer substrate gauge

The dual thin film probe for total gas temperature measurements consists of two thin film sensors that are deposited each one on the stagnation point of a non-conductive hemispherical head (see Figure 1-3). Both heads are identical and operate at different temperatures. Prior to the test, one of the two heads is heated and although the thin films measure different heat flux rates, the heat transfer coefficient is the same when both heads feel the same flow. Thus, this combination of two thin films allows gas temperature measurements. The high frequency response and the robustness of the dual thin film probe make it highly attractive compared to thermocouples and cold wires. The second main part of the thesis is concentrated on the optimization of this probe and its applications in real turbomachinery environment.

Most common design



(The dimensions correspond to the VKI achievements)

Figure 1-3: The dual thin film probe

1.4 Heat transfer and temperature measurements in turbine stages

1.4.1 Steady component

Heat transfer: the hot gas stream leaving the combustion chamber of a gas turbine that flows through the cooler turbine blades generates high heat transfer rates that are dominated and controlled by the boundary layers. Although the turbines are characterized by an accelerating flow, which normally produces laminar boundary layers and thus lower heat transfer rate, turbulent boundary layers can also occur when there is a local decelerating flow, or an area with flow separation (Wilson, 1984). However, there is a high uncertainty regarding the starting point and the extent of the region of boundary layer transition from laminar to turbulent. Thus, the knowledge of an accurate heat transfer distribution around the blade can facilitate and make more efficient the choice of blade cooling structures that are most of the time already complicated (Figure 1-4).

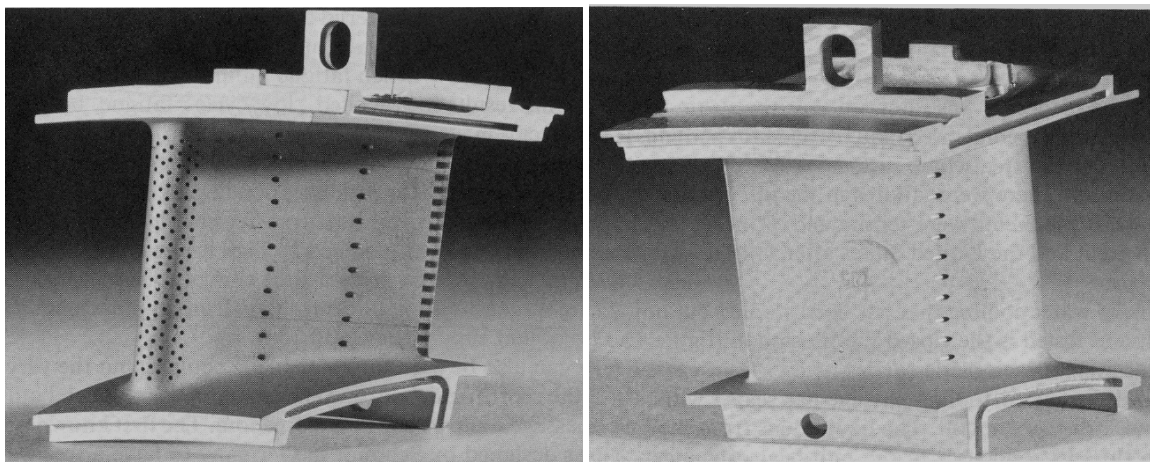


Figure 1-4: Turbine nozzle vane with impingement and film cooling – Courtesy Detroit Diesel Allison Division of General Motors Corporation (Wilson, 1984)

The two-layer thin film gauges are the most suitable instrumentation technique for heat transfer rate measurements on the blade surfaces in short duration tunnels. These experimental data determine the boundary conditions used in numerical calculations of the flow around the blade. Although the application of the thin film gauges is not really valid in real engines, the measurements in the simulating engine flow environment using the model turbines in tunnels allows the extraction of the above information for real engines.

Temperature: a simple cycle analysis in gas turbines can easily demonstrate that the turbine work output and efficiency could be mainly increased by increasing the turbine inlet temperature. Thanks to the recent advanced cooling techniques, this temperature is continuously increasing over the years (Figure 1-5), and its accurate control is of primary importance. Local overheating can burn out part of the blade or can result in high local temperature gradients on the blade and create catastrophic stresses. The blade partial or complete failure severely deteriorates the turbine efficiency by enormously increasing the total losses and eventually it will lead to the engine shutdown.

An accurate turbine inlet temperature measurement in short duration tunnels that simulate aero-engine conditions can be performed with the dual thin film probe. Its independence to gas composition and to other flow parameters such as Mach and Reynolds numbers, its application in unsteady compressible and/or high free stream turbulence flows makes the probe competitive to

thermocouples and cold wires, while the high robustness of the probe offers an advantage compared to the two other techniques. The gas temperature determination also contributes to accurate values of the measured turbine efficiency and the blade heat transfer rate.

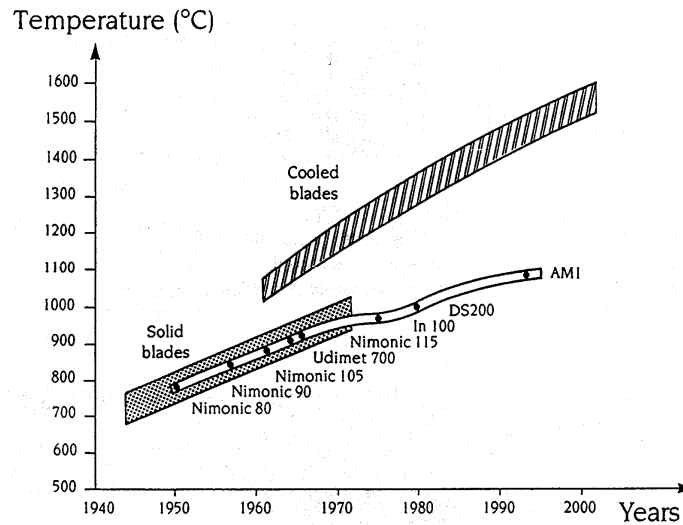


Figure 1-5: Variation of turbine inlet temperatures over the years
(graph from Lasalmonie et al. 1995)

1.4.2 Unsteady component – Rotor stator interactions

The unsteadiness in turbomachines is mainly generated by the aerodynamic interaction between the vanes of the stator (the non rotating part of the turbine that leads the flow to the rotor inlet) and the blades of the rotor (the rotating part that extracts the power from the high pressure, high enthalpy flow). This phenomenon is known as rotor-stator interaction. In a transonic flow at the exit from the vanes, the interactions are combinations between direct and reflected shocks and the vane wakes.

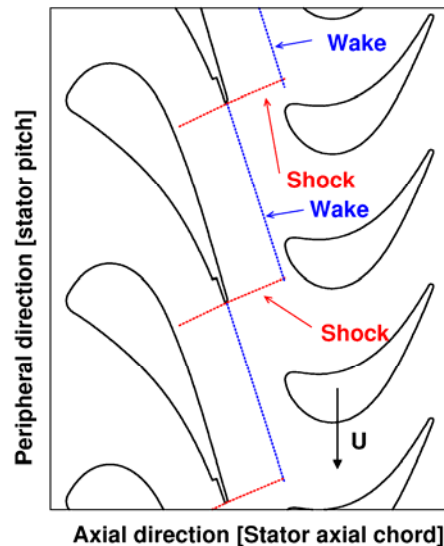


Figure 1-6: Transonic gas turbine vanes (and blades) – (Isentropic) exit Mach number 1.05
(Denos et al., 2001)

For exit Mach numbers close to 1 (Figure 1-6), the shock position is vertical to the vane trailing edge, while the wake follows the direction of the trailing edge. For higher exit Mach numbers, the shock angle gets smaller, while the wake is always at the same position. In both cases, as the blades rotate behind the vanes, the shock waves periodically impinge on the rotor blade, sweeping from the crown to the leading edge with a varying intensity, while the vane wakes pass through and are chopped by the rotor blades. Thus, the blade boundary layer feels variable pressure gradients that not only generate blade cycle fatigue over the time, but also can alter transition and highly affect the heat flux to the blade (additional thermal fatigue). Understanding this unsteady heat transfer on the blades is very important for those trying to design blades especially because of the high frequency of these interactions that range between 1 and 10 kHz.

The two-layer gauges are the most suitable technique for highly unsteady heat transfer measurements on the blade walls. Being non-intrusive to the flow development with a high frequency response, the gauges are able to capture the history of the boundary layer transition and to give valuable data for the blade modeling.

The dual thin film probe measures the gas temperature fluctuations determining the attenuation of the flow unsteadiness and the periodicity of the shock waves and the wakes further behind the vanes and the blades. The choice of the distance between the stator and the rotor is a complex problem, because on one hand the space and weight limitations of a jet engine requires them as close as possible, on the other hand the high flow unsteadiness gets less strong with distance by firstly mixing before reaching the rotor blades.

1.4.3 Complex three dimensional turbomachinery flows

One of the most complicated turbomachinery flows is the flow across a rotor blade tip. During turbine operation, the turning of the rotor requires a small gap between the rotor tip and the inside casing of the engine. Flow then is leaking through this gap across the blade tips. As a result the stage losses are increased and high heat transfer coefficients are generated in the near tip regions; further catastrophic results are the erosion and the loss of the blade material (particularly at the blade trailing edge, Figure 1-7, where cooling is more difficult) that produce even higher losses. Heat transfer measurements in the tip blade region often supply the required knowledge to employ tip leakage sealing treatments and thus reduce the high losses and avoid other undesirable effects. The two-layer gauges that are glued on the blade tip measure mean and fluctuating wall heat flux in simulated aero-engines in an easy and reliable way.



Figure 1-7: Material loss at the blade tip due to high heat transfer coefficients generated by the leakage flows across the tip (General Electric rotor blade)

1.5 Application on short duration tunnels

The instrumentation techniques based on the thin film sensor operation under a constant current of the Wheatstone bridge are mainly developed to operate in short duration wind tunnels. Moreover, the advantage of the thin film to respond at transient very high frequencies such as 50kHz permits high quality heat transfer experimental data of the complex high frequency three dimensional phenomena occurring in the turbine components. Thus, in turbojets, short duration wind tunnels are combined with cascades and turbines for boundary layer and cooling studies on the blades with the use of the thin film sensors.

Short duration wind tunnels were first built to generate high enthalpy flows to simulate the re-entry from earth orbit or from the moon (Schultz and Jones, 1973). The inability to generate continuous re-entry flows led to a range of short duration facilities shown in Figure 1-8. A short description of each facility is given in the next five paragraphs.

Shock tubes: they are devices that use a high-pressure gas to set up a shock wave which will compress a low-pressure gas and heat it to very high temperatures (Pope and Goin, 1965). The shock tube is made of two tubes separated by a diaphragm; one of the tubes is filled with a 'driver' gas at a high pressure and the other tube is filled with the 'driven' gas at low pressure. At time zero t_0 , the diaphragm bursts and the pressure step splits into:

- a) a shock wave, which propagates into the driven section,
- b) an expansion wave, which propagates into the driver section.

The shock wave compresses and heats the driven gas. The shock tube can be used as a short duration wind tunnel by utilizing the flow behind the shock wave (Liepmann and Roshko, 1957). More information about the unsteady wave motion can be found in Anderson (1990).

Shock tunnel: it includes a shock tube, a nozzle attached to the driven section of the shock tube and a diaphragm between the driven tube and the nozzle. When the shock tube is fired and the generated shock reaches the end of the driven tube and it is reflected, the diaphragm breaks. The heated and compressed air behind the reflected shock is available for operation of the tunnel.

Gun tunnel: the VKI longshot facility consists of a driver tube and a driven tube (barrel). The barrel is separated from the hypersonic nozzle (convergent-divergent) by valves (Simeonides, 1992). The piston is held in position by an aluminum disc at the junction of the driver chamber and the barrel. The driver is pressurized with nitrogen at $300\text{--}1000\text{bar}$ and the barrel at $1\text{--}15\text{bar}$ and the test section is almost at vacuum. Then the piston is released from the disc and accelerates down to the barrel to a speed of 600m/s . A shock wave propagates ahead of the piston and is reflected at the end of the barrel. When the pressure starts to increase, the gas is allowed to expand through the hypersonic nozzle by rupturing a diaphragm. When the reflected shock strikes the piston face, the piston decelerates, while the shock is reflected back to the barrel end. Then, follows a number of shock reflections between the piston face and the barrel end. When the piston velocity reaches zero, the valves at the end of the barrel close automatically, so that there is no flow back from the test section. Since a finite volume of test gas expands through the nozzle, the stagnation conditions decay with time, also limiting the duration of the test.

Isentropic light piston tunnel: a high gas total temperature can be obtained by an isentropic compression of modest pressure ratio from an initial ambient temperature (Brooks et al., 1985). The test gas is contained within a tube and is compressed isentropically by a piston, which is driven along the tube by a flow of air from a high pressure reservoir. When the gas has been compressed, a fast acting valve is opened and allows the gas to flow into the test section. The initial pressure in the pump tube is pre-set to control the Reynolds and the Mach numbers of the flow and the gas to metal temperature ratio in the test section. The area of the throat that controls the mass flow of the pressurized air in the tube behind the piston is matched to the throat area behind the test section so that the volumetric flow rates into and out of the tube are equal;

thus the total conditions in the test section are constant over most of the test time. More information can also be found in Jones et al. (1993).

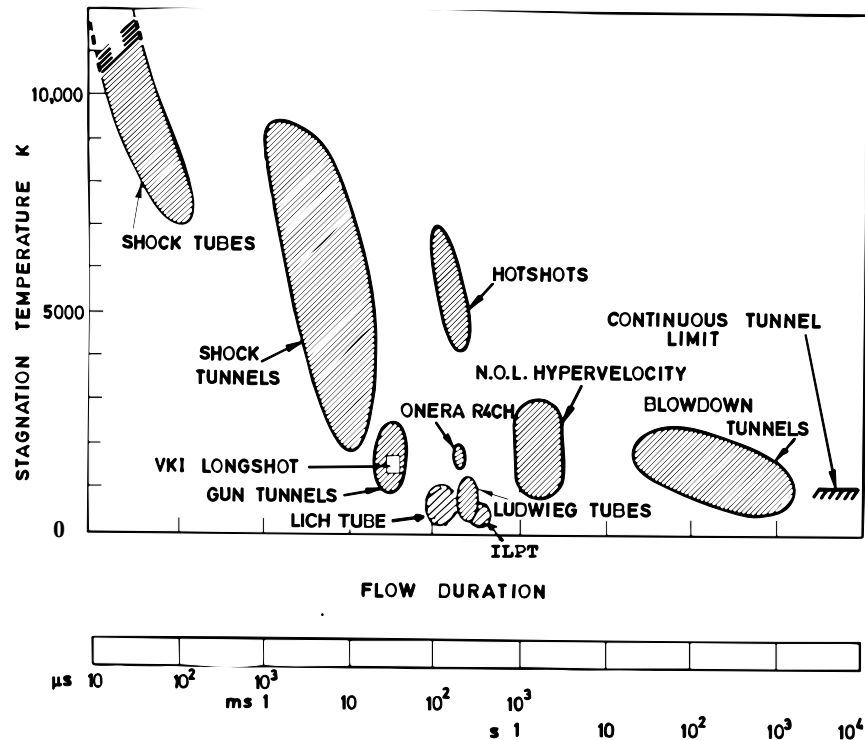


Figure 1-8: Stagnation temperature versus run time for short duration tunnels (Schultz and Jones, 1973)

Blowdown tunnel: pressurized air is stored in high pressure reservoirs and is heated in a storage heat exchanger prior to entering the tunnel settling chamber (Simeonides, 1992). This air expands in a convergent-divergent nozzle to the test section, which is either at almost vacuum or connected to a supersonic ejector.

The two measurement techniques, the dual thin film probe (Figure 1-3) and the two-layer gauges (Figure 1-2), that investigated in this thesis, were tested and used in the two VKI isentropic light piston tunnels CT2 (Consigny et al., 1979) and CT3 (Sieverding and Arts, 1992). The test section of CT2 is a cascade and that of CT3 is the VKI one and a half stage turbine. Both facilities are designed to simulate as close as possible the operating conditions of modern aeroengines with respect to Reynolds number, Mach number, gas to wall temperature ratios and wall to coolant flow temperature ratios. The importance of these facilities is based on their capacity of generating high power at low costs compared to equivalent continuous running installations.

The operation of the two-layer gauges in a gun tunnel such as the VKI longshot is straight forward. Although the stagnation temperature of the longshot is much higher than that of CT2 or CT3, the run time is shorter, so that the gauges can still measure in a transient mode. Their operation, as it is exactly established in this work, is not suggested in blowdown facilities, as the run time is usually more than 10s. During this time-period, the heat conduction inside the gauge substrate can not be considered as one dimensional, as it is the case for the tests in CT2 and CT3. Thus, in order to use the gauges in blowdown facilities, the lateral conduction effects inside the gauge substrate should also be taken into account. In theory, the gauge operation in shock tunnels and shock tubes could be possible, if their transient operation can be supported. In case of extreme stagnation temperatures, a suitable selection of the gauge substrate materials and their

electronics could optimize the measurement technique and certify their resistance at much higher temperatures. However, the run times of the shock tubes are extremely short (maximum a few milliseconds) and the gauges are never tested at frequencies higher than $25\text{-}50\text{kHz}$ (corresponding to $40\text{-}20\mu\text{s}$); it would be though interesting to challenge the gauge operation in an even more severe environment.

The possibilities of the application of the dual thin film probe in the other short duration tunnels than CT2 and CT3 are limited in the same way as these of the two-layer gauges. However, in addition, this probe demands ‘enough heating’ to measure accurately the gas temperature and the higher the value of the gas temperature is, the higher the heating is selected. Thus, its application in gun tunnels and shock tunnels could eventually be possible only with a suitable choice of the probe materials.

1.6 Scope of the thesis

The following work is motivated by the blade design requirements of a fast and accurate determination of the steady and unsteady heat transfer and gas temperature in turbojets. The design and the development of the two measurement techniques, the two-layer gauges and the dual thin film probe, is based on space and time resolution, material choices, high signal to noise ratio, easy implementation, high robustness and good repeatability.

The two-layer gauges are validated on the second stator of the VKI one and a half stage turbine of CT3. The heat transfer during CT3 operation is measured once with the two-layer gauges and once with the well validated technique of single-layer gauges. The comparison between these techniques is satisfactory and the repeatability is good.

The dual thin film probe is validated downstream a cascade in CT2. The total gas temperature during CT2 operation is successfully measured and compared to a thermocouple located upstream of the cascade. The same tests also show the superiority of the probe to measure high temperature peaks at the beginning of the tests. The probe is also validated behind the rotor and the second stator of the VKI one and a half stage turbine of CT3. The steady and unsteady gas temperatures are successfully captured and compared to previous thermocouple and cold wire measurements.

The application of the two-layer gauges on the blade tip heat transfer measurements in CT2 reveals the special features of the tip leakage flow for specific blade geometry, for different flow conditions. Transonic exit Mach numbers (0.9 and 1.1), as well as high Reynolds numbers (that both correspond to real engine conditions) are selected for this study and demonstrate their influence on tip leakage structures.

The chapters that follow concern:

- the literature survey on the two-layer gauges,
- the operating principle and the calibration technique of the gauges,
- the validation of the gauges on the second stator of CT3,
- an application of the two-layer gauges on heat transfer measurements on a blade tip in CT2,
- the literature survey on the dual thin film probe,
- the operating principle and the calibration technique of the probe,
- the validation of the probe in CT2 and CT3.

1.7 References

Anderson J.D., 1990, *‘Modern compressible flow with historical perspective’*, McGraw-Hill series in aeronautical and aerospace engineering, McGraw-Hill, Inc, ISBN 0-07-001673-9, United States of America

Brooks A.J., Colbourne D.E., Wedlake E.T., Jones T.V., Oldfield M.L.G., Schultz D.L., Loftus P.J., 1985, *The isentropic light piston annular cascade facility at RAE Pyestock*, Heat transfer and cooling in gas turbines, AGARD-CP-390, pp 31.1-31.23

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., Arts T., Paniagua G., Michelassi V., Martelli F., 2001, *Investigation of the unsteady unsteady rotor aerodynamics in a transonic turbine stage*, ASME 2000-GT-0435, J. of Turbomachinery, vol. 123(1), pp 81-89

Jones T.V., Oldfield M.L.G., Ainsworth R.W., Arts T., 1993, *Transient cascade testing*, Advanced methods for cascade testing, AGARD-CP-328, pp 103-152

Kays W.M., Crawford M.E., 1980, *Convective heat and mass transfer*, McGraw-Hill, Inc, ISBN 0-07-033457-9, United States of America

Liepmann H.W., Roshko A., 1957, *Elements of gasdynamics*, Galcit aeronautical series, John Wiley & Sons, Inc., ISBN 0471534609, Library of Congress Catalog Card Number: 56-9823 United States of America

Pope A., Goin K.L., 1965, *High-speed wind tunnel testing*, John Wiley & Sons, Inc., Library of Congress Catalog Card Number: 65-21435, United States of America

Rolls-Royce, 1986, *The jet engine*, The technical publications department of Rolls-Royce plc, ISBN 0902121235, Derby, England

Schultz D.L., Jones T.V., 1973, *Heat transfer measurements in short duration hypersonic facilities*, AGARDograph Report 165

Sieverding, C. H., 1984, *Transonic flows in last stages of big steam turbines*, course note 120, von Karman Institute, Belgium

Sieverding, C. H., and Arts, T., 1992, *The VKI compression tube Annular Cascade Facility CT3*, ASME paper 92-GT-336, Koln, Germany

Simeonides G., 1992, *Hypersonic shock wave boundary layer interactions over compression corners*, Ph.D. thesis, University of Bristol, April 1992, United Kingdom