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Development of gas temperature imaging by Laser-Induced Fluorescence for internal cooling channels

PhD Dissertation

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Before researchers become researchers they should become philosophers.

Masanobu Fukuoka

Abstract

Forced convection is a phenomenon already widely investigated in literature. However, there remain potential important improvements on its understanding and numerical prediction. The classical RANS approaches, widely used in industry for the design of cooling systems, are based on a constant *turbulent Prandtl number* value and isotropic turbulence. This results in a limited fidelity for the prediction of the convective heat transfer coefficient (at best 10-15% of accuracy). The present investigation, therefore, aims at supporting the development of CFD codes by providing detailed and accurate experimental data. Unlike most of the investigations available in literature, which provide the wall heat transfer and/or the velocity fields, the present research addresses the flow temperature. This temperature information allows obtaining the *turbulent heat transport term* $\overline{v'T'}$ required for the determination of the *turbulent Prandtl number* value.

Laser-Induced Fluorescence (LIF) has the advantage to provide a 2D temperature distribution by a non-intrusive optical approach. Gas-phase measurements, required for a consistent heat transfer investigation, were never applied before in internal flows as in the present application. First of all, the use of a fluorescent tracer is investigated regarding its impact on the Prandtl number value of the gas. After a detailed evaluation of the technique, including the image processing, the first experiments in a static cell show encouraging results of the first two-color measurements. A novel facility was designed and built at the von Karman Institute (VKI) to extend the study to the selected application. For simplicity, the test section is a smooth high aspect ratio duct to investigate a quasi 2D internal flow, as this configuration is closer to a cooling channel.

The measurements performed with the one-color methodology and using toluene as the fluorescent tracer show a good agreement between the obtained mean temperature profile and the one resulting from a traversing thermocouple probe. On the other hand, temperature fluctuations are strongly affected by the signal fluctuations recorded by the camera. The facility is prepared for possible nitrogen flow in order to eliminate the undesirable effect of oxygen quenching. Besides, the implementation of a Particle Image Velocimetry (PIV) system allows simultaneous velocity and temperature measurements with results of the *turbulent heat transport term*. The deep discussion and conclusions allow the author to outline possible future perspectives for further development of this technique.

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Contents

Nomenclature xi		
1	Introduction 1.1 Cooling in gas turbine technology 1.2 Blade Cooling 1.3 Internal Cooling by forced convection 1.3.1 Geometric parameters 1.3.2 Flow field 1.3.3 Governing equations and similarity 1.4 Research Objectives 1.5 Document output	1 2 6 8 8 10 11 13 14
2	LIF 2.1 LIF thermography 2.2 LIF tracers 2.2.1 Acetone-based LIF 2.2.2 Toluene-based LIF 2.3 LIF-mixture Prandtl number 2.4 Required instrumentation 2.4.1 Camera noise sources	17 20 22 23 24 26 28 30
3	1D acetone LIF: two-color and spectral measurements 3.1 Two-color measurements 3.1.1 Test section 3.1.2 Experimental set-up 3.1.3 Selection of the LIF filters for two-color acetone measurements 3.1.4 Data acquisition and processing 3.1.5 Results 3.1.6 Conclusions 3.21 Experimental set-up 3.2.1 Experimental set-up 3.2.2 Methodology 3.2.3 Results 3.2.4 Conclusions	 33 33 34 35 36 38 39 42 43 43 45 45 46
4	Facility and Experimental Set-up4.1Test section	49 49

	4.2	Piping and flow control	51
		4.2.1 Nitrogen flow implementation	53
	4.3	LIF experimental instrumentation and set-up	54
		4.3.1 Simultaneous PIV and LIF set-up implementation	56
	4.4	Flow characterization	57
	4.5	In-situ Temperature calibration	59
5	One	-color toluene measurements	61
	5.1	Methodology and image processing	61
		5.1.1 Image and Data acquisition	61
		5.1.2 Image processing	63
	5.2	Temperature calibration	71
	-	5.2.1 Image and data processing	71
		5.2.2 Results	71
	5.3	Results	73
		5.3.1 Air-Toluene	74
		5.3.2 Nitrogen-Toluene	76
		5.3.3 PIV/LIF experiments	77
	5.4	Measurement uncertainty	79
	0.1	5.4.1 Reynolds number uncertainty	79
		5.4.2 LIF temperature uncertainty	80
		5.4.2 Introchiperature uncertainty	00
6	Con	clusions and future perspectives	85
	6.1	Conclusions	85
	6.2	Future work	87
Ар	pend	lices	91
Λ	Lah	view script for real time control of the Roynolds number and	
~	tho	tracor concontration	03
		Operation of the LabView script	03
	A.1	Calculation of the Dermolds number and tracer concentration	95
	A.2	A 2.1 Maga flow and Darmalda number calculation	94
		A.2.1 Mass now and Reynolds number calculation	94
		A.2.2 Estimation of the tracer concentration	90
В	Insta	antaneous velocity/temperature images	101
Bib	oliogi	raphy	103

x

Nomenclature

Roman Symbols

A	Area	$[m^2]$
A_a	Antoine equation's constant	$[m^2]$
A_n	Invariant	[-]
BG	Background	
C	Discharge coefficient	[-]
$Cali_{rec}$	Calibration image signal	[counts]
$Cali_{the}$	Theoretical calibration curve	[-]
C^+	Log law constant	[-]
C_{CL}	Confidence level coefficient	[-]
C_s	Sunderland coefficient	[-]
c_P	Isobaric specific heat	[Jkg ⁻¹ K ⁻¹]
D	Internal diameter of the piping system	[m]
D_h	Hydraulic diam	[m]
d	Internal diameter of the orifice plates	[m]
Ec	Eckert number	[-]
E_{rand}	Random error	[-]
F_{HV}	Fuel calorific value	[Jkg ⁻¹]
Fr	Froude number	[-]
f_s	Sampling frequency	[Hz]
H	Channel height	[m]
h	Rib height	[m]
I_L	Laser intensity (fluence)	$[Jm^{-2}]$
I_{LIF}	LIF signal	[counts]
I^*	Normalized LIF signal (Eq. 5.4)	[-]
K	von Karman constant	[-]
k	Thermal conductivity	$[Wm^{-1}K^{-1}]$
k_B	Boltzmann constant	[-]
M	Molar mass	[gmol ⁻¹]
N_s	Specific power	[J kg ⁻¹]
n_{tr}	Tracer number of density	[mol]
n_{binn}	Number of binned pixels	[-]
P	Pressure	[Pa]
Pr	Prandtl number	[-]
Pr_t	Turbulent Prandtl number	[Pa]
Q_e	Camera quantum efficiency	[-]
q_m	Mass-flow	$[kgs^{-1}]$

q_V	volumetric rate	$[m^{3}s^{-1}]$
$q_p h$	photon flux rate	[Cpixel ⁻¹ s ⁻¹]
\hat{R}	Read out noise	[Cpixel ⁻¹]
Re	Reynolds number	[-]
S	Signal	[counts]
SFC	Specific fuel consuption	[kg s ⁻¹ N ⁻¹]
T	Temperature	[K]
T_0	Sunderland coefficient	[K]
t	Integration time	[s]
$U_b u l k$	Bulk velocity	[ms ⁻¹]
u	Stream-wise velocity	$[ms^{-1}]$
V_c	Collection volume	$[m^3]$
v	Wall-normal velocity	$[ms^{-1}]$
W	Channel width	[m]
Х	Stream-wise direction	[-]
Y	Wall-normal direction	[-]
Ζ	Direction perpendicular to X and Y	[-]

Greek Symbols

α	Thermal diffusivity	$[m^2 s^{-1}]$
α_t	Turbulent eddy diffusivity	$[m^2 s^{-1}]$
β	Diameter ratio of the orifice plates	[°]
γ	Specific heat ratio	[-]
Δ	Variation, difference	[-]
ε	expansibility factor	[-]
η	Efficiency	[-]
θ	Non-dimensional temperature	[-]
λ_1	Light wavelength	[nm]
μ	Dynamic viscosity	$[Pa \cdot s]$
ν	Kinematic viscosity	$[m^2 s^{-1}]$
$ u_t$	Turbulent eddy viscosity	$[m^2 s^{-1}]$
π	Pressure ratio	[-]
ρ	Density	[kgm ⁻³]
σ	Molecular absorption cross-section	$[m^{-2}]$
Φ_{ij}	Interaction coefficient	[-]
ϕ	Fluorescence quantum yield	[-]
φ	Angle of attack	[-]
χ	Molecular concentration	[-]
Ψ_{ij}	Interaction coefficient	[-]

Subscript

amb	Ambient conditions
bub	Bubbler
c	Compressor
cc	Combustion Chamber
corr	Corrected
eff	Effective
fl	Fluid
hw	Hot Wall
mix	Mixture
OP	Orifice Plate
opt	Optical
ref	Reference
sat	Saturation
t	Turbine
th	Thermal
tr	Tracer
up	Upstream

Superscript

+ Non-dimensional wall coordinates

Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
CFD	Computational Fluid Dynamics
CW	Cold Wire
FFC	Flat Field Correction
HW	Hot-wire
IC	Integrated Circuit
LCT	Liquid Crystal Thermography
LDV	Laser Doppler Velocimetry
LES	Large Eddy Simulations
LIF	Laser Induced Fluorescence
PIV	Particle Image Velocimetry
PLIF	Planar Laser Induced Fluorescence
RANS	Reynolds Averaged Navier-Stokes Simulations
ROI	Region Of Interest
SNR	Signal to Noise Ratio

TETTurbine Entry TemperatureTITTurbine Inlet TemperatureVKIvon Karman Institute for Fluid Dynamics

Chapter 1

Introduction

Despite the present research in the frame of cooling channels focuses on the full understanding of the flow and heat transfer phenomena in gas turbines, its interest can be extended to many other fields of engineering (e.g. oil industry, automotive, nuclear environments). Cooling and, in general, heat transfer are important phenomena used both at large and very small scales. Figure 1.1 represents four applications. On the top left, the European JET Tokamak during (right) and after operation. The fusion plasma inside the machine has a temperature about 15 million °C. The divertor, positioned at the bottom of the vacuum vessel, is the component responsible for the heat extraction as well as for the exhaust of waste gas and impurities.

The typical temperature of a nuclear reactor core is about 1700 K (on the top right of Fig. 1.1). Several power plants use a once-through or open-cycle cooling system where water is withdrawn from an external source, such as a lake, a river or a large reservoir. The water passes through the condenser and is then returned to its original source with a normally small rise of temperature on the aquatic environment.

Several oil or water cooled injectors are used in marine internal combustion engines (picture on the bottom left). Due to the high temperatures at which the injectors are exposed, nozzle cooling is required. Cooling research is also very active in small scale micro channels (between 30 and $300\mu m$). It is the case, for instance, of IC chips (on the bottom right). Considering the increased density of devices and 3D IC circuits, heat removal has become a real challenge.

All these applications have a common point: the importance of the heat transfer quantification in internal ducts. In most of the cases, forced convection is the major contribution to the cooling effect. Convection is the transmission of energy when conduction, linked to molecular interaction, and advection, associated to motion and enthalpy fluxes, work simultaneously. Literature refers to forced convection when the fluid motion is generated externally, for instance, by the use of pumps or blowers. Heat is extracted from the internal walls thanks to the forced fluid current and moves with it towards the exit of the channel.

These cooling passages were initially designed with smooth walls. Very quickly their surfaces have been equipped with various obstacles (ribs, pin fins,



Figure 1.1: Cooling channel applications. Top left: European JET Tokamak [2]. Top right: deep inside the cores of large commercial nuclear reactors [3]. Bottom left: Example of a Diesel engine fuel injector [4]. Bottom right: An example of a cooled IC chip [5].

dimples, ...) to increase the thermal exchange area and the local mixing. The main objective is to increase the efficiency of these systems, and the maximization of the heat transfer is vital to achieve this. Besides, it is important to keep the pressure drop as low as possible. Indeed, as the thermal exchange area increases the flow blockage and, therefore, the energy loss through the apparatus increases as well. The reason why forced convection still plays an important role in turbomachinery is related to the possible improvements on the engine performance. Improvements can be achieved with a more accurate prediction of the heat transfer coefficient. A better understanding of the physics is able to further support the CFD development, with a particular interest on turbulence modeling. More details are presented in this chapter to justify the importance and the motivation of the present research.

1.1 Cooling in gas turbine technology

Gas turbine engines are nowadays largely used in several engineering fields, from aero-engines to land-based gas generators to produce e.g. electricity. In 1872 the first true gas turbine engine was designed by Dr. F. Stolze whereas, the first successful built (by Aegidius Elling) appeared in 1903 [6]. The fast development up to today was mostly driven by the aviation industry. Gas turbines are generally composed by a compression section where the air is pressurized; then the latter passes through a series of combustion chambers where fuel is injected and burned at constant pressure; finally the hot, high pressure gasses are expanded in a turbine where energy is extracted. More complex configurations are developed for different applications with supplementary components or added shaft(s) [7]. Nowadays, the most used configuration for driving civil airplanes is the turbofan. An example is given in Fig. 1.2 by the Rolls-Royce Trent XWB (R) the world's most efficient large civil aero engine. The high mass-flow which by-passes the engine core allows to achieve large thrust and fuel efficiencies (up to 42-43%) as well as reducing the engine noise. Another crucial part of the engine is the core which includes all the components except the fan. The performance of the core engine, of course, strongly affects the overall functioning of the gas turbine. Since this research focuses on the internal cooling of the hot components, the latter will be discussed more in-depth. In order to justify the importance of the subject some thermodynamic aspects will be introduced.



Figure 1.2: Gas Turbine engine section of the Rolls-Royce Trent XWB (*R*) which drives the Airbus A350 [8].

The real Joule cycle describes the functioning of a turbomachine (Figure 1.3). It is linked to the engine core and represents the thermodynamic transformations through the compressor, the combustion chamber(s) and the turbine represented here in a total temperature versus entropy chart.

The fundamental Joule cycle is composed by isotropic compression and expansion and a constant pressure combustion ([9]). However, the real transformations have some losses. In the Real Joule Cycle the compression and the expansion are polytropic (respectively 1-2 and 3-4) while inside the combustor a small pressure drop is considered (transformation 2-3). Equation 1.1 presents the specific power of the cycle defined as the power available on the shaft per unit mass-flow. The latter is computed as the difference between the work extracted through the turbine and the work performed on the compressor. Both are expressed by the change of enthalpy, assuming no variations of kinetic energy. Also the variations of the specific heat at constant pressure are considered negligible. η_c and η_t are the isentropic efficiencies of the compressor and the turbine respectively whereas $\eta_{cc} = P_2/P_3$ quantifies the pressure drop in the combustion chamber (not considered in the ideal Joule Cycle). π is the pressure ratio P_2/P_1 .



Figure 1.3: Real Joule Cycle diagram representative of the transformation inside a gas turbine engine core.

$$N_{s} = c_{P} T_{1} \left[\eta_{t} \frac{T_{3}}{T_{1}} \left(1 - \frac{1}{(\eta_{cc} \pi)^{\frac{\gamma-1}{\gamma}}} \right) - \frac{1}{\eta_{c}} \left(\pi^{\frac{\gamma-1}{\gamma}} - 1 \right) \right]$$
(1.1)

Perhaps more important, another parameter to consider is the thermal efficiency η_{th} (Eq. 1.2) defined as the ratio of the extracted work by the machine (difference between the energy generated by the turbine and the one required by the compressor) and the input heat provided in the combustion chamber. This parameter is directly linked to the specific fuel consumption of the engine through the aircraft velocity V_0 , the propulsive efficiency η_p and the fuel calorific value F_{HV} (Eq. 1.3). The expression is obtain by the ratio between N_s and specific heat provided in the combustion chamber.

$$\eta_{th} = \frac{\eta_t \frac{T_3}{T_1} \left(1 - \frac{1}{(\eta_{cc} \pi)^{\frac{\gamma-1}{\gamma}}} \right) - \frac{1}{\eta_c} \left(\pi^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\frac{T_3}{T_1} - 1 - \frac{1}{\eta_c} \left(\pi^{\frac{\gamma-1}{\gamma}} - 1 \right)}$$
(1.2)

$$SFC = \frac{V_0}{\eta_p \eta_{th} F_{HV}} \tag{1.3}$$

Both the expression of N_s and η_{th} clearly depend on the pressure ratio π and the Turbine Inlet Temperature T_3 . The latter is usually named in different text books as TIT (Turbine Inlet Temperature) or TET (Turbine Entry Temperature). In this document TIT will be used. T_1 is the compressor inlet temperature and γ the specific heat ratio. All the quantities have to be considered as total quantities.

Figure 1.4 shows the strong effect of TIT (T_3) on the specific power N_s and on the thermal efficiency η_{th} . In this graph T_1 was assumed to be 300 K and γ was 1.4. The three different colors are used to differentiate the different TIT showed in the legend and the black dashed line connects the location of the maxima of both specific power and thermal efficiency curves. It is clear that a higher TIT value not only shifts upward both curves but also moves the location of the maximum to higher values of the pressure ratio. Together with an increase of the TIT, an increase of the pressure ratio allows to an even higher increment of the thermal efficiency. It is, therefore, not a coincidence to see the Rolls Royce Trent XWB having a pressure ratio of 50:1. The latter confirms that a lower specific fuel consumption is definitely the major design goal for the novel aeroengines for civil transportation. On the other hand, when keeping the same TIT, a larger pressure ratio decreases the specific power. Indeed, the value of π where N_s is maximum is lower than the one where η_{th} is maximum.

As most of the physical parameters, the TIT is limited by the technology of gas turbines. Higher temperatures at the exit of the combustion chamber require higher thermal resistance of the materials and/or effective cooling and protection of the hot components of the HP turbine. The most important restriction is set by the creep temperature for rotor blades, subjected to very high mechanical stresses due to the centrifugal forces as well as the aerodynamic loads (the latter also for static blades). Besides, the life span is also directly affected by thermal gradients. The higher the thermal gradients, the larger the thermal stresses, which reduce the lifetime. In order to increase the latter when thermal stresses are high, the overall temperature needs to be reduced. From the '60s, researchers have been working on the properties of the construction materials and on different cooling techniques to limit the blade temperature (Figure 1.5). This allowed an increase of the TIT by more than 600 K since 1960. Nowadays the blades of the HP turbine are manufactured by single



Figure 1.4: Specific power (top) and thermal efficiency (bottom) of the core engine versus the pressure ratio at different Turbine Inlet Temperatures (T_3) .

crystal casting and are thermally coated. Internal and external blade and endwall cooling is applied and discussed more in details in the following section.



Figure 1.5: Evolution over the years of the Turbine Inlet Temperature [10].

1.2 Blade Cooling

Different methods can be applied to limit the metal temperature of a turbine blade. An example of an air cooled blade is sketched in Figure 1.6 where the heat transfer occurs by forced convection, impingement, film cooling and effusion (Figure 1.7). The first method (a) is to insert in the internal passages of Figure 1.6 some obstacles (ribs, pin fins, dimples, ...) which do not only enhance the level of turbulence but also increase the thermal exchange area.



Figure 1.6: A sketch of an aircooled blade section with internal, tip and impingement cooling [11].



Figure 1.7: Blade Cooling Techniques [13].

As will be discussed later, these obstacles are also able to trigger the formation of secondary flows which are very effective for energy extraction from the walls. Several orifices through an insert plate produce strong air jets impinging the internal surface of the blade for a significantly high heat transfer (b). This technique is really effective and largely used for the leading edge due to the direct impact of the hot gasses. In addition, inclined holes create a fresh air layer which protects the external surface of the airfoil from the main hot flow (c,d). The external flow is affected by the cooling air going out of the blade and in some cases it is also used to reduce the turbine secondary flows. Dust holes are also present on the blade tip where the friction increases even more the metal temperature. Permeable materials can be also used for the blade construction to have a similar effect (e), however they are not used nowadays for this application. A wide review of investigations on cooling techniques can be found in [11] and the recent evolution of turbine cooling is largely discussed by Bunker [12]. The case of internal cooling by forced convection (a) is considered in the present work.

1.3 Internal Cooling by forced convection

The development work related to Internal Cooling Channels in turbine blades up to 2013 is reviewed by Ligrani in [14]. More recently Bunker spoke about the Evolution of Turbine Cooling [12]. There have been many experimental and numerical contributions during the last decades. Several channel geometries were studied and characterized within their complexity. Although the model in Fig. 1.8 does not represent a real internal cooling channel it allows to understand the physics inside these apparatus as well as to give a suitable support for CFD modeling. The fist measurements appeared in the late '80s and in the early '90s. The main goal was to evaluate the performance of different types of turbulators and other geometrical parameters discussed in section 1.3.1 (e.g. [15, 16]). Most of the experiments were conducted by means of point-wise thermocouples attached on the walls in order to retrieve the wall heat trasfer. By that time, with the development of new technologies, facilities and measurements techniques (especially optical approaches as Infrared Thermography [17] and Liquid Crystal thermography [18]) experiments became more accurate and spatially resolved. In the late '90s, researchers started looking at the aerodynamics inside such devices to understand better the physics: first with flow visualizations and Laser Doppler Velocimetry (LDV) [19, 20], and after with Particle Image Velocimetry (PIV) [21]. Several studies were conducted in rotation; the latter has been shown to have a large effect on the heat transfer [22]. However, this topic is not discussed in detail since it would go out of the scope of the present research. In the following sections the outputs of some experimental studies are summarized and discussed in detailed with the effect of the geometrical parameters on the heat transfer and the contribution of the detailed velocity field. Despite this research has not been performed in a ribroughened channel, the following sections are giving an idea of the challenges of these type of flows and the importance of accurate and high resolved experimental data.

1.3.1 Geometric parameters

Figure 1.8 shows a canonical configuration of a cooling channel. Although it is not realistic, it is useful to identify different geometrical parameters and their effects on the performance of such devices. Several studies were carried out looking at the heat transfer and the pressure drop produced changing some non-dimensional parameters. A brief summary follows.

The augmentation of the blockage ratio h/D_h increases the heat transfer on both the ribbed wall and the smooth one (top wall); $D_h = 2WH/(W+H)$ is the hydraulic diameter . Nevertheless the pressure drop increases at a faster rate [15], due to the higher acceleration imposed by the higher contraction. Han observed from his studies that for a heat transfer benefit of 300%, pres-



Figure 1.8: Geometrical parameters of a simplified ribbed cooing channel.

sure drops increase by 500% in a square channel with a typical rib geometry $(h/D_h=6\%,~g/h=10~{\rm and}~\varphi=45$) at a Reynolds number around 30,000 [16]. A conclusion of this work is that a smaller rib height is more efficient for higher Reynolds number flows. The pitch-to-rib height ratio g/h affects the flow behavior and, in particular the boundary layer development after the reattachment region. An optimum value in terms of heat transfer is found between 7 and 13 depending on the flow conditions and the blockage ratio [11]. Furthermore, the angle of attack φ affects the secondary flows near the lateral channel walls [17]. The best performances are reported in [18], for a value between 60° and 30° with significant variations depending on the channel aspect ratio W/H and on the flow conditions as well. Different rib shapes and profiles, such as V-shaped or wedge-shaped ribs, are investigated in [19–21, 23]. Again, Han [16] found V-shaped and Delta-shaped ribs to have a better performance in terms of better heat transfer for a given pressure drop penalty compared to typical angled ribs. The effect of the number of ribbed walls is studied in [24] where a stronger increase of the heat transfer is shown going from zero to one single roughened surface rather than going from one to two opposite ones. On the other hand, the channel aspect ratio presents a strong effect on the secondary flows strength and therefore on the optimization of the other geometrical parameters [25]. However, the *aspect ratio* changes according to the channel position along the blade chord.

These studies provide useful guidelines for the internal cooling design, largely used in industry with empirical correlations. Characteristic values of the blockage ratio and the pitch-to-rib height ratio are set as a good compromise between the obtained heat transfer and the generated pressure drop. The effect of each parameter on the heat transfer is related to the modification on the flow patterns inside the channel (i.e. acceleration/diffusion above the ribs, boundary layer development after the reattachment point, secondary flows strength and redistribution). A suitable support to CFD can only be given, therefore, by addressing both the aerodynamic and thermal fields together. This is the main reason for the more frequent flow field investigations on cooling channels.

1.3.2 Flow field

The flow field over a ribbed wall was already analyzed in several investigations. The time-average streamlines are shown in Fig. 1.9. The presence of the rib imposes a blockage to the flow which has therefore to accelerate when approaching the obstacle. It forces the boundary layer to separate generating a vortex in the corner between the rib front face and the wall. From the separation point, a free shear layer is created and grows above the rib. If the inter-rib pitch is large enough, the flow reattaches on the wall and a new boundary layer starts to develop. This shear layer separates the main flow from a low momentum area under it. Due to the shear stresses transmitted a recirculation motion at very low speed is created (separation bubble in Fig. 1.9). Besides, the reverse flow close to the bottom wall separates when approaching the rib. Also in this case a corner vortex, of a smaller size due to the lower inertia of the flow, appears. The instantaneous flow field is slightly different than the time-average. The recirculation bubble does not appear in the instantaneous field and the shear layer shows a typical flapping motion. A good explanation of the flow field characteristics and the mechanisms of the unsteady behavior of the flow can be found in the time-resolved experiments of Cardwell et. all [26]. The instability of the mixing layer causes the formation of two counterrotating vortices responsible for a high velocity jet in the wall-normal direction that breaks the mixing layer and allows a rapid ejection of the inter-rib flow into the main flow. The mixing layer then reorganizes before starting again the same process.

Secondary flows come from boundary layers and from the stream curvature imposed by the presence of an obstacle. The latter produces a centrifugal force towards the bottom balanced by a pressure gradient. Due to the lower centrifugal force close to the lateral walls because of the boundary layer, the pressure gradient pushes the flow upwards and creates the vortices shown in Fig. 1.10 and confirmed by the PIV measurements of Casarsa [27]. In his aero-thermal analysis [28], Liou found the direction and the strength of the secondary flows to be the dominant factor affecting the heat transfer enhancement in a square channel, followed by the convective mean velocity. On the other hand, the turbulent kinetic energy distribution seems to be less correlated. Casarsa [27] also proposed a methodology of the heat transfer footprint prediction by the flow field using the $\overline{u'v'}$ component of the *Reynolds stresses*.

Although this level of understanding seems sufficient, Large Eddy Simulations (LES) are required to represent the main features of the unsteadiness and the secondary motion of the flow. The cost for these computations, unfortunately, is still very high compared to the performance of computers nowadays. This does not allow the rapid and flexible analyses of the data required in industry. Internal cooling designers are asked to run several simulations to analyze different designs and operating conditions; this is not possible with LES and their high computational cost. This is the main reason why classical



Figure 1.9: Average flow field over a rib in the symmetry X-Y plane of an internal cooling channel [29].



Figure 1.10: Rib-induced secondary flow direction where generated inside a ribbedchannel (adapted from [30]).

Reynolds-Averaged Navier-Stokes approaches (RANS) are still largely used for this purpose. RANS simulations, on the other hand, are less accurate due to some assumptions discussed in the next chapter. They also require to model some parameters and the present research has the goal to provide useful experimental data for the development of these tools.

1.3.3 Governing equations and similarity

When speaking about heat transfer in fluid dynamics three conservation equations are taken into account: the conservation of mass, the conservation of momentum and the conservation of energy. Their non-dimensionalized compact forms by the π -Buckingham theorem [31] for incompressible flows are shown by Eq. 1.4 to Eq. 1.6. When applying temperature gradients, density gradients are generated (order of 15%). Although the author is aware about the latter, the equations shown in this section are obtained with the assumption of incompressible flow for the only reason of simplicity.

$$\nabla^* \cdot (\boldsymbol{u}^*) = 0 \tag{1.4}$$

$$\frac{D\boldsymbol{u}^*}{Dt} = -\nabla P^* + \frac{1}{Re}\nabla^2 \boldsymbol{u}^* + \frac{1}{Fr^2}\boldsymbol{g}^*$$
(1.5)

$$\frac{D\Theta}{Dt} = \frac{1}{RePr} \nabla^2 \Theta + \frac{Ec}{Re} \Phi^*$$
(1.6)

The quantities with the superscript * represent the non-dimensionalized variables of the velocity vector \boldsymbol{u} with the bulk velocity U_b , of the pressure P with the product of the reference density and the square of the bulk velocity $\rho_0 U_b^2$, the gravitational acceleration vector \mathbf{g} , the temperature with the non-dimensional expression of $\theta = \frac{T-T_0}{T_w-T_0}$ and the viscous dissipation tensor Φ . It can be clearly noticed that to work in similarity the non-dimensional numbers in front of some therms should be maintained constant. Normally the square of the Froude number Fr is large enough to neglect the gravitational force. The ratio of the Eckert number with the Reynolds number $\frac{Ec}{Re}$ is very small

and viscous dissipation is therefore usually not considered. With this considerations the *Reynolds* (*Re*) and *Prandtl* (*Pr*) numbers are the most important for the specific application if $\frac{1}{Fr^2}$ and $\frac{Ec}{Re}$ are kept as small as possible. In this research, experiments will be made by inserting a fluorescent tracer into the flow. Whereas *Re* is controlled by setting the velocity of the flow, *Pr* is a property of the working fluid. Section 2.3 discusses and analyses the effect of a tracer on *Pr*.

As the present research wants to contribute at improving the heat transfer predictions made by *RANS*, *Reynolds-averaging* is introduced by writing the time-dependent variables as the sum of the mean and the fluctuating components. In order to simplify the equations, the density variations in space and time are assumed to be small with respect to their mean value. This is something reasonable for the test conditions of the present research and most of the studies in literature, but it is not the case for the real application. In the same way variations of the variables in the Z-direction are considered negligible compared to the X- and Y-directions (Fig. 1.8). In addition, the terms $\frac{\partial^2 \bar{u}}{\partial x^2}$ and $\frac{\partial \bar{u'}'^2}{\partial x}$ of the already simplified *Navier-Stokes equation* are very small compared to the other terms $\frac{\partial^2 \bar{u}}{\partial y^2}$ and $\frac{\partial \bar{u'}T'}{\partial y}$ variations in the Y-direction. A similar consideration, it is applied for the terms $\frac{\partial^2 T}{\partial x^2}$ and $\frac{\partial \bar{u'}T'}{\partial x}$ of the *energy equation* relative to $\frac{\partial^2 T}{\partial y^2}$ and $\frac{\partial \bar{v'}T'}{\partial y}$. Here, the viscous dissipation term is also negligible compared to the heat transfer. Taking into account all of these assumptions and approximations, Eq. 1.7 represents the conservation of energy.

$$\overline{u}\frac{\partial\overline{u}}{\partial x} + \overline{v}\frac{\partial\overline{u}}{\partial y} = -\frac{1}{\rho}\frac{d\overline{P}}{dx} + \frac{\partial}{\partial y}\left(\nu\frac{\partial\overline{u}}{\partial y} - \overline{u'v'}\right)$$
(1.7)

$$\overline{u}\frac{\partial\overline{T}}{\partial x} + \overline{v}\frac{\partial\overline{T}}{\partial y} = \frac{\partial}{\partial y}\left(\alpha\frac{\partial\overline{T}}{\partial y} - \overline{v'T'}\right)$$
(1.8)

The terms $-\overline{u'v'}$ and $-\overline{v'T'}$ are the ones of particular interest since they require a model for *RANS* computations. Dimensionally multiplied by the density ρ , the first one represents an *apparent stress* due to the turbulent flow $\tau_t = -\rho \overline{u'v'}$. Prandtl postulated that the macroscopic transport of momentum (also heat) in turbulent flow is similar to the one of molecular transport in laminar flow [32]. Introducing the concept of the *mixing length* and, then, the *apparent kinematic viscosity* or the *turbulent eddy viscosity* ν_t , the *turbulent stresses* τ_t can be re-written in relation to the gradients of the mean streamwise velocity \overline{u} in the Y-direction (see coordinates in Fig. 1.8).

$$\tau_t = -\rho \nu_t \frac{\partial \overline{u}}{\partial y} \tag{1.9}$$

Similarly, the apparent heat flux $q_t'' = -\rho c_P \overline{v'T'}$ is assumed to be function of the turbulent eddy diffusivity α_t and the mean temperature gradient.

$$q_t'' = -\rho \alpha_t \frac{\partial \overline{T}}{\partial y} \tag{1.10}$$

The most common models for ν_t are: Spalart-Allmaras (S-A), $k-\epsilon$ (k-epsilon), $k-\omega$ (k-omega), SST (Menter's Shear Stress Transport). Furthermore, in order to model only ν_t , α_t is usually obtained assuming a constant turbulent Prandtl number Pr_t .

$$Pr_t = \frac{\nu_t}{\alpha_t} \tag{1.11}$$

This is a strong assumption commonly used in *RANS*. Hirota et al. [33] showed a significant increase of Pr_t near the corners of a squared duct by means of *Hot Wire anemometer* (*HW*) and *Cold Wire thermometry* (*CW*). The authors concluded that the assumption of constant Pr_t is invalid for turbulent heat transfer in this configuration. The uncertainty of *HW anemometry* in 3D flows is high¹, especially on the velocity fluctuations. Besides, *CW* measurements are strongly dependent on the position of the probe and present some issue regarding the magnitude of the temperature fluctuations [1]. They are also able to measure only temperature fluctuations related to the small vortices. The question arising is the following: "Are experiments able to measure accurately this parameter?" which justifies the definition of the research goals.

1.4 Research Objectives

As concluded from the last section, the strong assumptions and modeling needs of RANS approaches appear to be the main reasons of their low reliability on the heat transfer prediction. Uncertainty might be estimated at 10 - 15% on the heat transfer coefficient. Indeed, industries use these results for the design but they are eventually corrected and scaled after the experimental validation in the real machine. It is, therefore, useful to improve the understanding of these complex phenomena. Models use several coefficients tuned with respect to the experimental outputs and so far are not able to reproduce correctly the physics. The present research has therefore the aim of contributing to CFD improvements not only by addressing more aero-thermal measurements but also by introducing novel information. Experiments in literature provide the wall heat transfer, the pressure drop produced by the obstacles (ribs) and, more recently, the aerodynamic field. The new, innovative information will be represented by the flow temperature which will help the understanding of the heat transport mechanism. Flow temperature and its fluctuations are very challenging to measure accurately. In order to be able to obtain the turbulent heat transport term $\overline{v'T'}$ and the turbulent Prandtl number Pr_t , temperature and

¹with single wire the error in the 3D flow is given by the cooling effect of the secondary motions; whereas, in the case of a 3-wire probe, the limitation is on the flow angle (\pm 40°maximum)

velocity fluctuations need to be measured simultaneously. Limitations of CWmeasurements have been mentioned. Therefore, the measurement approach selected is non-intrusive, has a very high frequency response (order of 50 MHz) and is highly spatially resolved in the plane of measurement. The technique is called *Laser Induced Fluorescence*, simply reduced to LIF or PLIF (*Planar*) LIF). It is a spectroscopy approach based on the absorption and fluorescence of some molecules. Although the output is promising, the technique is complex and challenging. It is then important to evaluate the feasibility of the measurement technique. Gas-phase LIF was never applied to channel flows. Therefore, a new development is required. A new facility must be designed and constructed (with a low budget). Along the same line, the experimental set-up has to be mostly composed by available instrumentation at the von Karman Institute (VKI). A crucial point is to develop a robust methodology for the measurements and data reduction (mainly represented by the image processing). The first challenge is to address correctly the temperature statistics (mean T and fluctuations T'). Further, simultaneous PIV and LIF measurements provide information about the turbulent heat transport term v'T' needed for the determination of Pr_t .

1.5 Document output

The thesis is organized in six main chapters. After the introduction, the measurement technique used for this study is described in details in chapter 2. The latter describes important information about the principle, the different available options and the performance. In the first part, the reader is guided through the fluorescence phenomenon. Then, the main parameters contributing to the fluorescence signal are identified in order to correctly retrieve the flow temperature. Among the different tracers used in gas-phase measurements, acetone and toluene were selected for different advantages. The molecular *Prandtl number* can be strongly affected when introducing a tracer into the flow. Its estimation, through numerical means, however, shows that this mixture is acceptable for this application. Finally, a discussion on the required instrumentation and the different sources of noise in cameras conclude the chapter.

The document follows with the preliminary 1D fluorescence study of chapter 3. Acetone two-color measurements are chosen in the beginning. Then, an experimental set-up is built for this purpose. The results in a static cell are really promising in terms of their temperature dependence on the signal. This behavior, however, is in contradiction with the initial numerical analysis of section 3.1.3. For this reason, a campaign to measure the emission spectra of acetone at different temperatures is carried out. The set-up is adapted for these measurements. With the data obtained, acetone turns out not to be a good candidate for two-color measurements. Alternative tracers and the onecolor methodology are taken into consideration at this point, considering going to a test in a continuous channel flow.

Chapter 4 presents the facility which was designed and constructed from scratch at the VKI. The design starts from an available aluminum channel embedded within the structure of the wind tunnel previously used in the rotating cooling facility at the VKI. The test section has to be slightly re-adapted for the LIF measurements. An upstream piping system delivers a flow at the required *Reynolds number* and *tracer concentration*. Everything is controlled by a Labview script presented in appendix A. A secondary modification to the facility is shown with the possibility to generate a nitrogen flow, instead of air, from a rack of high pressurized bottles. The measurement campaigns are obtained by an experimental set-up presented just after, with a secondary implementation for the simultaneous velocity measurements by means of PIV. The latter describes a fully turbulent and fully developed flow. The chapter ends with the design of the LIF in-situ temperature calibration.

The following chapter (5) presents the one-color toluene measurements. It starts with the methodology of the measurements and the image processing. The different steps performed during the experimental campaign are explained and all the data recorded are reported. The procedure of the image processing and the signal corrections to obtain the final results follows. Various images are required to obtain the normalized signal. The latter is then related to temperature through the temperature calibration procedure which requires additional experiments and image processing. It shows the temperature calibration and the obtained temperature statistics compared with the profiles measured traversing a thermocouple probe along the channel height. The section on the results (5.3) starts with the measurements obtained with the air-toluene mixture. The images obtained with a mixture of nitrogen and toluene are reported as well as the synchronized PIV and air-toluene LIF measurements for the determination of the turbulent heat transport term. The discussion is followed by the measurement uncertainty assessment (section 5.4). First of all, the uncertainty related to the *Reynolds number* is briefly obtained. In the second (main) part, the signal fluctuations show to be the most relevant source of the uncertainty on the measured temperature by means of LIF. The effect of the temperature calibration procedure is evaluated. The discussion is followed by the different random errors accounted for the mean and the fluctuating components of the temperature.

The document ends with the conclusions and the recommendations for future work considering the potential improvements for a further development of LIF thermography for the internal cooling technology.

Chapter 2

Laser-Induced Fluorescence

LIF (Laser-Induced Fluorescence) is a spectroscopic method used in many different fields for various physical, chemical and engineering analyses. The advantage with respect to the other techniques based on absorption and light scattering is that LIF provides high signals which allow planar measurements (when the laser beam is shaped into a laser sheet). The first 2D imaging of OH LIF for combustion species concentration were shown in [34] and [35] in 1982. Later, the studies have been spread on other combustion-relevant species as O2, NO, CH, CN, NH, C2 [36]. Nowadays LIF has become a suitable tool for quantitative measurements of temperature and pressure as well as species concentration. In order to have a better understanding of the phenomena involved, it is worth explaining where this technique comes from.

Fluorescence is basically the emission of photons produced by the excitation of some molecules. Someone might confuse the phenomena of fluorescence and phosphorescence. Figure 2.1 represents the energy of a photoluminescent molecule in its different energy states (Jablonski diagram). Fluorescence is always associated to singlet electronic states whereas phosphorescence is associated to triplet states. Both of them are deactivation processes which involve an emission of a photon radiation. From the ground level S_0 , molecules absorb photons of light and they go to a higher electronic singlet state $(S_1, S_2,$...). Each electronic state has different vibrational energy levels. This energy relaxes to ro-vibrational equilibrium (internal conversion) and may lose it's energy through a variety of processes. One of these is spontaneous emission (i.e. fluorescence). Both processes of deactivation are very fast. This is the reason why fluorescence always involves the transition of the lowest vibrational level of the excited state. An overlap between the vibrational states of singlet and triplet energy levels might favor the Inter-System Crossing (ISC) process and, therefore, the transition from *triplet-to-singlet* by the emission of phosphorescence. Besides, for some molecules, dissolved oxygen in a bath gas is responsible of the so called phenomenon of oxygen-quenching. The collision between the fluorescent molecules and the oxygen transfers part of the electronic energy charge and, therefore, the spontaneous emission of photons decreases. For further information and details of vibrational and electronic spectroscopy ref. [37] is recommended.

Different molecules have different absorption and emission spectra. After



Figure 2.1: Partial Jablonski Diagram for absorption, fluorescence, and phosphorescence. Figure taken from [38] by courtesy of Steve Pawlizak.

some possible vibrational relaxation and internal conversion, fluorescence occurs and its life time is of the order of 10^{-9} seconds [39, 40]. The latter allows the possibility to obtain very high temporally resolved data.

Typically, a single frequency laser light excites the selected molecule within the specific absorption spectra and the produced fluorescence is recorded by a camera sensible to the emission spectra. In practice, Planar LIF (PLIF) is performed by illuminating the fluorescent species with a laser sheet: this produces a bright image on the camera sensor in the laser sheet. For weak exicitation, a simplified expression of the signal intensity I_f as a function of the emitted wavelength λ and absolute temperature T is given by Eq. 2.1 [41]:

$$I_{LIF}(\lambda) = \eta_{opt}(\lambda) V_c n_{tr} I_L \sigma(\lambda, T) \phi(\lambda, T, P, \chi_i)$$
(2.1)

where η_{opt} is the efficiency of the optical detection system (camera, lenses, filters, ...), V_c the collection volume, n_{tr} is the number density of the fluorescent molecules, I_L the laser fluence [energy/unit of surface], σ the molecular absorption cross-section and ϕ the fluorescence quantum yield. The latter is the main term affected by the temperature in most of the available and gasphase fluorescent tracers. It represents the fraction of photons emitted by the molecules in comparison to the energy absorbed and it is function of the wavelength λ , the temperature T, the static pressure P and the concentration of other species χ_i responsible for the signal quenching. The tracer number density n_{tr} is directly linked to the tracer concentration χ_{tr} (Eq. 2.2). χ_{tr} is the mole fraction and k_B is the Boltzmann constant.

$$n_{tr} = \frac{\chi_{tr} P}{k_B T} \tag{2.2}$$

The simplified graph of Fig. 2.2 shows a typical spectral distribution of the fluorescence signal I_{LIF} (blue line), the molecule absorption σ (red line) and the laser excitation I_L (green line) of large molecules. In gas-phase molecules their absorption is in the UV range of light. The emission (blue line) is normally red shifted from the absorption and the excitation and the spectral distribution can overlap (as in the picture) the one of the absorption for some molecules. The fluorescence can also go to the visible range in same cases.



Figure 2.2: Diagram representing a typical spectral distribution of the fluorescence signal I_{LIF} , absorption σ and excitation I_L of large molecules.

The final output, registered by a detector, is an image with an intensity equal to the integral over the complete visible spectral band of the camera (Eq. 2.3).

$$I_{LIF} = \int_{0}^{\infty} \eta_{opt} \left(\lambda \right) V_{c} n I_{L} \sigma \left(\lambda, T \right) \phi \left(\lambda, T, P, \chi_{i} \right) d\lambda$$
(2.3)

Even with this simplified relationship, it is clear that the fluorescence signal does not only depend on temperature. As the latter is the objective of the measurements, the next section presents the different approaches to obtain this variable.

2.1 LIF thermography

The methods to establish the temperature of the molecules basically differ from the number of fluorescent molecules (only in liquid phase), spectral bands of the emission or excitations. In single-line LIF, the temperature can be obtained from Eq. 2.3 if all the constants are known. Even though a calibration of at least one known temperature is always needed, issues to determine the flow temperature arise when the tracer concentration χ_{tr} and the excitation laser power I_L vary in space and/or in time. Section 5.1 discusses the required assumptions and shows how variations of these two variables can be taken into account in the measurement set-up and the image-processing. If these requirements are not satisfied, the methodology of one-color (one excitation and one detection) cannot be used.

The alternatives are to increase the number of detections (e.g. the twocolor approach) or to use a two-line approach (e.g. dual-excitation). By these techniques, the dependence on the concentration of the dye is canceled in the expression of the ratio between the two different intensities 1 and 2 of Eq. 2.4.

$$R_{f} = \frac{I_{LIF,1}}{I_{LIF,2}} = \frac{\eta_{opt,1}}{\eta_{opt,2}} \frac{I_{L,1}}{I_{L,2}} \frac{\sigma(\lambda_{1},T)}{\sigma(\lambda_{2},T)} \frac{\phi_{1}(T(x,y))}{\phi_{2}(T(x,y))}$$
(2.4)

In order to have an intensity ratio R_f sensitive to temperature, the temperature dependence of the absorption or the emission must change with the wavelength. In the case of the absorption, the normalized σ might present a red shift with the temperature T as in the graph of Fig. 2.3. Two different excitations of the same molecule can be used where the absorption has different temperature dependencies (Fig. 2.6).



Figure 2.3: Features of the normalized absorption σ and fluorescence emission I_{LIF} of gas-phase large molecules for two-line LIF measurements.

Figure 2.4: Normalized absorption of gas-phase large molecules (σ) and the two laser excitations ($I_{L,1}$, $I_{L,2}$) for two-line LIF measurements.

In the case of two-color measurements, the fluorescence emission has a red

shift when the temperature increases (Fig. 2.5). The measurement of temperature is based on the selection of two spectral bands characterized by different temperature dependencies of the emission (e.g. the ones of Fig. 2.6). Two filters are applied to the detectors and the ratio of the intensities depends only on the flow temperature (Eq. 2.5). This method uses only one excitation source, therefore, R_f is also independent of the laser intensity and the complexity of the experimental set-up is reduced as well.

$$R_f = \frac{I_{LIF,1}}{I_{LIF,2}} = \frac{\eta_{opt,1}}{\eta_{opt,2}} \frac{\phi_1 \left(T \left(x, y\right)\right)}{\phi_2 \left(T \left(x, y\right)\right)}$$
(2.5)



Figure 2.5: Features of the normalized excitation, absorption and fluorescence emission of gas-phase large molecules for two-color LIF measurements.



Figure 2.6: Normalized fluorescence emission of gas-phase large molecules (I_{LIF}) and transmission of the two bandpass filters (f_1, f_2) for twocolor LIF measurements.

This technique is more sensitive within a certain temperature range ([42]) depending of the selection of the two detection bands. A wider range can be obtained by the multi-line approach with more different ground states (with different excitation wavelengths and detections). One, two or multi-line require one, two or multi-shots for the determination of an instantaneous temperature field. However, a good compromise should be determined between a high temperature sensitivity within the range of interest and a complex acquisition system. The required instrumentation for a multi-line approach is most of the time considered too complex and expensive. Depending on the application, the so called two-color approach (two observed spectral bands with only one excitation type) is usually a suitable choice when concentration varies considerably. The set-up is composed by one light source and two cameras. In the present case of highly turbulent flow and relatively bounded range of temperature (290-400 K), this approach represents a good alternative to the one-color approach.

More practically, the aforementioned approach of two-color LIF requires the calibration of the intensity ratio R_f with different points of tracer temperatures as shown in the experiments of chapter 3 for acetone. Most of the time these measurements are performed in a static cell ([43–45]) and the data are normalized by the ambient conditions. Several molecules have been studied addressing their photo-physics. According to section 1.3.3, for heat transfer measurements a realistic Pr of the working fluid is required. Therefore, the next section presents a literature survey of gas-phase fluorescent tracers that do not alter Pr.

2.2 LIF tracers

If the flow under investigation does not contain fluorescent molecules, a fluorescent dye must be added to the main flow. The choice of the latter influences the accessible temperature range as well as the evaluation procedure. A wide and relatively recent review about tracers for practical combustion measurements is presented in [46]. The present section provides information for temperature measurements. Several temperature measurements have been performed using atomic, diatomic (e.g. OH, NO, O2, iodine, CH and C2) and organic molecules (e.g. aromatic hydrocarbons and ketones). Mono- and diatomic molecules typically have absorption and fluorescence emission spectra in the UV range whereas in larger molecules they are generally shifted towards higher wavelength and characterized by a wider band. Further, strong transitions are easily saturated for atomic tracers. The limitation on the excitation power is the major cause of the very low signal produced [46]. The original application of organic molecules is the study of the mixing process between fuel and air in combustion system. Commercial fuels naturally contain fluorescing compounds. The latters produce high signals but, on the other hand, do not allow quantitative measurements of the flow properties. Therefore, reaserchers started to use only one of the fluorescing compounds of the fuels. In gasoline, benzene and toluene are contained whereas naphthalene is part of diesel fuels. Benzene, however, is carcinogenic. Toluene is not and is also less toxic. More recently anisole has been identified and found to be able to provide even stronger signals than toluene [47]. These compounds have very high absorption in the UV [48] and a high fluorescence quantum yield (0.17 - 0.82) [46]. The conclusion is that they are able to produce very high signals, favorable for high accuracy measurements as discussed in section 5.4. The drawback, instead, is represented by the strong quenching by oxygen. In this case the signal does not depend only on the tracer concentration but, inversely, also on the oxygen concentration.

Ketones are also widely used for LIF. Typically, these types of compounds have the absorption and the emitted fluorescence spectral distributions at


Figure 2.7: Normalized fluorescence quantum yield dependence with temperature for different tracers excited with a 266 nm laser light in N_2 at 1 bar [52].



Figure 2.8: Normalized fluorescence quantum yield dependence with temperature for different tracers excited with a 266 nm laser light in air at 1 bar [52].

higher wavelengths. Acetone started to be used for its very high vapour pressure which makes it an ideal tracer for gaseous flows [49]. Other important advantages are the low toxicity and low cost of this tracer [41]. 3-pentatone, instead, was suggested for its boiling and transport properties similar to the one of gasoline [50]. The disadvantage is its very low fluorescence quantum yield (e.g. 0.002 for acetone)[51] and absorption cross-section compared to aromatic molecules. A wide comparison of the mostly used tracers in gas-phase diagnostics is presented in [52]. In Fig. 2.7 the authors show the fluorescence quantum yield dependence on temperature in a nitrogen bath at 1 bar. In this graph toluene is the tracer with the highest temperature dependence whereas acetone has the lowest. Things change a lot when, instead of nitrogen, air is used as the main fluid (Fig. 2.8). Ref. [52] also discusses the level of signal per volume, where, for example, toluene emits a signal theoretically 70 times higher in nitrogen than in air.

2.2.1 Acetone-based LIF

Since the investigation of Lozano [53], acetone based LIF started to be used for species concentration (e.g. [54]) because of the aforementioned tracer advantages. Thurber, in his PhD thesis [55], assessed the dependence of acetone fluorescence on temperature, pressure, composition and excitation wavelength. Measurements of the absorption (225-320 nm) spectrum at different temperatures are published in [41] and reported in Fig. 2.9. Although the curves are not normalized, the shift of the absorption peak towards higher wavelengths is clear. This behavior is the same as discussed before and reported in Fig. 2.4 for two-line measurements of temperature. Regarding the emission spectra, Bryant reported the information in [49]. The distribution is between 320 nm and 550 nm (Fig. 2.10).





Figure 2.9: Absorption spectral profiles of acetone at different temperatures [41].

Figure 2.10: Normalized fluorescence signal spectral distribution measured by Bryant [49].

The measurements of Thurber [41] also reported a temperature sensitivity at low temperatures clearly higher for lower excitation wavelengths. The estimated uncertainty of single- and two-wavelength PLIF approaches was evaluated in [56]. Low uncertainty is found at high sensitivities. The dualwavelength approach shows a higher uncertainty due to the lower temperature sensitivity compared to the one of the single-line approach. Although the single-wavelength approach seems to be better in terms of accuracy, the investigation was performed at isobaric and isothermal conditions. Indeed, by changing pressure and concentration in space and time the technique is not reliable. A fluorescence lifetime of 2.7 ns was measured by Breuer and Lee [39].

Regarding the safety of using acetone, the Material Safety Data Sheet (MSDS) of Acetone 99% provides a maximum allowed human exposition of 750 ppm in Belgium. On the other hand, no limitations are set for the emissions of its vapor in atmosphere.

2.2.2 Toluene-based LIF

As well as acetone, toluene has been widely characterized in [57] for its absorption (240-290 nm) and fluorescence emission characteristics (260-340 nm) in a 1 bar nitrogen bath [57]. Another paper reports and assesses the phenomenon of oxygen quenching [58]. The measurements in a 1 bar nitrogen bath are reported in Fig.2.11 and 2.12, respectively, for absorption and fluorescence. Due to a significant red shift of the emission spectrum, toluene has been used largely for two-color measurements [59] in different applications as well as time resolved measurements [60], also in supersonic flows [61]. The fluorescence lifetime of toluene was investigated in ref. [62]; it was at the order of 50 ns in a nitrogen bath and 0.6 ns in air at 1 bar. As already seen in Figures 2.7 and 2.8, in the presence of oxygen, not only the level of the signal produced changes but also the dependence of the latter on temperature.



Figure 2.11: Absorption spectra of toluene at different temperature at 1 bar nitrogen bath [63].



Figure 2.12: Peak-normalized fluorescence spectra of toluene at different temperatures in 1 bar nitrogen bath [63].

In Belgium, the Material Safety Data Sheet (MSDS) of Toluene 99% limits the vapor exposition to 50-100 ppm depending on the duration. Also in this case no limitation are set for the emissions in atmosphere.

The conclusion is that toluene is slightly more toxic than acetone. Acetone is also cheaper and has a spectral emission in the UV and visible spectral ranges. Other advantages of acetone are the absence of oxygen quenching and the fluorescence re-absorption¹. Toluene, on the other hand, requires a complete UV detection system, its fluorescence is quenched by oxygen and the emission and absorption spectra overlap. However, it presents different advantages. It is suitable for both one-color and two-color measurements. It also has significantly higher signal and temperature dependence compared with acetone in the temperature range of interests (290-400 K). In a first step acetone was selected for simplicity, lower cost and less toxicity. After the measurements in the cell (chapter 3), the use of toluene was considered more appropriate.

The first part of the research intended to evaluate the feasibility of the twocolor technique. The purpose was to answer to the question if it is able to correctly measure the real temperature distribution in a cooling channel. In order to do that a study of the *Prandtl number* of the operating fluid-tracer mixture inside the channel was conducted and is described in the next section.

¹when absorption and emission spectra overlap, part of the fluorescence is re-absorbed by the molecules. The effect on the recorded signal significantly depends on the absorption cross-section, the tracer concentration and the fluorescence quantum yield.

2.3 LIF-mixture Prandtl number

According to what was shown by the similarity analysis of the governing equations in section 1.3.3, an important parameter, together with the *Reynolds* number, is the molecular *Prandtl number Pr*. Indeed, at different *Pr numbers*, changes occur not only for the mean temperature profile but also for the temperature fluctuations [64]. Therefore, in order to provide reliable data for CFD validation and modeling purposes, the operating *Pr number* in the experiments should match the one of the application. The present research used mixtures of air-acetone, air-toluene and N_2 -toluene. Both acetone and toluene are inserted in their liquid phase in a vapor generator, also called "bubbler". More details are described in chapter 4. After evaporation, the evaluated mixture is totally in a gas-phase and regulated by the Amagat's and Dalton's laws. The present section aims at evaluating how the *Pr number* varies in function of the tracer concentration for the different mixtures aforementioned. This value is compared with the real *Pr number* of the application. Its value can be estimated as follows.

For an airplane flying at an altitude of 10 km the atmospheric conditions are around 223 K for the temperature and 26.5 kPa for the pressure. Considering an engine pressure ratio π of 50 and assuming the isentropic compression efficiency ($\eta_c = 0.85$) at the exit of the compressor, the air used for cooling purposes will be at 1325 kPa and 760 K. At these conditions air has a dynamic viscosity of $1.35 \cdot 10^{-5} \frac{kg}{m.s}$, a specific heat capacity at constant pressure c_P of $1.087 \frac{kJ}{kg\cdot K}$ and a thermal conductivity k of $5.509 \cdot 10^{-5} \frac{kW}{m\cdot K}$ which leads to a Prnumber value of 0.686. However, this value represents an upper bound considering that other engines have much lower pressure ratios and the air bleed from the compressor most of the time is taken from multiple intermediate positions and not only at the exit of the HP compressor. These positions depend where the coolant air is mixed with the hot gas flow.

A first consideration is made about the partial pressure of the tracer P_{tr} . The vapor saturation pressure $(P_{v,sat})$ of the used tracer represents its highest partial pressure $(P_{tr,max})$. On the other hand, a higher partial pressure of the vapor in certain conditions would result in partial condensation in small liquid droplets. It is therefore important that $P_{tr} \leq P_{v,sat}$. From the Dalton theory about partial pressures, its value is proportional to its volume fraction χ_{tr} . Therefore, Eq. 2.6 shows the existence of a maximum allowed depending on the pressure of the fluid-tracer mixture P.

$$\chi_{tr,max} = \frac{P_{v,sat}}{P} \tag{2.6}$$

The NASA Glenn Research Center has developed a database with several species available with their thermodynamic and transport properties. The available website [65] allows to use this database to compute these properties for a given mixture of gases. However, this code is based on the assumption of chemical equilibrium. This means that the introduced species in the code are evaluated after a theoretical infinite period of time. In the specific case of acetone, from the computed species at the equilibrium condition, acetone has disappeared because of the different reactions which have happened. Fortunately, the manual of the algorithm used by NASA [66] clearly explains the way these properties are computed starting from the species composition at the equilibrium condition. Regarding this investigation, the quantities are computed assuming the integrity of the two species (main fluid and tracer) during the experiments and no reactions between them which might modify even more the properties. Equations 2.7, 2.8 and 2.9 are the ones used for a multi-species gas specific heat $c_{P,mix}$, viscosity μ_{mix} and thermal conductivity k_{mix} . The indexes i and j represent the fluid (air or nitrogen) and the fluorescent tracer (acetone or toluene). Φ_{ij} and Ψ_{ij} are the interaction coefficients computed respectively with Eq. 2.10 and 2.11. χ_i is the concentration of the species *i*. It is used as the molecular (volume) concentration for the dynamic viscosity in $Pa \cdot s$, the thermal conductivity in $W/(m \cdot K)$ and the mass concentration for the specific heat capacity in $kJ/(kg \cdot K)$.

$$c_{P,mix} = \frac{\sum_{i=1}^{N} \chi_i c_{P,i}}{\sum_{i=1}^{N} \chi_i M_i}$$
(2.7)

$$\mu_{mix} = \sum_{i=1}^{N} \frac{\chi_i \mu_i}{\chi_i + \sum_{j=1}^{N} \chi_i \Phi_{ij}}$$
(2.8)

$$k_{mix} = \sum_{i=1}^{N} \frac{\chi_i k_i}{\chi_i + \sum_{j=1}^{N} \chi_i \Psi_{ij}}$$
(2.9)

with

$$\Phi_{ij} = \frac{1}{4} \left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{\frac{1}{2}} \left(\frac{M_j}{M_i}\right)^{\frac{1}{4}} \right]^2 \left(\frac{2M_j}{M_i + M_j}\right)^{\frac{1}{2}}$$
(2.10)

and

$$\Psi_{ij} = \Phi_{ij} \left[1 + \frac{2.41 \left(M_i - M_j \right) \left(M_i - 0.142 M_j \right)}{\left(M_i + M_j \right)^2} \right]$$
(2.11)

Thermodynamic and transport properties were obtained for air, nitrogen, acetone and toluene vapors and reported in Tab. 2.1.

	c_P		μ		k	
	$[kJ/(kg \cdot K)]$		$[\mu Pa \cdot s]$		$[W/(m \cdot K)]$	
	$20^{\circ}\mathrm{C}$	$100^{\circ}\mathrm{C}$	$20^{\circ}\mathrm{C}$	$100^{\circ}\mathrm{C}$	$20^{\circ}\mathrm{C}$	$100^{\circ}\mathrm{C}$
air	1.0045	1.0104	18.424	22.027	0.02592	0.03118
nitrogen	1.0040	1.0042	17.600	21.200	0.025598	0.03075
acetone	1.271	1.502	8.20	9.80	0.0110	0.0178
toluene	1.682	1.975	7.0	8.7	0.0150	0.0180

Table 2.1: Specific heat c_P , dynamic viscosity μ and thermal conductivity k of air, nitrogen, acetone and toluene vapors used for the estimation of the Prandtl number of the different mixtures.

The results are shown in the six graphs of Fig. 2.13. The plots show the Pr number of the mixture in function of the tracer molecular concentration. On the left, the results at 20 °C are represented whereas, on the right, the investigated temperature is 100°C. The first row is related to the air-acetone, the second to the air-toluene and the third to the nitrogen-toluene mixtures. Acetone, due to its high vapor pressure, can reach a maximum molecular concentration of about 25% in air at ambient conditions. This is the main reason why on the first row (Fig. 2.13 a and b) the variations of the Pr number value are more important. However, the Pr number increases by less than 2% with a concentration of 15% and by less than 5% in saturation condition. Furthermore, allowing 25% of acetone into the flow is very hard due to the considerably high latent heat of the tracer that decreases the temperature in the seeder. On the other hand, at ambient conditions, the maximum concentration of toluene is about 3% and this amount is not able to modify the *Pr number* value of the main fluid (air or nitrogen) by more than 1%. In all the cases, the temperature variations during the test do not have a significant effect (the right column with respect to the left column of Fig. 2.13). In addition, the values of the Prandtl number in a nitrogen-toluene mixture (more similar to the nitrogen value) are a bit closer to the specific application and less to the values of air at ambient conditions where other tests available in literature have been conducted.

The results shown in this section were obtained at the beginning of the research to prove that the test conditions respect the intended application. The author concluded that no significant effect of a tracer on the observed physics should be expected.

2.4 Required instrumentation

As introduced in section 2.1, the one-color and two-color techniques to determine the flow temperature need only one excitation source. It can be either pulsed or continuous. However, continuous lasers require very high power or



Figure 2.13: Prandtl number at 20 °(left column) and 100 °C (right column) of air-acetone (a,b), air-toluene (c,d) and N2-toluene (e,f) mixtures.

need too long camera exposure times. This implies a worse temporal resolution. The light frequency needs to be properly chosen according to the absorption of the selected tracer. In particular, all the molecules used for gas-phase LIF require ultraviolet excitation. From ref. [41], the best excitation wavelengths in terms of temperature dependence for acetone are 248 nm and 266 nm. These wavelengths have been also used for toluene based LIF measurements. The 248 nm wavelength is produced by excimer KrF lasers, whereas the 266 nm can be obtained by quadrupling the infrared frequency of diode lasers, which has a wavelength of 1064 nm. Other frequencies can be obtained by using different dyes. Excimer lasers are normally more expensive and require a bigger space whereas diode lasers are usually more compact and cheaper. The important features of the excitation source, except for the wavelength, are the power and the shape of the laser beam and its stability. Enough power is required to provide high signals and to be able to investigate a larger field of view. Enough means not too much power (less than 20 mJ/cm^2 [40]) because of the saturation of the signal at high excitation. As will be discussed later in section 5.1.2.2, it is important to operate in the region where the fluorescence is proportional to the laser energy. A smooth and mostly uniform laser beam is required for a uniform laser sheet. Despite the fact that some non-uniformities can be corrected by a proper image processing, the latter is not able to eliminate all of them as well as spurious reflections. The same arguments hold for the laser power stability. Some fluctuations can be corrected but large ones increase the measurement uncertainty of the one-color approach.

When a tracer is excited, it emits fluorescence in all directions. The light needs to be collected on one (one-color technique) or two (two-color technique) sensors. The first thing to take into account in order to select a proper detection system is the sensor sensitivity to light, also known as quantum efficiency. The latter is the ratio between the produced photo-electrons in the circuits of the pixels with respect to the photons impinging the sensor. This ratio varies with the frequency of the light. Therefore, depending on the emission spectrum, a suitable detection system needs to be selected. A detection system is represented not only by the sensor but also by everything placed between the molecules emitting fluorescence and the sensor: optical windows, filters, camera lenses etc.

In the specific application it is important to have optical windows able to transmit both the laser and the fluorescence UV light. Commercial Plexiglas (\mathbb{R}) is often used for optical measurements. However, transmission starts at about 400 nm and no UV light is able to pass [67]. Sapphire, fused silica and quartz are the suitable alternatives. These constraints were applied for both the final channel in the facility and the measurement cell used for the preliminary study shown in the following chapter.

Looking at the emission spectra of acetone (300-550 nm) of Fig. 2.10, its fluorescence is easier to detect than the one of toluene; it allows using a normal CCD sensor (CMOS sensors are usually not able to detect light below 400 nm). However, as discussed in the next chapter, the produced signal intensity is very low. In order to use toluene as a tracer, a UV detection, instead, is needed (see Fig. 2.12 for the emission spectra). There are two options: the sensor of the camera can be UV sensitive or an intensified phosphor layer which produces green light might be used together with a commercial sensor. The latter option is the case also for some ICCD cameras (intensified CCD). Note that also the intensifier (phosphor layer) has to be UV sensitive. In order to discuss what is the best option it is important to introduce the reader to different type of noise sources in cameras.

2.4.1 Camera noise sources

Sakakibara and Adrian [45] underline the fact that the major source of temperature uncertainty in two-color PLIF is due to camera noise. The detailed explanation of ref. [68] identifies sources of noise by differentiating pattern and random errors. The former is effectively a spatial noise as seen by the observer of the image and does not change significantly from frame to frame. It is the opposite for the random noise that can be reduced by averaging successive frames. It is typically described by statistical distributions. The pattern noise mainly depends on the sensor and on the technology (normally CCDs have lower pattern noise than CMOSs). A brief overview of the main types of random noise on CCD camera systems can be found in ref. [69]. They are the *shot noise* (also known as *photon noise*), the *dark noise* (sometimes named *thermal noise*) and the *read-out noise* (or simply *read noise*).

- The shot noise refers to the statistical process of the incident photon flux on the single pixels. The number of photoelectrons collected by a CCD exhibits a *Poisson distribution*; it has a square root relationship between signal and noise.
- Dark noise arises from the statistical variation of thermally generated electrons within the silicon constituting the CCD. Dark current describes the rate of generation of thermal electrons at a given CCD temperature. Dark noise, which like photon noise exhibits a Poisson distribution, is the square root of the number of thermal electrons generated within a given exposure time. High-performance CCD camera systems reduce dark noise by cooling the sensor. However, the latter is irrelevant for the short exposure time in the current work.
- The process of quantifying the electronic signal on the CCD is represented by the so called *read noise*. This electronic noise is inherent to the camera system and the CCD. The major component of *read noise* arises from the on-chip preamplifier. Spurious charges also contribute to the overall read noise of the imaging system.

The signal-to-noise ratio (SNR) for a CCD camera can be calculated as follows [68].

$$SNR = \frac{n_{binn}q_{ph}Q_e t}{n_{binn}\left(q_{ph} + BG\right)Q_e t + MDt + R^2}$$
(2.12)

where n_{binn} is the number of binned pixels, q_{ph} is the incident photon flux (photons/pixel/second), BG is the possible undesired background light, Q_e represents the CCD quantum efficiency, t is the integration time (seconds), D is the dark current value (electrons/pixel/second), and R represents the *read* noise (electrons rms/pixel).

Knowing the different kinds of noises in cameras it is possible to select the best imaging system depending on the level of the signal in the set-up. In particular, if the signal is very low, it is highly affected by the read noise and the dark current. In this case an intensified detection is required. On the other



Figure 2.14: Signal rms and the effect of the read-out noise [70].

hand, as soon as out of the read noise level, a higher gain on the intensifier does not increase the S/N ratio since it amplifies also the shot noise and even adds additional noise. A more visual sketch is represented in Fig. 2.14. In the case the signal is high enough with and unintensified camera, the latter is recommended because affected by a lower noise which is not amplified.

In conclusion, the two-color and one-color techniques for gas-phase temperature measurements are promising. The feasibility of the technique has been proven by the negligible effect of the tracer on the *Prandtl number*. If the concentration can be assumed constant for the highly turbulent flow (high mixing between tracer and main fluid) and the laser power fluctuations can be corrected (considering the same fluence distribution inside the laser sheet) the one-color approach can be applied using the *flat field correction* (FFC). Oxygen quenching might represent an issue with aromatic tracers as toluene. Regarding the instrumentation, one UV laser source and one or two cameras are required. Depending on the level of the signal and the relative contribution of the *read noise*, an intensification might be suggested.

Chapter 3

1D acetone LIF: two-color and spectral measurements

In the previous chapter the principle and the feasibility of LIF thermography have been discussed. One of the last section addresses the required instrumentation for the measurements. The goal of setting preliminary experiments was to evaluate the performance of the process in terms of temperature dependence, uncertainty and measurement issues. The experiments discussed in the following section use acetone as a tracer and the two-color methodology.

3.1 Two-color measurements

The objective of the present experiments was to link the *intensity ratio* R_f of Eq. 2.5 to the assumed uniform temperature inside a measurement static cell and to define the sensitivity and the performance of the technique. According to some available data of the emission spectra of acetone at two different temperatures obtained at VKI (Fig. 3.6) [71], two-color acetone LIF thermography was performed.

The choice of acetone was done because of its low toxicity, its cost and the spectroscopic advantages largely discussed in section 2.2.1. Moreover, the twocolor approach allowed the author to neglect possible variations of laser power and tracer concentration during the experiments (in time and/or in space). A preliminary analysis was conducted to select the proper filters to place in front of the two cameras of the experimental set-up in Fig. 3.5. The two spectral bands were selected in the way suggested in [44] to maximize the sensitivity. Different possible couples of filters were first evaluated numerically and finally the SHX350 and the XUL0385 units from Asahi Spectra® were used. The expected performance of this filters are evaluated in section 3.1.3.

The first step was to create a static measurement cell able to respect the requirements of the technique. Then, a detection system was assembled with the available instrumentation at VKI in order to observe the signal in the two different spectral bands.



Figure 3.1: Sketch of the static aluminum cell used for the point-wise acetone LIF measurements.

3.1.1 Test section

The static cell was designed for uniform flow temperature measurements. All the components are sketched in Fig. 3.1. It is mainly composed of two aluminum pieces in order to be rapidly opened and cleaned between successive experiments. The bottom part is fixed on an aluminum plate by screws and presents a base for a small fan in order to mix properly the air with the evaporated tracer. A tap on the lower part allows the liquid tracer (acetone in this case) to be inserted with a syringe. On top of the fan, another tap is connected to a pressure transducer in order to control the tracer concentration. The vapor saturation pressure, important to estimate the tracer concentration, depends on the temperature of the environment. Besides, this information is crucial in order to associate R_f with the recorded temperature during the experiments. For this purpose, four thermocouple probes where inserted at the expected height of the laser sheet: two in the front and two behind at a distance of 5 mm between each pair and of 10 mm from left to right (Fig. 3.3). Two pipes provided with bore valves were inserted with the original idea of using an external flow heater and entrap the heated air inside the cell. However, this device was finally not used because of the low temperature achieved due to the thermal losses and the low mass-flow allowed as consequence of the high pressure drops. The groove on the top surface accommodates a layer of black gum and the lateral walls of the upper part of the cell. These two components create a sealed environment by pressing them together mechanically with a clamp. The top part is composed by five aluminum walls. Each of the four lateral ones (set on the groove) are provided with a quartz window for the laser and the cameras optical accesses. The windows are square quartz plates of $25 \ge 25 \text{ mm}^2$ and 3 mm thickness. A screwed aluminum plate presses the windows on the lateral walls squeezing two o-rings inside the grooves present on the external plate and the lateral walls. Both of the latter are provided by a hole of 15 mm diameter which is the opening of all the four optical accesses. All the external walls are thermally insulated by 15 mm thickness foam (Fig. 3.2). A small part of the tracer is inserted at the bottom in its liquid phase.

The amount has to be lower than the volume to saturate the air. If this is not the case, part of the liquid will not evaporate and when mixed with the fan it will dirty the optical windows. A couple of minutes are needed to allow the tracer to completely change phase. After that, the fan is turned on for about 10 seconds before taking the measurements.



Figure 3.2: Complete view of the static measurement cell with the top insulation uncovered.



Figure 3.3: Static measurement cell basement.

3.1.2 Experimental set-up

As already mentioned, the two-color technique requires mainly two detectors and one excitation source. The latter was provided by a Nd:Yag laser (Quantel Big Sky Laser®). It provides 266 nm wavelength pulses of 33 mJ and 532 nm wavelength pulses of 180 mJ. Downstream the laser beam, two dichroic mirrors at 45° allow to decrease the unwanted green light power. The tracer does not absorb light at 532 nm but it is important to cut down, as much as possible, reflections inside the cell. After the dichroic mirrors the beam passes through a fused-silica spherical lens (f = 750mm) in order to focus the beam in the middle of the cell.

The main issue of the set-up is represented by the location of the two cameras (LaVision Imager Intense). It is important that they observe as well as possible the same area with the same magnification. In order to decrease the number of degrees of freedom and to use only one camera lens the set-up built for the experiments is the one shown in Fig. 3.4 and sketched in Fig. 3.5. The fluorescence generated by the molecules in the laser beam is focused by a 100 mm fused-silica spherical lens and divided by a ND filter (NDUV01B item from Thorlabs®) positioned at 45°. The latter acts as a beam splitter. The transmitted light goes to the camera in line with the light path whereas the reflected fluorescence is sent to the camera at 90°. The two band-pass filters are mounted directly in front of the two sensors of the cameras. The camera with

the long pass filter (XUL0385) is also provided by a stopband filter (500-600 nm) in order to cut down the green reflected light. A bellow mounted between the splitter cage and the first camera, allows the focusing of both detectors at the same time. According to the light path of the two detectors the following section estimates the variation of the intensity ratio R_f with temperature.



Figure 3.4: Experimental setup used for two-color acetone PLIF for uniform temperature measurements.



3.1.3 Selection of the LIF filters for two-color acetone measurements

In this section, the numerical analysis for selecting the suitable filters for twocolor acetone LIF is presented. Here, only the results of the selected filters are shown, though other combinations have been studied in parallel. Some results of the spectral measurements of the fluorescence emission of acetone performed at VKI are shown in Fig. 3.6 [71]. During the experimental campaign, different tracers have been investigated, among which acetone. The experimental set-up is very similar of the one of section 3.2. It exclusively differs in the measurement cell (originally made of plastic) and the absence of the energy monitor. Only two temperatures were investigated (20°C and 40°C) and the output is a very noisy signal. However, literature does not present more accurate and detailed data. The emission is normalized with the highest signal value around 420 nm.

Together with the emission spectrum, the transmissions of the eventually selected filters (SHX350 and XUL0385 from Asahi Spectra®) are shown in Fig. 3.2. From the black and the green curve, the emission at 20°C and 40 °C respectively, different temperature dependencies are recorded below and above 350 nm. This is the reason of the selected filters for the two-color acetone investigation of section 3.1. By selecting these two spectral bands, the ratio between the blue channel (signal recorded by the camera provided with the SHX350 filter)



Figure 3.6: In black and green the acetone spectral signal recorded at respectively 20°C and 40°C. In blue and red the transmission of the filters. Data from ref. [71].

and the red channel (signal recorded by the camera provided with the XUL0385 filter) should increase with temperature (at least in the range 20-40°C). The expected performance of these filters is of articular interest. The latter has to be computed taking into account all the optical transmission between the molecules and the circuits of the imaging sensor.

The experimental set-up used for the two-color acetone calibration measurements in the static cell is shown in section 3.1.2 (Fig. 3.5). In order to use only one camera lens and observe the same area from the same side, this configuration was chosen. The fluorescence has to be divided into the two sensors. The best option would be to use a dichroic mirror able to reflect wavelengths lower than 350 nm and transmit the rest. An alternative is to use a Neutral Density (ND) filter to cut down the cost of the optics despite the lower amount of light sent to the sensors. According to the previous analysis, the intensity in the blue channel was 10 times smaller than the one recorded by the other camera due to the higher intensity of the emission beyond 350 nm. This is the reason why the NDUV01B filter from Thorlabs® was selected. The latter allows to transmit about 80% of incident light (directed to the blue channel) and reflect 10% of it (sent to the red channel). The purpose is to have a similar amount of light on the two detectors. The transmission of the ND filter over the wavelength is shown in Fig. 3.7. A drop of the transmitted light at the low wavelengths is clearly visible. Another important parameter to be taken into account is the sensitivity of the camera sensor (also known as quantum efficiency) as well as the camera lens transmission. Their combination is displayed in Fig. 3.8 and it is also taken into account for the following results.



Figure 3.7: Transmission and reflection of the NDUV01B filter from Thorlabs®. Data from the manufactures.

Figure 3.8: Combination of the camera quantum efficiency and the camera lens transmission. Data from the manufactures.

The curves of the fluorescence emission are multiplied by the filters' transmission as well as the quantum efficiency of the camera and the transmission/reflection of the beam splitter (NDUV01B). The plots of Fig. 3.9 show the trend of the intensities of the blue and the red channels with temperature. The graph shows a positive dependence of the blue channel whereas a negative one is detected for the red channel. The fluorescence emission decreases with temperature all over the spectrum. However, since the emission curves are normalized with their peak at 400 nm, the temperature dependencies of the two channels are shifted. However, the important value is the difference between the two, which is represented by the variation of the intensity ratio R_f (Fig. 3.10). The conclusion is an increase of the intensity ratio about 9.5% over a temperature difference of 20°C.

3.1.4 Data acquisition and processing

A series of 400 pictures are recorded at a 3 Hz repetition rate for each investigated temperature inside the cell. Binning of 8 x 8 *pixels* is used to reduce the relative contribution of *read noise*. An image of the target plate for the spatial calibration of the cameras and the background (image without tracer) Figure



40 20 **3.9:** *Intensities* ofthe blue (SHX350) and red (XUL0385) channels variation with temperature normalized

1.1 1.08 **n** 1.06

Intensity ratio 1.04

1.02

0.98

0.96

Figure 3.10: Normalized intensity ratio R_f in function of the temperature.

25 30 35 Temperature [°C]

are acquired in the same conditions.

condition (20 °C).

with the intensity at ambient

The image processing was performed entirely in Matlab(R). The first operation is the background subtraction where background images were taken in the absence of the tracer. After that, the spatial calibration is applied by means of the pictures of a target plate equipped with a graph paper located at the same position as the laser beam. Translation, rotation and magnification are used to match exactly the two fields of view. In order to have the corresponding pixels at the same location, a linear interpolation is applied for the correction of all images. The results are shown by Fig. 3.11 and 3.12; they represent the average intensities recorded by the two cameras at 48°C where the location of the laser beam is brought to the same place on the two pictures after applying the spatial calibration. Further comments on the intensities are reported in the following section. After this operation, the intensity ratio is computed in every location of the laser beam. The mean and the standard deviation are obtained both in space and in time.

The same statistics are computed for the signal of the thermocouples in order to assess the spatial uniformity and the variation of the temperature during the single experiments. This methodology is designed to evaluate the performance of the measurement technique described in the following section.

3.1.5 Results

The resulting R_f of this measurement campaign is summarized by the instantaneous image of Fig. 3.13 and its average over the 400 samples (Fig. 3.14).



Figure 3.11: Average image at 48°C of the camera at 90°with respect to the fluorescence light path with the SHX350 filter. The color bar represents the number of counts in a 12 bits camera.



Figure 3.12: Average image at 48°C of the camera in the direction of the fluorescence light path with the XUL385 filter. The color bar represents the number of counts in a 12 bits camera.

The highest intensity in Fig. 3.11 and Fig. 3.12 is located in the middle of the laser beam that pass through the cell from left to right. The intensity outside is due to the fluorescence reflections in the measurement cell and the remaining background that cannot be eliminated subtracting only the laser reflections. Indeed, in the region just outside the laser beam but not close to the windows edges, R_f is close to 1 (out of the color scale on top of the figures). Indeed, the non-zero signal in this region due to fluorescence reflections are about the same order in the two images. At the same height of the laser and close to the right edge of the window, R_f shows significant variations. The reason has to be found in the detection system and a possible difference in the angle of view between the two cameras. A slight inclination and mismatch of the laser beam location between the two pictures is still present. It is interesting to notice the distribution of R_f inside the laser beam. Likely due to the same mismatching, the value along the vertical axis Y presents a Gaussian-like distribution.



Figure 3.13: Instantaneous distribution of R_f at $48^{\circ}C$ inside the field of view.

Figure 3.14: Average distribution of R_f at $48^{\circ}C$ inside the field of view.

Furthermore, in the middle of the window the value has a tendency to slightly decrease. This is confirmed by the further analysis of the graph in Fig. 3.15. The latter represents the value of R_f extracted in a horizontal line in the middle of the laser beam (Y=-0.9 mm). The value is represented only between X=-5 mm and X=+5 mm. All the curves for the different investigated temperatures are shown. For all of them, R_f has a similar pattern. A first observation is a decrease of the intensity ratio towards the horizontal axis direction. Besides, some peaks are present at X=-3.5 mm and X=2.5 mm. The reason is found in the two pictures of Fig. 3.11 and 3.12 after the spatial calibration. The peak with the highest intensity is located at a different X position. Indeed, the brightest area on the laser beam of Fig. 3.12 is located more on the right compared to Fig. 3.11. Although these comments are important, the same trend with the investigated temperature has been observed in each position of the laser beam. The results can be improved by a more accurate procedure for the spatial calibration. The spatial calibration is able to bring the two images to the same real coordinates. However, the methodology does not correct for possible image distortions. More appropriate instrumentation, as image intensifier or UV-sensitive sensors, can be used to enhance the level of the signal and possibly open the actual laser beam into a wide laser sheet. In particular, the transmission of all the optics in the light path has to be taken into account in order to increase the the incoming photons to the camera sensors. This approach will generate a more uniform distribution of R_f within the investigated area.



Figure 3.15: Intensity ratio in function of the horizontal position of X extracted in the middle of the laser beam (Y = -0.9 mm) for the different corresponding temperatures.



Figure 3.16: Intensity ratio extracted in one point (X=-2)mm, Y=-0.9 mm) and plotted in function of the corresponding temperature.

Fig. 3.16 shows the final output of the measurements in the static cell: R_f as a function of the temperature. On the ordinate the intensity ratio is represented, extracted at X=-2 mm and normalized with its value obtained at the

lowest temperature investigated (48°C). The error bars represent the standard deviation over the 400 samples. The latter is of the order of 7.3% of the ratio value for a 95% confidence level. This means that, for the determination of the temperature, the latter may be determined within a range of \pm 8°C since the ratio varies by 46% in a 50°C temperature change. This value is based on the standard deviation and it is relative to the single shot. In section 5.4 a further discussion on the measurement uncertainty differentiate the latter with the one linked to averaged data. Furthermore, this value needs to be compared with the measurement range in a specific application. The bigger the range the smaller the effect of the uncertainty on the measurements. It means that for a measured range of 100°C the uncertainty is about 8%. The main contribution on the random error is given by the camera noise. Its effect on the measurements can be limited only by increasing the signal itself. The energy fluctuations of the laser pulses were not quantified. However, the method is theoretically not affected by these variations in the range of proportionality. During the experiments the thermocouples have shown variations between 1°C and 1.8°C, whereas non-uniformity in the spatial dimension are at maximum 0.8° C. The variations of the pressure inside the cell are less than ± 2 Pa and, therefore, its effect on the measurements was neglected. The results obtained were considered encouraging. Important improvements required to fulfill the project goals are discussed in the next section.

3.1.6 Conclusions

The presented results represent an encouraging starting point for the final objectives of this research. The presence of the relatively high temperature dependence of the intensity ratio is important for detecting the thermal boundary layer in the case of internal flows. Furthermore, this experiment put in evidence some aspects which need to be deeply analyzed:

- the signal is very low (on the order of 70 to 200 counts over 4065) and, therefore, the *read noise* plays an important role for the determination of the measurement uncertainty;
- No other two-color measurements with acetone are found in literature. The filters applied for these measurements were expected to provide a maximum variation of 24% of the signal within a 50°C variation (see section 3.1.3). Data present in literature of the acetone spectral emission are not detailed enough to draw conclusions on the possibility to perform two-color measurements [49].

For what concerns the low signal, in order to get rid of the *read noise*, the level of the signal has to be increased (see section 2.4.1). The two options are: either more sensitive optics and sensors have to be used, or intensifiers.

Although, with the latter, the *shot noise* is amplified together with the signal, the *read out* contributes less to the measurement uncertainty. Either the CCD cameras require two intensifiers or they can be replaced by two ICCDs. The fact that literature does not provide detailed spectral measurements of acetone, brought this research to a more accurate test of the acetone emission spectra at different temperatures in order to improve the understanding of the spectroscopic features of this tracer.

3.2 Acetone spectral measurements

Concerning the unexpected behavior of acetone during the previous experiments and being unaware about possible other physical reasons, the investigation of the fluorescence emission spectrum was needed in order to explain what was found in Fig. 3.16.

3.2.1 Experimental set-up

In this experimental campaign, the measurement cell is exactly the same as the one of the previous experiments. The detection system of Fig. 3.5 is replaced by a spectrometer (PI Acton $\text{Sp2750}(\widehat{\mathbf{R}})$) connected to an ICCD camera (PI-MAX 3(R)). A laser energy monitor is added to the system (Fig. 3.17). A small portion, i.e. 1 to 5% of the incoming light, is reflected by a quartz plate. More attenuation optics are placed in front of a photodiode as well as a filter (FGUV5-UV from Thorlabs(R)) in order to remove the remaining green component. The photodiode produces a current proportional to the incident light. The output signal is then integrated by a Boxcar Averager from Stanford Research Systems (R) (Fig. 3.18). The laser provides high-energy pulses during 8 to 5 ns. In order to resolve the complete peak a sampling frequency of 500 MHz would be needed. It is, therefore, more efficient to integrate the signal of the photodiode over a selected gate. The laser Q-switch is used as a trigger for the Boxcar Averager that produces a DC output updated for every light pulse. An acquisition system is used to store this data as well as the one of the thermocouples inside the measurement cell. A reference of the laser power is provided for each pulse and this value is used to normalize the intensity of the recorded fluorescence.

The fluorescence is collected by a 100 mm fused silica spherical lens and let pass through a vertical slit before getting inside the box of the spectrometer. The latter has a *turret* with three different gratings in order to split the different frequencies of light on the horizontal spatial dimension X. On the other hand, the Y-axis represents the vertical (spatial) dimension. The wavelength full range recorded by the used grating is about 100 nm. Five sets of measurements are used to cover the entire spectral emission of acetone from 300 nm to 600 nm with an overlap of 20 nm. Binning of 2 x 2 is used, leading to a



Figure 3.17: A sketch of the experimental set-up for measuring the fluorescence spectral emission of acetone seen from the top.

resolution of 0.1 nm. 500 images are recorded and averaged. The temperature is kept at the same level while the four sets of data are acquired. Together with the images, temperature from the four thermocouples, pressure and energy levels are recorded. The calibration of the system is performed using a halogen/deuterium lamp (Fig. 3.19). The intensity calibration is important since the camera response is different for each pixel and each wavelength.



Figure 3.18: Fast gated integrators and boxcar averagers model SR250 from Stanford Research System(**R**).



Figure 3.19: DH-2000 deuterium and tugsten-halogen light source from Ocean Optics(R).



Figure 3.20: Theoretical spectral distribution of deuterium and tungsten-halogen light from the lamp provider.



Figure 3.21: Measured spectral distribution of deuterium and tungsten-halogen lamp.

3.2.2 Methodology

The theoretical and the recorded emissions of the halogen and the deuterium lamps are represented respectively in Fig. 3.20 and Fig. 3.21. The sensitivity of the intensified camera (phosphor absorption coupled with its emission and the quantum efficiency of the sensor) and, probably, also the grating efficiency are the main reasons of the recorded spectrum of the two lamps compared with their theoretical curves. Therefore, the calibrated signal S is computed from the recorded intensity S_{rec} by subtracting the background image BG and applying the required correction:

$$S = (S_{rec} - BG) \cdot \frac{Cali_{rec} - BG}{Cali_{the}}$$
(3.1)

where $Cali_{the}$ is the theoretical emission of the calibration lamp and $Cali_{rec}$ is the recorded signal of the lamp. The BG image subtracted from the measurements is taken without tracer and in the different spectral ranges used. Therefore, it is required to acquire different BGs for each setting in the acquisition.

3.2.3 Results

All the measurement sets are taken to reconstruct the emission spectrum of acetone for each investigated temperature. The plot of Fig. 3.22 presents the latter normalized with the peak value (at 400 nm) obtained at ambient temperature (20°C). A clear dependence with temperature is observed. The signal decrease with temperature is in accordance with the study of Thurber [41]. Furthermore, the same picture shows a higher dependence of the signal at lower temperatures and the gap between the curves at 20 and 40°C is bigger than the one obtained between 40 and 80°C. It is common in literature to show the

results normalized by the correspondent value of the peak (Fig. 3.23): in this case at 400 nm. This allows to detect any red shift with temperature or any other shape change. In the investigated range, between 20 and 80°C, however, none of these phenomena are observed. All of them collapse in one single curve, except for some errors when overlapping the considered wavelength ranges. The choice to show the results up to 500 nm is due to the remaining laser green light scattered from the fluorescent molecules to the sensor. This amount of light is much less compared with the recorded broadband fluorescence of acetone.



Figure 3.22: Calibrated fluorescence spectra of acetone measured at different temperatures normalized by the value obtained at 20°C and at 400 nm.



Figure 3.23: Calibrated fluorescence spectra of acetone measured at different temperatures normalized by the peak value at 400 nm for each curve.

3.2.4 Conclusions

In conclusion, acetone is not a suitable tracer for two-color thermography since it shows the same temperature dependence at every wavelength. The experiment is not able to explain the results of sec. 3.1.5 and the encouraging temperature dependence of Fig. 3.16. Further analysis of the two-color measurement conditions is required to understand the physical phenomena involved. It might be photodecomposition of the acetone at the very high fluence. However, the investigation of the latter goes beyond the goal of the project to bring a suitable tool for providing accurate temperature measurements in a cooling channel. It was more interesting to test the detection set-up for a continuous flow. Due to the low level of the signal, the high uncertainty and the low repeatability of the measurements, the author selected a suitable and more reliable alternative for the temperature measurements. Looking at the studies in literature especially discussed in section 2.2, tracers as anisole and toluene are more suitable for two-color thermography. They also have a significantly higher fluorescence quantum yield. The one-color approach, besides providing a higher signal level due to the observation of the whole fluorescence spectrum, presents a higher temperature dependence and a lower uncertainty for both anisole and toluene. In a nitrogen bath, toluene provides fluorescence signal more sensitive to temperature than the one given by anisole molecules. The reason why, in this project, one-color toluene LIF was not considered from the beginning is because of the slightly higher toxicity of toluene compared to the one of acetone, its cost, the possible fluorescence re-absorption and the signal quenching by oxygen, not present in the case of acetone. For what concerns the two-color methodology, it was chosen in order to relax the necessity of a correction for laser power fluctuations and possible variations of tracer concentration. However, these difficulties were easily overcome. In the last campaign, the monitoring of the laser power by a photodiode was developed. Another clear advantage is the possibility of using a less complex detection system, replaced by only one camera. In the next chapter the new facility to investigate the temperature in a channel flow is presented. The idea behind its design is to build a new facility with mostly available components at the VKI with the goal to compare the results of a forced convection phenomenon with different measurements technique.

Chapter 4

Facility and Experimental Set-up

According to the conclusions of the previous chapter, the design of the facility has the purpose to investigate a forced convection phenomenon in a channel flow with PLIF. The results of the temperature boundary layer profile have to be easily compared with different measurement techniques. The final output is a facility composed of a wind tunnel with a re-adapted test section available at the institute, a new piping system in order to provide a certain seeded massflow, and the instrumentation for the measurements. All the components are supported by aluminum profiles as shown in in Fig. 4.7. More details about the design and the working conditions are given in the following sections of this chapter.

4.1 Test section

An already available channel designed for the rotating facility RC-1 and investigated in ref. [72] was selected. The cross section is 240 x 40 mm^2 and the length is 1390 mm. Its high *aspect ratio* (6) allows to assume the existance of a 2D flow. As a first step, this simplifies the job for possible out of plane influence. Fig. 4.1 represents the 3D design with some additional ducts, the settling chamber and the contraction. The facility is entirely made of aluminum for keeping the structure as light as possible. Indeed, under rotation (not considered here), the latter is subjected to significant mechanical stresses. All the components in the picture were taken and used for building the new LIF facility.



Figure 4.1: 3D view of the test section and the wind tunnel designed for the RC-1 facility.

There are four optical accesses, originally made of $Plexiglas(\mathbf{\hat{R}})$ for the PIV measurements: two at the inlet of the test section and two in the fully developed flow region (1150 mm downstream). They allow optical access for the laser and the camera. In the present case, as previously mentioned in section 2.4, the UV components of the laser and the fluorescence emission require another material for transmission. Commercial Plexiglas is opaque for light below 400 nm [67]. Therefore, the windows located in the fully developed flow area have been redesigned and replaced by quartz plates. These allow the laser to enter in the test section and the emitted fluorescence by acetone or toluene to be collected by the camera. The first part of the emission spectrum of toluene is reduced. Nevertheless, the recorded signal is definitely higher than the one of acetone with the same camera. Quartz and other UV transparent materials are significantly more expensive than Plexiglas, more fragile and more difficult to be machined. For instance, particular tools are required for cutting and making holes. Thus, two aluminum pieces supports the relatively small quartz slots in Fig. 4.2. The accesses for the camera have been redesigned with a quartz plate of $40 \ge 40 \ge 8 \text{ mm}^3$. The complete height of the channel was taken in order to be able to observe the wall even from a long distance (Fig. 4.2 (a)). The main frame is made from aluminum whereas two small brass screwed pieces fix the quartz plate inside the frame. On the other hand, the access for the UV laser was ensured by a small window ($60 \ge 25 \ge 4 \text{ mm}^3$). Also in this case the latter is inserted in a groove on the main aluminum frame and kept in position by a thin copper screwed plate (Fig. 4.2 (b)).



Figure 4.2: Camera (a) and laser (b) optical windows designed for the LIF experiments.

In addition to that, to create a temperature gradient the bottom wall of the channel has been provided with thin resistances (Minco HAP694^(R)). Ten heaters have been mounted with 3 µm thickness 3M^(R) double face adhesive (Fig. 4.3). Each of them is characterized by a resistance of 39 Ω and two branches made of five of them have been connected in parallel to an AC voltage regulator (Fig. 4.4). The maximum voltage provided is 260 V leading to a power of 1000 W. This heating system is able to increase the wall temperature up to 70/75°C in normal flow operating conditions. Assuming the inlet temperature about 20°C the temperature ratio $\frac{T_f}{T_{hw}} = 0.81$ is similar to the one of the real application (0.84). The test also represent in the same way the heat transfer exchange: cold flow and hot wall.





Figure 4.3: Picture of the bottom wall of the test section provided with 10 thin resistances.

Figure 4.4: Sketch of the connections between the resistances and the power supply.

The goal is to obtain the temperature profiles in order to compare the results with other experimental means (e.g. thermocouple or cold wire measurements). A low *Reynolds number* based on the momentum thickness ($Re_{\theta} = 400$) has been selected to generate a thicker boundary layer, easier to measure. On the other hand, the resulting *Reynolds number* based on the channel height $Re_H = 6700$ is large enough to produce a fully turbulent, fully developed flow (verified and shown in section 4.4). The corresponding mass-flow to be provided is about 30 g/s leading to a bulk velocity of 3 m/s.

4.2 Piping and flow control

The big challenge was to produce a flow seeded with the desired amount of fluorescent tracer. The simplest way would be to use a compressed air pressure line with two different exits: one passing through a vapor generator with a fluorescent tracer inside and a bypass. By means of two mass-flow meters in the two different lines the total mass-flow and the tracer concentration can be computed and regulated as required. However, the availability of only one pressure regulator forced the author to use only one exit. Fig. 4.5 represents the final configuration of the piping system that produces and controls a flow with the desired *tracer concentration* χ_{tr} and Re_H .

The flow is provided by the 7 bar compressed air line of the VKI and is



Figure 4.5: Sketch of the piping system upstream of the wind tunnel and of the test section.

splitted in two branches. One passes through the so called bubbler to generate a flow seeded with the fluorescent tracer vapor and the other one is used to dilute the mixture. They merge again and are connected to the inlet of the wind tunnel. The flow then passes through the test section and it is finally extracted outside of the building for safety reasons. The level of toluene and acetone in the room must be limited to respectively 50 and 750 ppm. The pipes are made of PE100 Black 63 mm external diameter and 5.8 mm thickness, resistant to pressurized air up to 16 bars and able to withstand both acetone and toluene vapors (solvents for commercial PVC). Different types of massflow meters have been considered and finally orifice plates have been chosen for the required mass-flow. The length of the pipes and the position of the orifices respect the British standards [73] for this type of pressure differential devices [74]. Orifices with a *diameter ratio* β of 0.6 were chosen to produce typical pressure drops of the order of 10 mbar. The bubbler generates a flow seeded with vapor. The internal diameter is 150 mm and the height is 280 mm. The inlet pipe exit is designed to be inside the tracer liquid in order to enhance the evaporation through bubbles. The partial pressure of the tracer at the exit of this device is assumed to be the one of saturation at the temperature measured inside by a type-K thermocouple. This assumption is not used for quantification but only to monitor the maximum concentration in order not to create condensation.

A code to estimate χ_{tr} and Re_H in the test section was written to control those values in real time in LabView (a) by taking the signal from five different *Differential Pressure Transducers* and three *type K thermocouples* in the system. The NI cDAQ-9174 (a), through the modules NI 9215 and NI 9212, acquires all these data. In particular, the various inputs are the static pressure upstream the orifice plates, the differential pressure across them, the pressure inside the bubbler, the temperature just downstream of the orifice plates to compute the density and the temperature in the bubbler. For more details about the used formulation, the assumptions and the code, the reader is referred to appendix A. The code allows to monitor and control in real time the target parameters of the flow by changing the opening of the valves iteratively.

4.2.1 Nitrogen flow implementation

As previously discussed in section 2.2.2, the fluorescence signal and its temperature dependence might considerably increase by lowering the oxygen content flowing inside the facility. With a high turbulent mixing, the facility is expected to generate a uniform nitrogen-toluene flow. The uncertainty of the measurements would benefit from this. Therefore, a way to supply nitrogen instead of air was developed and will now be presented.

The inlet of the piping system (black pipes of Fig. 4.7) has been connected to a three-way ball valve where the user can chose the injection: air, nitrogen or a mixture of the two. Since the institute is not provided with a nitrogen generation plant, a rack of eight cylinders of 50 *liters* at 200 *bar* connected to each other is used to provide the required mass flow. A regulation and safety system is needed between the three-way valve and the exit of the nitrogen bottles.

The sketch of Fig. 4.6 represents all the components of the flow regulation after the implementation of using nitrogen as the main gas (as well as the use of the PIV seeding generator to be described later, in section 4.3.1). Despite the large volume of the bottles, due to the high mass flow required, the nitrogen is expected to last for about 50 minutes of test. It means that the pressure can decrease considerably during a test of 5 min plus the required time to stabilize the flow. When the upstream pressure decreases, a single-stage pressure regulator is not sufficient to provide a constant mass flow. Therefore, two pressure regulators are installed in series. The first one is a single stage PRU200 pressure regulator from NEWFLOW^(R) to pass from a maximum inlet pressure of 300 bar to an outlet between 0 and 25 bar. It can also operate between -40° C and 175°C which is important considering the strong expansion of nitrogen from the bottles. The second stage is a RP500 proportional pressure regulator from Specken-Drumag(\hat{R}) to decrease the pressure from a maximum of 12 bar to 0-8 bar. The opening of the valve is controlled by a signal input in current (4-20 mA). This system allows a fine tuning of Re_H during the experiments, controlled by adjusting the DC signal generated from the NI 9265 4-Ch AO module by LabView(R). The first pressure regulator is controlled manually, however, theoretically, when the pressure between the two regulators is stabilized, only



Figure 4.6: *Piping sketch after the implementation of nitrogen cylinders in the facility.*

the second stage regulates the desired Re_H . At the expected pressure of 4 bar downstream the second regulation, the expected temperature of nitrogen is about - 20°C. Thus, the system is provided with an electrical heater to bring back the temperature to an ambient temperature condition inside the facility. Between the two pressure regulators a 150 liters buffer was inserted to decrease the pressure fluctuations during the operation. At the exit, a safety valve of 10 bar is used for not damaging the second pressure regulator as well as for the safety of the laboratory and of the operator. An oxygen detector is used during the test in the remote case that a large amount of nitrogen fills the room.

4.3 LIF experimental instrumentation and set-up

The 3D view of the facility of Fig. 4.7 shows the location of the laser and the cameras for the LIF measurements. The detection system used in section 3.1 has been replaced for the one-color measurements by the same ICCD camera of the spectral measurements (Fig. 4.8). The Nd:YAG laser head is mounted on an aluminum plate supported by four posts fixed to the camera structure. The advantage is that, once camera and laser are aligned, the illumination system

can move horizontally together with the field of view of the detector. The required optics used for the acetone spectral measurements (section 3.2) are also mounted on the laser support. A clearer sketch is presented in Fig. 4.9, where the additional spherical and cylindrical lenses produce the desired laser sheet brought into the test section vertically by a UV enhanced aluminum mirror hanging on a horizontal support (seen in Fig. 4.8). A gimbal mount allows a fine alignment in the same location as the calibration plate in the middle of the channel.



Figure 4.7: Complete 3D view of the facility with the location of the instrumentation.



Figure 4.8: *Picture of the LIF experimental set-up mounted in the supports of the facility.*

As previously mentioned, the detection system has been mounted in the lower level of the laser rack. The top view of this level is sketched in Fig. 4.10. The laser sheet reflected by the mirror from the top enters in the test section through the quartz plate mounted on the top optical window (Fig. 4.2 (b)). The fluorescence produced by the toluene is collected by a UV lens Sodern Cerco (R) sending the photons to the ICCD. In order to avoid the reflections of the remaining green light of the laser (532 nm) and possible visible external light, a short pass filter of 400 nm (Edmund Optics (R)) was placed in front of the camera together with the Semrock 266nm RazorEdge (R) ultrasteep long-pass filter. The latter, on the other hand, is used to remove the reflections of the UV light (266 nm) produced by the laser inside the test section when impinging and passing through the walls.

The camera is synchronized with the laser by a Stanford DG535 Digital Delay/Pulse Generator®. Although the laser has two cavities only one is used. The signal generated by the image acquisition of the camera in used to trigger the NI cDAQ-9174® recording all the pressure and temperatures as well as the photodiode signal. The acquisition starts with the first image. In this way it is easy to correlate each image with the laser reference power for the correction of section 5.1.2.2.



Figure 4.9: Sketch of the experimental set-up: the top view of the upper stage of the laser and optics until the mirror mounted of the test section's structure. On the bottom the lateral view of the camera looking inside the channel.



Figure 4.10: Sketch of the experimental set-up: the top view of the lower level of the camera looking inside the channel.

4.3.1 Simultaneous PIV and LIF set-up implementation

One of the goals of the present research is to accurately determine Pr_t . To do that, the term $\overline{v'T'}$ must be measured. Velocity and temperature have to be obtained simultaneously. Thus, the set-up was complemented with a PIV system in order to achieve this goal.

There are three main differences with the original set-up showed in the previous section:

- the PIV particles are generated by a *Laskin nozzle* smoke generator (Aerosol generator PivPart14 series[®]) and introduced in the piping system in the same branch as the one of the LIF bubbler (see Fig. 4.6);
- the dichroic mirrors in front of the laser are removed to use the green light to illuminate the PIV particles;
- the PIV camera is introduced next to the ICCD.

The particles used for the experiments are oil particles. The oil used is DEHS since it does not feature absorption in the UV spectral band of the toluene spectral emission. The camera used is the double frame PCO PixelFly SensiCam(**R**). It is placed next to the ICCD with an angle of approximately 10° from the normal to the laser sheet plane (Fig. 4.11). The low angle of view still allows a good accuracy on the spatial calibration (0.9 pixel of standard deviation).



Figure 4.11: Sketch of the detection system with the implementation of the *PIV* camera.

Another change is the synchronization sketched in Fig. 4.12. The number of channels required exceeds the one of the Stanford DG535 used previously. For this reason the latter is replaced by the Motion Pro Timing Hub® by IDT Vision® with 8 channels available instead of the 4 of the Stanford DG535. In this case, it is required to use both laser cavities. The second one needs to be synchronized in order to shoot at the right instant to observe the desired particles displacements (300 µs of Δt). The Q-switch delays of the two cavities is set in order to produce similar particle size in the two PIV frames. The PIV camera is synchronized with the given signal from the ICCD as done for the acquisition system in order to start the recording with the first LIF image.

4.4 Flow characterization

For the specific application and in order to produce the same conditions as in most of the studies reported in literature, the desired flow is fully turbulent and fully developed. Therefore, it was important to verify the aerodynamic features. To do so, a PIV measurement campaign was carried out. A LaVision PIV system is used, replacing the ICCD in the set-up (no synchronized PIV/LIF experiments but only PIV). The flow field is measured on the 2D symmetry plane. The seeding is generated by a PITEC (\mathbf{R}) smoke generator (same as the previous section 4.3.1) provided with Ondina oil (\mathbf{R}). 1000 pairs



Figure 4.12: Timing of the laser flash lamp (FL1 and FL2) and Q-switch (QS1 and QS2), the PIV and the LIF cameras for the simultaneous PIV and LIF experiments.

of images are recorded with a repetition rate of 10 Hz. The post-processing is performed by Davis (software for acquisition and image processing by LaVision GmbH(\mathbb{R})) with a multi-pass algorithm, with an initial window size of 128 x 128 pixel² and a final of 32 x 32 pixel². The resulting spatial resolution is exactly 1 x 1 mm^2 . A more resolved field of view is obtained with an overlap of 50%. Statistics were calculated from all the samples, in particular, for the mean stream-wise velocity profile and the mixed *Reynolds stresses* $\overline{u'v'}$.



Figure 4.13: Non-dimensional stream-wise mean velocity profile along the channel height.

Figure 4.14: Non-dimensional mixed Reynolds stresses profile along the channel height.

The results presented in Fig. 4.13 show a symmetric profile. The two wall
boundary layers develop from the inlet and meet in the middle of the channel. The flow is fully developed; this is demonstrated by the linear distribution of the *Reynolds stresses* across the central part of the channel (Fig. 4.14). The friction velocity is obtained from the extended line of the Reynolds stresses on the Y-axis in order to non-dimensionalize the velocity and define the wall-normal coordinate. Fig. 4.15 represents the boundary layer velocity profile in the u^+ and y^+ coordinate system. The PIV data show a good agreement with the logarithmic law obtained with the typical constants applied for internal flows ($K = 0.37, C^+ = 5.1$) [32].



Figure 4.15: Comparison of the velocity boundary layer with the logarithmic law for internal flows.

4.5 In-situ Temperature calibration

Since most of gas-phase LIF studies were performed in internal combustion engines or other applications where a temperature calibration in-situ is really difficult to perform, some alternative methods were developed in order to retrieve the correct temperature profile [75]. The field of internal combustion engines does not require accurate absolute temperature [76]. For this specific application, instead, a suitable temperature calibration needs to be carried out.

The advantage of performing an in-situ calibration is that a different configuration of the set-up might change the temperature effect on the signal. It has been shown that the signal recorded in a cell does not present the same behavior with temperature in the test section in most of the experiments in literature. Ref. [77], for instance, provides a methodology to correct the results by anchor the few points measured with a thermocouple in an IC engine. However, this does not take into account the possibility of a different shape of the calibration curve and uses only two points for the calibration. The idea shown in this section is to create a flow, in the same conditions as the test, at different known temperatures in order to build an accurate calibration curve in different regions of the field of view. Indeed, certain areas might behave in different ways due to fluorescence reflections which are not present in the background image. The ideal methodology would be to create a flow, in the same conditions as the test in terms of species concentration, at a uniform known temperature. The latter is hard to produce for the large section of the present channel. Therefore, the author decided to produce only a limited portion of the flow at elevated temperature. A sketch of the experimental calibration set-up is represented in Fig. 4.16. The flow goes from left to right and two lateral fences direct the mass-flow to the center of the cross-section (not represented in the picture). In this way the flow is constraint to pass through the heater. The latter is a simple pipe equipped with electrical resistances (AHP-3741 form Omega(R)). The flow coming out of the tube is hot and its temperature is measured by a thermocouple probe at 5 mm downstream the jet. In the same location the LIF signal is extracted. The latter is displaced along the channel height by means of a traversing system. The sealing is ensured by three PTFE's bushes installed on the top wall where the probe stem slides smoothly. Therefore, the probe can move both horizontally (three possible positions) and vertically by means of another traversing system. The heated tube can be traversed vertically in the same way. Three measurements can be performed (three horizontal positions of the probe) for each heater position along the channel height.



Figure 4.16: In-situ calibration set-up sketch. A pipe with internal resistances heats the flow passing through. A thermocouple probe measures the temperature in the same location as the laser sheet.

Chapter 5

One-color toluene measurements

5.1 Methodology and image processing

5.1.1 Image and Data acquisition

The required data to measure a temperature distribution in a plane by means of LIF is summarized as follows:

- a background image;
- a *Flat Field*;
- a series of measurements.



Figure 5.1: Raw image of background, flat field and measurements with the bottom wall heated.

An example of raw images is shown in Fig. 5.1. The *Background Image* (BG) is normally recorded to take into account possible laser reflections in-

Image series	Number of images acquired
Dark Images	50
Background	50
Spatial Calibration	50
Flat Field	1000
Heated channel Measurements	1000

Table 5.1: Summary of the number of images acquired for the one-color toluene LIF measurement campaign.

side the test section, therefore, with the laser on but without any tracer (no fluorescence). The *Flat Field* is required to normalize the image by possible non-uniform detection response and the non-uniform laser power distribution. It must be taken in the absence of any temperature gradients and this is the reason why it is also called a *isothermal image*. Another image must be taken for the spatial calibration. In the present research, the latter calibration is performed inside the Davis using the average image of 50 samples of a dotted plate.

In the specific investigation, also a *Dark Image* (DI) is acquired. The latter is recorded without any light source (normally with the camera lens closed) in order to take into account the intensity generated by the dark current in the circuits of the sensor and, especially, the A/D offset. The subtraction of DIis normally embedded in most of the camera acquisition softwares. Although this was possible to do in the software used for the acquisition (Lightfield (\mathbb{R})) it was decided to do it externally with the complete post-processing work. In such a way, everything can be monitored after the acquisition.

Due to the strong noise on the recorded pictures, a series of 50 images are acquired for the DI and the BG. Regarding the experiments related to the the *heated wall* and the *isothermal* conditions, because of the required statistics for the first one and the required precision for the second one, 1000 images are acquired for each of set of data. Table 5.1 summarizes the number of acquired images for this investigation.

The ICCD camera can acquire images at a maximum rate of 20 Hz. However, the limitation is set by the laser (maximum 15 Hz). In order to reduce the consumption of tracers and to limit the test duration, it is recommended to test at the highest rate possible. The stability of the laser power of the fourth harmonic (266 nm) depends on the temperature of the crystal and a very high pulse frequency might increase too much this temperature. Along the same line, the camera, with the intensifier, should be able to discharge the current in the circuits between two subsequent exposures. Unfortunately the measurements acquired at 10 Hz at the *isothermal conditions* show an increase of the average signal when increasing the number of samples (Fig. 5.2). The average signal is computed over an area of $16 \ge 16 pixel^2$ in the middle of the laser sheet and shows a drift of the signal in time. When decreasing the acquisition frequency to 3 Hz this phenomenon is not observed anymore (Fig. 5.3).



Figure 5.2: Signal convergenceFigurewith an acquisition rate of 10with anHz.Hz.

Figure 5.3: Signal convergence with an acquisition rate of 3 Hz.

All the data and signals connected to the NI acquisition system described in section 4.2 have been acquired by triggering the acquisition of LabView with the camera signal generated when recording. This is done to make sure that the acquisition system starts with the first recorded image of the sequence. All the data are stored in order to retrieve all the test conditions. It is possible to recalculate, with the voltages of the pressure transducer and the temperature of the thermocouples, Re_H and χ_{tr} and, more importantly, to normalize the intensity of the images with the reference power of the laser.

Once the methodology of the measurements in defined, processing of the data, images and signals is required to produce the desired results.

5.1.2 Image processing

In the present research the image processing is crucial to link the flow temperature to the recorded fluorescence signal (function of different parameters as expressed in Eq. 2.1). The spatial calibration, the laser power and the flat field corrections are required for each one-color LIF temperature test. With the assumptions described in the next sections, the LIF normalized signal I^* (Eq. 5.4) depends only on the temperature and can be calibrated with the method described in section 5.2. Furthermore, image processing is used in order to improve the accuracy and the influence of different steps is discussed later in section 5.3.1.2. The intensity normalization and a 2D Gaussian filter are introduced, especially for a better estimation of the fluctuating component of the temperature.

5.1.2.1 Spatial Calibration

The image of Fig. 5.5 is the average of 50 images taken inside the test section where a dotted plate is placed in the same location as the laser sheet (Fig. 5.4). The methodology of the spatial calibration done by the Davis software does not only move the image in the correct position but also corrects for optical distortions in the field of view and provides each pixel with the physical position X and Y in mm. This is done through a process where the user defines the space between all the dots and their diameters. Different patterns can also be used such as crosses or a chessboard. Then the software recognizes the center position of each dot in the image. It reorganizes all of them in rows and columns using a 3^{rd} order polynomial interpolation between them. In this way, each row of the image has only one value of X and each column only one value of Y.



Figure 5.4: Dotted plate inserted inside the test section for the spatial calibration.



Figure 5.5: Average picture of the dotted plate for performing the spatial calibration.

5.1.2.2 Laser Power correction

The measurements follow the one-color methodology. This means that only one ground state is taken into consideration and that the signal provided by the tracer might be strongly affected by variations of the laser excitation I_L and the tracer concentration χ_{tr} (Eq. 2.1). Therefore, a proper correction needs to be applied at this moment. The laser sheet power distribution changes in time are considered negligible whereas the signal of each image at isothermal and warm conditions as well as all background images are normalized by the reference power measured by the photodiode (Laser power correction) as explained in section 4.3. The linearity of the signal (without dark noise and background) is shown in Fig. 5.6.



Figure 5.6: *Linearity of the reference signal compared with the integrated value obtained from the photodiode.*

Measurements of the fluorescence at ambient conditions are performed for different laser powers by changing the Q-switch delay of the laser cavity. The average fluorescence signal in a window selected within the laser sheet is then compared with the integrated value of the photodiode. The signal at the highest power differs by about 20% from the proportionality. However, the previous point is used for the measurements, characterized by a signal decrease of 13%. The saturation model used (red line) is the one extracted from ref. [40] by the following expression:

$$I_{L,eff} = I_{L,sat} \cdot \frac{1}{1 + \frac{I_{L,sat}}{I_L}}$$
(5.1)

 $I_{L,sat}$ represents the intensity, or better, the local fluence (energy per unit of surface), of the laser at which the LIF signal does not change anymore. The laser power correction is performed, therefore, using the effective laser power. The latter allows to perform a proportional correction. The background images are subtracted from the average of the 50 dark images (\overline{DI}), normalized by the related effective photodiode reference I_{L,eff,BG_i} and averaged (Eq. 5.2). In a very similar way, the fluorescence images are corrected normalizing the level of the background as it was taken with the same laser power of the measurements (Eq. 5.3). The images, exceptionally in these two equations, are shown in bolt to differentiate them from the scalar quantities.

$$\overline{BG_{corr}} = \frac{1}{N} \sum_{i=1}^{N} \left(BG_i - \overline{DI} \right) / I_{L,eff,BG_i}$$
(5.2)

$$\boldsymbol{I_{corr,j}} = \left(\boldsymbol{I_{raw,j}} - \overline{\boldsymbol{BG_{corr}}} \cdot \boldsymbol{I_{L,eff,j}} - \overline{\boldsymbol{DI}}\right) \cdot \frac{1}{\boldsymbol{I_{L,eff,j}}}$$
(5.3)

 $I_{raw,j}$ represents the raw signal of the image j, $I_{corr,j}$ the corrected one and $I_{L,eff,j}$ the instantaneous value of the photodiode reference for the image j.

Although the methodology seems to be very effective in the current measurement campaign, it does not reduce the signal fluctuations. Theoretically, with the presented saturation model, the absolute value of the fluence in each position of the image must be known. This information is not very simple to retrieve. For simplicity, it is considered that $I_{L,eff} = I_L$. Indeed, the signal recorded by the photodiode does not seem to be correlated with the LIF signal computed in a 16 x 16 pixel² area (Fig. 5.7). Figures 5.8 (a), (c) and (e) show the evolution in time of the signals (average in the reference area) compared with the output of the photodiode for three different ROIs respectively at the top, center and bottom of the laser sheet. On the right of each of those pictures, instead, the resulting signal oscillations after a linear correction of the signal are presented. It seems obvious that the improvements are not the ones expected. The standard deviation also slightly increases (see section 5.3.1.2). The reason of the non-correlated LIF signal with the photodiode reference can be found on a low fidelity of the instantaneous photodiode measurements and/or the much more important noise on the cameras compared to the laser fluctuations.



Figure 5.7: Location of the three reference areas within the laser sheet of the image at ambient conditions.

5.1.2.3 2D Gaussian filter

Very high noise is present and visible in each image recorded. Within the reference areas there is a standard deviation of the signal, in the *isothermal image*, of about 5.7%. This is the reason why a proper spatial filter is required. Its application can affect the spatial resolution. It is then interesting to evaluate the latter in the recorded images. The fluorescence is emitted by the molecules in all the directions. Therefore, the signal produced in one pixel can contribute



Figure 5.8: On the left column: the average signal of the three ROIs of Fig. 5.7 compared to the signal generated by the photodiode. (a): ROI 1, (c): ROI 2, (e): ROI 3. On the right column: the normalized signal. (b): ROI 1, (d): ROI 2, (f): ROI 3.

to the signal recorded in the neighbours. In order to obtain this information, researchers have developed the slanted-edge methodology [78]. However, this method is not very easy to implement inside the actual design of the test section. This is the main reason why it was chosen to block the laser in some points just before entering and observe the effect of the diffusion of light. Indeed, the image taken in Fig. 5.9 allow to study the step response of the signal in space by looking only at the red rectangle. This image was averaged over 1000 samples, then, normalized with the *isothermal image*. Each horizontal profile was shifted by the tangent of the observed angle times the vertical displacement. In this way a sub pixel resolution is achieved for the step function response. The latter is given by the smooth profile of Fig. 5.10. In this case, it takes 6.6 pixel (about 0.85 mm) to rise the signal from 2% to 98% of the step.



Figure 5.9: Image produced in isothermal condition by blocking the laser before entering the test section with a grid.



Figure 5.10: Spatial response of the fluorescent signal to a step generated blocking the laser sheet at the entrance of the test rig.

A 2D Gaussian filter is applied with σ equal to 3 pixel and a kernel of 8 x 8 pixel². With the same procedure, the spatial resolution is evaluated after the filter. The result is an increase from 6.6 to 10.9 pixel (Fig. 5.11). On the other hand, it allows to significantly decrease the *pixel-to-pixel noise*.



Figure 5.11: Spatial response of the fluorescent signal to a step after the 2D Gaussian filter.

5.1.2.4 Intensity normalization

During the measurement, some pulses of high and low intensity were observed in the whole image and it was interesting to see if it was possible to take into account this anomaly that clearly affects the results and increases the recorded fluctuations in time of the signal. Figures 5.12 (a), (c) and (e) (left column) show the average signal in the three ROIs compared to the average signal in the area of the whole laser sheet (Fig. 5.13). Since only the *isothermal image* was taken into consideration it is possible to exclude any temperature change. This behavior might be addressed to laser power fluctuations but it remains even after the laser power correction. It could come from clouds of high and low concentration of the tracer but this behavior was observed even without any tracer when taking the BG samples. Most likely it is due to the detector response and especially the low stability of the intensifier.



Figure 5.12: Location of the reference area used to normalize the whole image.

The signal fluctuations of ROI norm are very similar to the ones recorded in the ROI 1 and the ROI 2. It is not exactly the case for the ROI 3, where the proximity of the bottom wall seems to have an effect on the fluctuations of the signal, much higher than in the other two regions. This might be due to some fluorescence reflections from the bottom surface. Figures 5.12 (b), (d) and (f) (right column) show the effect of the correction compared to the original signal in the three regions. Visually the fluctuations decrease, especially for the first two ROIs as it could be expected. Further quantitative information of the effect of this correction and filters are given in section 5.3.1.2.

The choice of the ROI is also important. Ideally there should be no temperature fluctuations. However temperature fluctuations are present in all the field of view. In the center of the channel, their magnitude is lower but it has been observed that the whole laser sheet was more representative for the three regions of Fig. 5.7. The disadvantage of this correction regards the absolute temperature. Indeed, if the instantaneous integrated temperature (in the field of view) is higher or lower than the one averaged in time, the real temperature is modified. The measurements will be able to see only the relative variations



Figure 5.13: On the left column: the average signal of the three ROIs of Fig. 5.7 compared to the integral signal in the area of Fig. 5.12. (a): ROI 1, (c): ROI 2, (e): ROI 3. On the right column: the normalized signal compared to the original one. (b): ROI 1, (d): ROI 2, (f): ROI 3.

within each image and the real fluctuations in time will be affected. On the other hand, if the field of view is sufficiently big compared to the integral scales of the temperature fluctuations, this correction will remove the fluctuations in time and measure correctly the instantaneous temperature. This is the case of the measurements where the structures observed in the images recorded with the heated bottom wall are relatively small.

5.1.2.5 Flat field correction

In order to take into account non-uniformities of the detection and variations in space of laser fluence and concentration, a *flat field correction* (FFC) [79] is applied using an image with a uniform known temperature in the field - the so-called *flat field* (FF). This image is recorded without heating the bottom wall, at ambient conditions. The corrected signal is obtained by applying Eq. 5.4 where the corrected instantaneous image $I_{hw,j}$ is divided by the averaged corrected FF image taken at ambient conditions I_{amb} .

$$I_j^* = \frac{I_{hw,j}}{I_{amb}} \tag{5.4}$$

5.2 Temperature calibration

In order to link I_j^* with the real temperature, the procedure of the measurements developed in this work is the one shown in section 4.5. Each LIF experiment is followed by 5 points thermocouple measurements in the core of the heater. The averaged signal of I^* is then related to the average temperature measured by the thermocouple in the same window. The choice of using an averaged window instead of one single point is because this allows the acquisition of a lower number of image for the same desired accuracy of I^* , highly affected by the *pixel-to-pixel* and the *image-to-image noise*. 200 images are then recorded. The profile of temperature has been reconstructed by this five points and the averaged temperature is computed by computing the integral of the profile, divided by the distance between the first and the fifth point. Although the system is designed for performing a 4 x 3 sub-region temperature calibration, only one horizontal position of the thermocouple has been used for simplicity and because of the long time required for the experiments.

5.2.1 Image and data processing

An example of the average image obtained during this experiments is shown in Fig. 5.14. The same image processing to obtain the LIF signal I^* is applied for the temperature calibration images. However, the latter requires a further correction due to a different condition of the test compared to the isothermal case. Specifically, it has been noticed that the signal outside the region of the heater (also within the laser sheet) presents, in some cases, different values. This might be due to the same behavior as the oscillations presented in section 5.1.2.4. Therefore, a similar correction is applied for this phenomenon. The signal is corrected considering this decrease or increase of the signal in isothermal conditions. The results of the calibration curves obtained and applied to the profile of I^* are then presented in section 5.2.2.

5.2.2 Results

The advantage of using this methodology has been already discussed. In order to remind the reader, this allows the user to achieve a high resolution in temperature between ambient conditions (around 20°C) and maximum 100°C.



Figure 5.14: Example of the average fluorescence images of the temperature calibration measurements with the heater at the four different vertical position. In all the images the temperature was the maximum used.

Furthermore, different areas of the field of view are investigated for possible changes of the temperature response. The way the results are obtained is deeply explained in sections 4.5 and 5.2. The graph of Fig. 5.15 shows the calibration points and the linear interpolation functions for the four vertical positions of the heater. These results come after the complex processing of the image and the data of the thermocouple. The interesting behavior is a common down-shift of the curve when approaching the bottom wall of the channel. This means that the same value of I^* is representative for a lower temperature of the fluid close to the bottom wall compared with the higher parts of the channel. This variation of the detection response with temperature along the channel might be due to two reasons. In the proximity to the bottom wall, although provided with a quartz window, some possible laser, but especially fluorescence, reflections and/or shadowgraph effects are affecting the observed signal. The second cause might be addressed to a simple detection non-uniformity. Indeed, all the optics in between the generation of the fluorescence and the sensor have possible different spectral transmission in different areas. The temperature of the channel during the calibration test is also a parameter that could introduce some shifts.

The increase of the signal I^* with the temperature can be related to the increase of the relative fluorescence quantum yield shown in Fig. 2.8 and measured by Faust in 2013 [52]. However, the latter varies only by about 5% in the temperature range of this investigation. On the other hand, ref [59] shows a decrease of the toluene signal with temperature in air. The variables used in these two references are normalized with the number of molecules. This normalization is not possible in the present research. Nevertheless, a higher temperature would decrease the number of molecules, therefore, lowering the

signal recorded, which is not the case. The difference might be due to a different detection system response and fluorescence transmission or a different purity of toluene.



Figure 5.15: Temperature versus I^* and interpolation functions for the four vertical position of the heater inside the channel. The data are used for the temperature calibration of one-color toluene LIF.

For simplicity the author decided to use a linear function. However, possible other curves could fit better the data with more points. With the four temperatures observed for each calibration curve the choice of the fitting does not change the quality. As already mentioned and largely discussed for the measurement uncertainty (section 5.4.2.1), the scatter of the data on the interpolated function accounts for the uncertainty of the procedure (1.88°C for a 95% confidence level). The latter introduces a source of error on the determination of the average temperature taken into account in the previous chapter.

5.3 Results

After explaining the complete implementation of the image processing implemented and the sources of the measurement uncertainty, the results are shown and discussed in this paragraph. The complete methodology has been applied for a channel flow of an air-toluene mixture whereas measurements using nitrogen as the main fluid are shown only for the *isothermal condition*. Finally, some results of synchronized PIV and LIF measurements are shown and discussed.

5.3.1 Air-Toluene

The results shown in this section are the consequence of an iterative process between different measurement campaigns and processing methods before getting to the last methodology explained in this document. They are followed by the LIF results compared with a thermocouple probe traversed along the channel.

5.3.1.1 Measurement statistics

In order to compare the LIF measurements with the temperature inside the test section a type-K thermocouple probe was traversed along the channel height. The mean temperature, measured with the LIF and the thermocouple is shown in Fig. 5.16. The black diamonds represent the average temperature measured by the thermocouple over 1000 samples taken at 100 Hz (maximum frequency response of the thermocouple probe). Instead, the red line represents the temperature profile measured with the LIF technique extracted in the middle of the laser sheet, in the same location as the thermocouple probe. It is clear that comparing these results with DNS computations would not bring the author to any conclusions. Indeed, the available data in literature are obtained with different boundary conditions and assume that the flow is thermally established. Although the latter has been shown to be fully developed and fully turbulent, a thermally fully established flow is characterized by a linear temperature profile between the temperatures of the bottom and the top walls. It means that the heating length is clearly not sufficient to produce a fully established flow. It is important to point out that not only the bottom wall was warmer ($\sim 70^{\circ}$ C) than the fluid (about 20°C) but also the top wall (~ 35°C). This is due to the conduction trough the aluminum walls of the channel.

The profile matches quite well the one obtained with another measurement technique. Some discrepancies are put in evidence close to the walls. These are important in order to be accurate with the temperature gradients that appear in the *Reynolds averaged energy equation* (1.8) as well as to determine Pr_t . As already discussed, the reason for these discrepancies may be due to fluorescence reflections and shadowgraph effect.

Fig. 5.17 shows, the comparison of the fluctuating component of the temperature $\sqrt{T'^2}$ between the two techniques. In this case the data strongly disagree. The LIF technique, at least in this case, overestimates the magnitude of the temperature fluctuations. The last statement seems to be reasonable considering the strong signal fluctuations in the *isothermal image*. The latter indicates the expected level of precision. However, the thermocouple also seems to underestimate the real temperature fluctuations that to the best of the author's belief should stay in the middle. The thermocouple has a maximum frequency response of 100 Hz. The characteristic frequency of the flow can be





Figure 5.16: Comparison of the temperature obtained by LIF (red line) and by a thermocouple probe traversed along the channel height (black diamonds).

Figure 5.17: Turbulent temperature fluctuations $\sqrt{T'^2}$ measured by LIF (red line) and by a thermocouple probe traversed along the channel height (black diamonds).

estimated assuming a characteristic length (0.25 H = 10 mm) and the flow velocity (about 3 m/s). It turns out that this value is about 300 Hz. In practice, the thermocouple does not see these high frequency fluctuations and averages their values. For this purpose *Cold Wire* measurements are more suitable for comparing temperature fluctuations and are suggested for a future comparison of the data.

Although the temperature fluctuations are overestimated, the next section describes the relevant effects of the image processing performed in the *isothermal image* in order to decrease the noise recorded in the experiments. The reason of using the *isothermal image* for this assessment is given by the fact that temperature fluctuations are negligible.

5.3.1.2 Influence of the image processing on the signal standard deviation

The assessment of the signal correction is summarized in Table 5.2. In particular, the effect of each step on the image processing can be shown. The three reference areas ROI 1, ROI 2 and ROI 3 of Fig. 5.7 are considered. The reported values are the standard deviation of the average signal inside these windows computed on the original image, after the laser power correction (5.1.2.2), after the 2D Gaussian filter (5.1.2.3) and after the intensity normalization (5.1.2.4).

Even with the graphs of Fig. 5.8 the improvements of a Laser Power correction is not expected to show any benefit on reducing the signal fluctuations. On the other hand, the intensity normalization method has a very large impact on the latter. The effect of the Gaussian filter is a bit more complex to analyze.

Ref.	Original	Laser power	Gauss filter	ROI norm
ROI 1	0.0467	0.0469	0.0467	0.0293
ROI 2	0.0520	0.0526	0.0522	0.0295
ROI 3	0.0758	0.0772	0.0768	0.0506

Table 5.2: Relative standard deviation of the signal in time in the three different reference regions before and after the image corrections of section 5.1.2.

It is mainly due to the fact that it is a spatial filter applied to each image. Its benefit in time appears to be very low. The temporal fluctuations are computed on areas of 16 x 16 pixel² whereas the Gaussian smoothing is done for a σ equal to 3 x 3 pixel². The effect on the spatial dimension is given in Table 5.3 which summarizes the decrease of the standard deviation in the three regions of interests. Another benefit of minimizing the *pixel-to-pixel noise* in the image by a spatial filter (or by a window average) is to accelerate the convergence of the standard deviation in time [80]. The latter normally presents an asymptotic behavior and tends to stabilize to the same value for different averaged (or smoothing) areas with an infinite number of samples. The effect is that, for the same accuracy, less images can be acquired.

Ref.	before	after
ROI 1	0.0560	0.0239
ROI 2	0.0523	0.0209
ROI 3	0.0616	0.0256

Table 5.3: Standard deviation of the signal within the three different reference regions before and after applying the 2D Gaussian filter of section 5.1.2.3.

5.3.2 Nitrogen-Toluene

The possibility of performing measurements with nitrogen is very promising because of the advantages discussed in section 2.2.2. Ideally, with no oxygen content, the signal produced by toluene increases by a factor of 70. As discussed in section 2.4.1 the latter helps to reduce the importance of the higher *photon* noise as well as the read-out leading to an important increase of the signal-to-noise ratio. The other benefit is related to the higher temperature dependence of the fluorescence quantum yield ϕ . The images acquired in isothermal conditions (Fig. 5.18) present a considerably lower pixel-to-pixel noise compared to the one obtained with air (Fig. 5.19). The two pictures are compared with the same color scale. However, the intensifier gain used for the experiments is 10% for the image obtained with nitrogen and 70% for the one obtained with air. The signal increases 10 times with nitrogen and the image noise decreases from 13% to 8%. However, this value is still affected by the visible vortices of Fig. 5.18 and, consequently, does not allow the one-color temperature detection.

The *isothermal image* can be subjected to the *white noise* introduced by the camera and the typical laser power distribution inside the laser sheet but it has to be as uniform as possible and constant in time since used as the *Flat Field* for the image correction. These vortices are clearly not due to temperature changes (maximum 0.1°C recorded traversing the thermocouple probe in the same condition). They can be attributed to a non-uniform toluene or oxygen concentration. It is a bit difficult to imagine that toluene distributes more on the bottom since this phenomenon does not occur when using air in the facility. The seeding procedure of the tracer is the same and the pressure and temperature in the seeder are kept at the same level in both experiments. On the other hand, the facility is an open loop wind tunnel and air can remain trapped inside some areas with low momentum and/or entrained from some possible leakages on the path. The author tried to eliminate this issue by introducing more flow mixing into the facility (a mixing box and six turbulators in the wind tunnel duct). Nevertheless, the problem was not solved.



Figure 5.18: Isothermal image obtained with a nitrogentoluene mixture with the same gray scale as in Fig. 5.19 and with an intensifier gain of 10%.



Figure 5.19: Isothermal image obtained with an air-toluene mixture with the same gray scale as in Fig. 5.18 and with an intensifier gain of 70%.

5.3.3 PIV/LIF experiments

The results of section 5.3.1 have shown difficulties on measuring the instantaneous temperature T' and the magnitude of the statistics $\overline{T'^2}$. Yet, it was of a particular interest and challenging to show the possibility to perform synchronized PIV and LIF measurements for the determination of $\overline{v'T'}$ and Pr_t . The latter can be really useful for the turbulence modeling. Fig. 5.20 presents the vector field (white arrows) coupled with the temperature field (colored contour). In the middle of the channel the temperature is about 20°C and increases closer to the wall. Whereas temperature vortices seem to appear from the LIF measurements, the same vortices are not recognized in the velocity field. More

examples of the instantaneous temperature and velocity fields are shown in appendix B.

Figure 5.20: Example of the instantaneous vector field coupled with the temperature measurement contour obtained by meas of air-toluene LIF.

 $\overline{v'T'}$ is expected to rise close to the hot walls for the higher turbulent exchange of heat. Nevertheless, the high uncertainty on the temperature fluctuations does not allow to correlate instantaneously v' with T'. For this reason, negative values of the term $-\overline{v'T'}$ are also found in some regions and reported in Fig. 5.21. In his work Hirota, also found regions in his squared duct with negative values of $-\overline{v'T'}$ [33]. His explanation is related to the secondary flows.

In this case of a 2D flow, however, the same justification is hard be used in this case. The PIV measurements allowed to retrieve the divergence of the out of plane velocity. The latter is in the range of $10^{-3} - 10^{-5}$. Therefore, a 2D flow is expected. More likely, the main reason is given by the high uncertainty associated to T'. On the other hand, an important increase of $-\overline{v'T'}$ is visible close to the walls. It is also important to point out that in the simultaneous PIV/LIF experiments the bottom wall, in the image, moved quite a lot (~ 7 mm) when the channel was hot. Thus, it was not possible to compute the temperature close to the bottom wall due to the absence of the correct signal of the *Flat Field*. A similar bump as observed in Fig. 5.16 is seen here. Possibly, the error on the mean temperature is attributed to $-\overline{v'T'}$ as well.



Figure 5.21: Turbulent heat transport term $-\overline{v'T'}$.

5.4 Measurement uncertainty

5.4.1 Reynolds number uncertainty

The uncertainty on the *Reynolds number* inside the channel is directly linked to the one on the orifice plate. The British standards [73] define the relative uncertainty of the mass flow with the theory of the error propagation:

$$\left(\frac{\delta q_m}{q_m}\right)^2 = \left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta \varepsilon}{\varepsilon}\right)^2 + \left(\frac{\delta D}{D}\right)^2 \left(\frac{2\beta^4}{1-\beta^4}\right)^2 + \left(\frac{\delta d}{d}\right)^2 \left(\frac{2\beta^4}{1-\beta^4}\right)^2 + \left(\frac{1}{4} \cdot \frac{\delta \Delta P}{\Delta P}\right)^2 + \left(\frac{1}{4} \cdot \frac{\delta \rho}{\rho}\right)^2$$
(5.5)

The contributions of the discharge coefficient C and the expansibility factor ε are estimated as suggested in ref. [74]. δD and δd are assumed about 0.2 mm as a combination of the manufacturing tolerances in the centering of the orifice and its size. The influence of the pressure drop ΔP is computed from the effect of the calibration procedure, the uncertainty on the pressure calibrator and the one on the acquisition system:

$$\delta \Delta P = \sqrt{\left(\delta \Delta P_{calibration}\right)^2 + \left(\delta \Delta P_{calibrator}\right)^2 + \left(\delta \Delta P_{acq}\right)^2} \tag{5.6}$$

where $\delta \Delta P_{calibration}$ is computed as the deviation of the samples from the calibration curve, $\delta \Delta P_{calibrator}$ is given by the producer of the calibrator and $\delta \Delta P_{acq}$ takes into account the random error due to the fluctuations of the signal and the uncertainty given by the producer of the acquisition system.

Finally, the uncertainty on the density is calculated from the ideal-gas law in function of the uncertainty on the measured pressure upstream of the orifice plate and the temperature T downstream of the orifice plate:

$$\frac{\delta\rho}{\rho} = \sqrt{\left(\frac{\delta P_1}{P_1}\right)^2 + \left(\frac{\delta T}{T}\right)^2} \tag{5.7}$$

The summary of all the contributions is given in Table 5.4. The final result is a *Reynolds number* characterized by an uncertainty of 1.62%.

$\frac{\delta C}{C}$	$\frac{\delta\varepsilon}{\varepsilon}$	$\frac{\delta D}{D}$	$\frac{\delta d}{d}$	$\frac{\delta \Delta P}{\Delta P}$	$rac{\delta ho}{ ho}$
0.605	0.022	0.389	0.650	0.178	0.341

Table 5.4: Relative uncertainty in percentage of each contribution of Eq. 5.5 to the relative uncertainty on the mass flow.

5.4.2 LIF temperature uncertainty

Regarding the contribution of this research to the field of Internal Cooling discussed in section 1.4, and considering the results shown in this document, the most interesting parameters are the gradients of the mean temperature and the *turbulent Prandtl number* Pr_t . In order to characterize the latter the most challenging term to measure is the *heat transport term* $\overline{v'T'}$. As shown in the results (section 5.3) the main issue is to have an accurate value of the instantaneous temperature in order to couple the instantaneous v' and T' values. Unfortunately, the latter is affected by the important fluctuations of the signal. These fluctuations come for other sources than only the temperature.

A detailed discussion of the possible sources of errors in PLIF concentration measurements for internal combustion engines with acetone is presented by Salazar and Kaiser in [81]. The detected noise is described, as stated in section 2.4.1, as a combination of the read-out and the photon noise. The laser power correction is applied as described in the previous chapter. Further, they show a drift of the signal due to a change of concentration. The latter is taken into account, in this methodology, with the intensity normalization of section 5.1.2.4. Other sources of errors are given by the changes of the laser power distribution in time, the laser absorption, the deviation from the "weak excitation", the background subtraction, the concentration variations in time and the detection response. Due to the very low concentration during the tests (about 0.3%) the laser power absorption is negligible for the specific investigation and no correction is applied. Possible stratification or non-uniform concentration and detection response are canceled with the *flat field correction* (section 5.1.2.5). A bias on the results can be generated by the background subtraction that does not take into account fluorescence reflections. On the other hand, non-corrected variations in time of some parameters contribute to the random error.

5.4.2.1 Temperature calibration

As stated by Coolen [82], the calibration procedure plays an important role on the temperature uncertainty when passing from the LIF signal I^* to T. The error can be estimated considering the following contributions:

- the error on the thermocouple measurements (0.15°C);
- the error on I^* , estimated as the random error of the averaged 200 samples (1.66°C);
- the error on the deviation of the points from the calibration curve (1.88°C).

The final uncertainty of the calibration procedure, combining these three errors, is about 2.5°C.

5.4.2.2 Mean Temperature profile

The results of the mean temperature profile have shown a very good agreement with the temperature measured by a thermocouple probe traversed along the channel height. The reason is that the averaged temperature is normally characterized by a random error. This *standard random error* is usually estimated by Eq. 5.8 as the ratio between the standard deviation or the rms and the square root of the number of samples minus one.

$$E_{rand} = C_{CL} \frac{rms\left(T\right)}{\sqrt{N-1}} \tag{5.8}$$

where C_{CL} is the coefficient that depends on the confidence level. For a 95% confidence level this value is equal to 1.96. The number of samples N (number of images in this case) has a very large impact on E_{rand} . Even though the standard deviation with 1000 images is about 5°C (10% of the temperature difference between the hot wall and the fluid), this lead to a random error of 0.32%. Possible systematic errors are not taken into account because of the way measurements are compared with the thermocouple output. Indeed, since the temperature calibration is performed in slightly different conditions, the results present a bias of 2°C. Therefore, the profile shown in section 5.3.1.1 (Fig. 5.16) is adjusted. The tracer concentration is very sensible to the position of the valve in the branch of the LIF bubbler. In addition to that, also the stability of the intensifier seems to have an impact.

However the uncertainty on the mean temperature and the calibration are reasonable for the present technique; problems arise when non-uniformities are present [83]. These non-uniformities are seen in space and in time and affect strongly the measurements.

5.4.2.3 Temperature fluctuations

Looking at the expression of the fluorescent signal, the latter can be influenced by different parameters. First of all the tracer concentration and the local laser excitation. The single effects related to these two parameters are difficult to separate from each other but visually it seems that the laser power distribution has the largest importance. The horizontal profile of the signal at the same height of ROI 1 is extracted for the first six samples of I_{amb} and represented in Fig. 5.22.

Earlier, Meyer showed similar discrepancies on the laser excitation [84]. Coolen addresses this phenomena also to the shadowgraph effect close to the walls, where strong gradients of temperature cause important variations of the refractive index [82]. Along the same line, the channel deformation due to the higher temperature might change slightly the inclination of the quartz windows as well as change their refractive index. Indeed, what it has been observed is that the walls, seen by the images, move considerably from the ambient condition when the test section is heated. Especially when the temperature is not



Figure 5.22: Normalized intensity profile of the isothermal image at Y = 37 mm for the first six samples.

steady, strong displacements of the walls are seen. In the present measurements, these strong fluctuations account for about 8.71% of the signal and are responsible for the high uncertainty on the instantaneous value of the temperature.

Chapter 6

Conclusions and future perspectives

6.1 Conclusions

The innovative information about the local, time-resolved flow temperature in a cooling channel can play a big role in order to improve the understanding of the forced convection mechanisms in this environment. At the same time, this research contributes to the development of low cost CFD simulations (e.g. RANS) in order to improve their reliability. These measurements, however, have to be as accurate as possible and, at least, highly spatially resolved for the correct estimation of the mean temperature gradients. The strong assumption of a constant Pr_t can be forgotten by CFD users using the data provided by the simultaneous PIV and LIF experiments. Optical measurements have shown several advantages compared to prior, more intrusive techniques: the possibility to be non-intrusive and to provide planar information in one shot. On the other hand, they require more complex facilities, expensive instrumentation and challenging image processing tools. The present work is a global assessment of the LIF technique that is able to be applied in a cooling channel. The main goal is to contribute to the field of Internal Cooling for HP turbine blades. Nevertheless, this work can easily be extended to other engineering applications. The research, indeed, is not only innovative in turbomachinery but it is the first study of gas-phase LIF thermography in a channel flow.

A large discussion of the possible tracers is presented; toluene and acetone were chosen as the best candidates for these measurements. The *Prandtl number* of the mixture was investigated for both tracers, demonstrating the feasibility of the temperature measurements for an air-cooling configuration. Some preliminary results were obtained with acetone. Two main methodologies were identified for this application: the one-color and two-color approaches. The latter was chosen in the beginning in order not to correct for variations of the tracer concentration and the laser power even though this approach generated a higher uncertainty. The acetone point-wise measurements showed an important temperature dependence of the intensity ratio R_f . The low level of the recorded signal within a thin laser beam and the high level of the noise suggested to move towards a more suitable tracer and methodology for the temperature detection. The higher fluorescence quantum yield and temperature dependence were the main reason to select another tracer. After building the set-up for the spectral measurements with acetone it was possible to take into account the laser power fluctuations in time and, due to a high local mixing, variations of the concentration were considered negligible.

A new facility was designed to test the technique in a continuous flow. The details are given in chapter 4. The goal was to investigate a forced convection phenomenon in a simple 2D channel flow. The set-up allowed to control in real time the *Reynolds number* and the *tracer concentration* inside the channel. The measurements were performed using the one-color methodology. However, space was left for a possible additional camera for the two-color detection. A new innovative procedure for the in-situ temperature calibration was also developed with the opportunity to be highly resolved in temperature.

The temperature measured by the one-color toluene-LIF was compared with the output of a thermocouple probe traversed along the channel height. The mean temperature profiles obtained with the two techniques matched quite well. Although the *random error* on the mean value was shown to be very small, a bias of 2°C was observed. This value was used to adapt the profiles measured by the thermocouple and by LIF. This mismatch is due to different test conditions between the temperature calibration and the measurements (manly tracer concentration and intensifier). Furthermore, despite the careful image processing and spatial filtering, the images still presented important signal fluctuations that are not caused by temperature variations. This is the major reason of the overestimation of $\overline{T'^2}$ but not only. When performing simultaneous PIV/LIF measurements, the high uncertainty on the instantaneous temperature and, therefore, the fluctuating component T' did not allow a proper match of the latter with the instantaneous fluctuating velocity v'. As these two variables were not correlated, the measurements of $\overline{v'T'}$ seemed not enough reliable. On the other hand these measurements represent the first simultaneous PIV/LIF experiments in gas-phase internal flows. Therefore, they present big challenges.

Unfortunately the fluorescence signal of toluene is strongly quenched by the oxygen molecules present in air. The problem of the low level of the signal and, therefore, the resulting low *signal-to-noise ratio* can be solved by eliminating, or at least reducing, the oxygen content in the flow. This is the reason why the author considered the option of flowing nitrogen instead of air in the open wind tunnel. Another important advantage is the higher temperature dependence of the toluene signal in nitrogen compared to the one obtained with air as the main gas. The facility was modified for allowing the required flow conditions from a rack of pressurized nitrogen bottles. Unfortunately, the recorded images did not show a uniform signal at isothermal conditions. A possible remaining non-uniform oxygen content is the main reason. More likely, a certain amount of air was still trapped in the facility or entrained from possible leakages. As the facility is not a closed loop were vacuum can be created before introducing nitrogen, it was not possible to find a solution to the stated issue is a reasonable

time. The problem probably requires not only more time but also an additional economical investment.

Despite the challenging measurement technique and its high requirements, this research achieved the main goals set in the beginning (section 1.4). The feasibility was demonstrated in the first part of the study showing the negligible effect of the tracer on the flow Pr number. The technique was developed for channel flows, although more improvements are required. With a low budget, a facility was designed and constructed from scratch. The experimental set-up was designed with the available instrumentation at the VKI. A robust methodology was developed for the measurements and for the data reduction, with possible improvements on the image processing. Good results are represented by the mean temperature profile. Due to the limitations of the instrumentation, the corrected temperature fluctuations and the Pr_t were not able to be detected at this time. However, the innovative measurements of simultaneous PIV/LIF were conducted for the first time in the current framework of internal flows. In conclusion, this work represents the first step for a positive contribution of flow temperature measurements in internal cooling channels with the assessment of the possible future development.

6.2 Future work

The promising results obtained in this research suggest some possible future work. There are three main areas to be considered:

- the facility, the test section and the instrumentation;
- the image processing;
- the two-color method;

Regarding the facility the main concern is the proper use of a nitrogen flow. This could be done in different ways. The easiest but also the most expensive is to convert the facility to operate in a closed loop. Creating vacuum first, nitrogen and toluene can then be inserted. The amount of tracer is more easily controlled. The drawback of this configuration, apart from the cost and the complexity of the facility, is the possible degradation of the molecules. Since they recirculate, the same molecules are excited and can start decreasing the emitted signal. Nevertheless, this possible issue has to be quantified compared to the number of laser excitations and the duration of the experiments. The second option is to redesign an efficient insulation of the present layout facility and possibly achieve the same results at a lower cost.

The quartz optical windows the slots used for these experiments showed to produce some fluorescence. Better (but more expensive) optical windows are required for more accurate measurements, especially close to the walls.

In order to increase the temperature difference between the bottom and the top wall of the channel the heated (bottom) wall should carefully be thermally insulated, in order to minimize the conduction losses. Another advantage would be the lower deformation of the test section. The latter possibly allows the user to match perfectly the experiments with the image of the flat field and, therefore, to measure very close to the walls. The heating length is presently too short to produce a thermally fully established flow and it would be nice to increase it to be able to compare the data with available DNS simulations. This work would require a new test section.

A polarization of the laser would definitely help to have a more stable profile. Regarding the camera, the problem of the intensifier has to be properly analyzed and solved. An alternative would be to investigate if a non-intensified UV-sensible CCD camera can be used with the higher signal of toluene in nitrogen. The latter would allow a significant drop of the noise generated by the intensifier.

A more fundamental research can be applied to improve the current image processing. The latter can be improved by developing a good criterion to discard the noise recorded in the *isothermal image* from the signal fluctuations of the measurements. Also the variations of the laser power distribution in the sheet might be corrected. It is important though not to eliminate the signal fluctuations due to the temperature fluctuations. It might be interesting also to block the laser light in some parts (as done for studying the spatial response) to use the signal where there is no laser to assess for the fluorescence reflections. In absence of the latter, the intensity should go to zero. Also a POD analysis might be useful to detect more accurately the reflections. On the other hand, some further post-processing might a secondary task if measurements with nitrogen can be performed correctly due to the higher level of the signal provided.

The problems related to the local laser fluence and the concentration variations disappear when using the two-color technique. In the case of using a single camera, splitting the sensor in two paths used as the blue and the red channels, the signal oscillations given by the intensifier instability also cancel out. Two band-pass filters and an image doubler are required for these measurements. Although this method seems to have only advantages the temperature dependence decreases as well as the signal level in the camera. Indeed, in one-color measurements the integral of the whole spectrum is recorded. On the other hand, with the two-color technique, the latter is gated for the two channels. A lower signal level, therefore a lower *signal-to-noise ratio*, together with a lower temperature dependence cause an increase of the measurement uncertainty. The latter might be more important than the advantages just mentioned if it is possible to eliminate the issue of non-uniform oxygen content in the nitrogentoluene experiments. Thus, a proper assessment of the methodology is needed to compare the results.

It is also important to remind the reader that for simplicity the study has been performed in a smooth channel representative for a 2D internal flow. The author believes that for adjusting the methodology, the test conditions are relevant. However, in the future the investigation will need to be exported to a more realistic geometry of an internal cooling channel. In conclusion, the major part of the work was successfully performed during this study. Most of the improvements can be achieved with an economical investment and technical work. However, not all the issue are expected to be solved without the fundamental research required for the image processing and the possible development of the two-color approach.

Appendices

Appendix A

Labview script for real time control of the Reynolds number and the tracer concentration

The purpose of this appendix is to show what are the assumptions and how the flow parameters Re_H and χ_{tr} are estimated from the data acquired during the experiments (static pressures and static temperatures in the facility). To do that, as already mentioned in the document, the signals are read and managed by a LabView script. The next section explain the working principle of this home written code for real-time monitoring and saving of the data.

A.1 Operation of the LabView script

The front interface is shown by Fig. A.1. Here, there are some data to introduce and options to select. On the top left, the ambient pressure in *mbar* is copied from the VKI's pressure server. On the bottom left, the user can introduce the main fluid (air or nitrogen) and the operating fluorescent tracer (acetone or toluene). The mass-flow throttle is used when operating with nitrogen to control the opening of the second pressure regulator (see Fig. 4.6 of section 4.2.1). The temperature of the bottom wall, the top wall, the probe, the temperature inside the seeder and downstream of the first Orifice Plate are shown in the front panel. The selection of (Re_min) allows to cut the power supply to the heater downstream of the second pressure regulator on the nitrogen path when Re_H is lower than this value. It is possible to change the name of the file and the directory as well as the acquisition frequency. The latter is computed as the product of the LIF images rate (Hz) and the number of points per each image. Then the number of the recorded LIF images (N of images) defines the number of samples to acquire. As written in the bottom right of the interface, the zeros of the transducers can be acquired and be subtracted from the signal recorded. They can also be saved before and after the experiments in order to subtract the average value. On the control tab, it is possible to monitor the raw signals of the instruments (Fig. A.2). Furthermore, in this panel, the constants related to the calibration of each pressure transducer can be manually changed.

The block diagram is presented in Fig. A.3. Three *Dacq Assistants* are used to lead the NI acquisition system and their modules. One of the Dacq Assis-

Chapter A. Labview script for real time control of the *Reynolds number* and the tracer 94 concentration

tant block is for the real time acquisition of all the signals in order to monitor and stabilize the flow conditions before the test. The second one also operates within the while loop to regulate the aperture of the RP500 pressure regulator. By changing the position of the Mass flow throttle, the NI 9265 4-Ch AO module produces the DC signal in current(4 - 20 mA) sent to the device. When the user pushes the bottom Rec, the real time while loop stops; the code enters to the Saving case structure where the third Dacq Assistant is used to save the data. The trigger, in this case, is given by the signal of the camera in order to start the acquisition with the first saved LIF image. In this way, the recording of the photodiode is correctly associated to each image to be normalized by the laser power.

Within the Matlab script on the block diagram the two mass flow passing through the two orifice plates are computed. From the total mass flow the value of Re_H is obtained. The combination of the two mass flow allow, instead, to know how much gas passes through the bubbler and how much is used to dilute the mixture. The *tracer concentration* χ_{tr} is then computed at each time of the experiment. The details of the calculations on the Matlab script follow in the next two sections.

A.2 Calculation of the Reynolds number and tracer concentration

As a reminder for the reader, the signals acquired in the instrumented facility are able to obtained the quantities shown in Fig. A.4. The fist goal is to compute, with this inputs, the mass flows through the orifice plates $(Q_{m,tot}$ and $Q_{m,1})$. The method suggested in the British standards is an iterative calculation explained in the following section.

A.2.1 Mass flow and Reynolds number calculation

As mentioned in chapter 4, the orifice plates were designed to measure the expected mass flows passing through the pipes with pressure drops of the order of 10 mbar. The geometry selected is summarized by Table A.1.

Pipe's diameter D	51.4 mm
Diameter ratio β	0.6
Internal diameter d	30.84 mm
Upstream tap location in diameters L_1	1

 Table A.1: Orifice plate geometry parameters.
The flow properties are calculated starting from the main gas properties (air or nitrogen) stored in the relative case structure. With the recorded $P_{up,OP}$ and T_{OP} in correspondence to the two orifice plates, the density is computed considering the perfect gas assumption. The temperature also affects the dynamic viscosity, calculated with the Sutherland equation:

$$\mu = \mu_{ref} \cdot \frac{T_0 + C_s}{T_{OP} + C_s} \cdot \left(\frac{T_{OP}}{T_0}\right)^{\frac{3}{2}} = \lambda \cdot \left(\frac{T_{OP}}{T_0}\right)^{\frac{3}{2}}$$
(A.1)

where the Sutherland coefficients differ according to the main gas:

	C_s	T_0	μ_{ref}	λ
	[K]	[K]	$[\mu Pa \cdot s]$	$[\mu Pa \cdot s]$
Air	120	291.15	18.27	1.51
Nitrogen	111	300.55	17.81	1.41

Table A.2: Suntherland coefficients used for air and nitrogen flows.

The Reynolds number based on the pipe diameter Re_D is calculated through an iterative method. The latter follows the Reader-Harris/Gallagher equation (Eq. A.2) as a product of the invariant A_n and the discharge coefficient Cwhich depends itself on Re_D .

$$Re_D = A_n \cdot C \tag{A.2}$$

 A_n is a function of the expansibility factor ε , the flow properties ρ_1 and μ_1 and the orifice plate's geometry (Eq. A.3).

$$A_n = \frac{\varepsilon d^2 \sqrt{2\Delta p\rho_1}}{\mu_1 D \sqrt{1 - \beta^4}} \tag{A.3}$$

 ε is defined as well from the orifice plate geometry and the flow conditions:

$$\varepsilon = 1 - \left(0.351 + 0.256\beta^4 + 0.93\beta^8\right) \left(1 - \frac{p^{\frac{1}{\gamma}}}{p_1}\right) \tag{A.4}$$

In the specific conditions, the discharge coefficient C is defined by Eq. A.5 with $M_2 = 2.5$ and $L_1 = 1$. The first guess of C is computed with Re_D tending to infinite which allows to neglect some terms (not dominant).

Chapter A. Labview script for real time control of the *Reynolds number* and the tracer **96** concentration

$$C = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521 \left(\frac{10^6\beta}{Re_D(i-1)}\right)^{0.7} + (0.0188 + 0.0063A_C)\beta^{3.5} \left(\frac{10^6\beta}{Re_D(i-1)}\right)^{0.3} + (0.043 + 0.08e^{-10L_1} - 0.123e^{-7L_1})(1 - 0.11A_C)\frac{\beta^4}{1 - \beta^4} - 0.031 \left(M_2 - 0.8M_2^{1.1}\right)^{1.3} + 0.011 \left(0.75 - \beta\right) \left(2.8 - \frac{D}{25.4}\right)$$
ith $A_C = 19000 : \frac{\beta^{0.8}}{2}$

with $A_C = 19000 \cdot \frac{\beta^{0.8}}{Re_D}$.

When the value of Re_D has converged, the mass flow can be obtained from Eq. A.6.

$$q_m = Re_D \mu \pi \frac{D^2}{4} \tag{A.6}$$

where $q_m = \rho v A = \rho v \pi \frac{D^2}{4}$ and $Re_D = \frac{\rho dv}{\mu}$. Finally, the *Reynolds number* with respect to the channel height is calculated with Eq. A.7 from the mass flow of the first orifice plate $q_{m,tot}$.

$$Re_H = \frac{\rho H U_{bulk}}{\mu} = \frac{\rho H U_{bulk} A}{\mu A} = \frac{q_{m,tot} H}{\mu A}$$
(A.7)

A.2.2 Estimation of the tracer concentration

The Antoine equation describes the relationship between the vapor pressure (in saturation condition) and the temperature for the pure components (Eq. A.8). The different constants A_a , B_b and C_c (Table A.3) are stored in the case structure of the block diagram for the acetone and toluene vapors as well as their molar mass in order to estimate the gas constant. Also in this case, the latter are considered perfect gas in order to estimate their densities.

$$log_{10} \left(P_{sat,tr} \right) = A_a - \frac{B_b}{T_{bub} + C_c} \tag{A.8}$$

The tracer concentration in the branch 2 of Fig. A.4 can now be calculated by Eq. A.9.

$$\chi_{tr,2} = \frac{P_{sat,tr}}{P_{bub}} \tag{A.9}$$

When the branch 2 merges with the branch 1, the concentration of the tracer is diluted. In order to estimate this value it is possible to assume the latter as the ratio of the volumetric flow rates q_V :

	A_a	B_b	C_c
	[K]	[K]	[K]
Acetone	4.35647	1277.03	237.23
Toluene	4.2368	1426.4480	-45.9570

Table A.3: Antoine Equation's coefficients used for acetone and nitrogen vapors.

$$\chi_{tr} = \frac{q_{V,tr}}{q_{V,tr} + q_{V,f,1} + q_{V,f,2}} \tag{A.10}$$

where $q_{V,tr}$, $q_{V,fl,1}$ and $q_{V,fl,2}$ are related respectively to the tracer, the main gas (fluid) in the branch 1 and the main gas in the branch 2. All of them are computed as the ratio of the mass flow rate and the local density.

The partial pressure of the main gas in branch 2 is obtained from the difference of the static pressure and the partial pressure of the tracer (Eq. A.11) in order to estimate the density in the same location (with the perfect gas law).

$$P_{fl,2} = (1 - \chi_{tr,2}) \cdot P_{up,bub}$$
(A.11)

The mass flow in the branch of the bubbler (2) can be obtain as the difference of the two mass flow measured with the orifice plate and also expressed as the sum of the mass flows of the main gas and the vapor of the tracer (Eq. A.12).

$$q_{m,2} = q_{m,tot} - q_{m,1} = \rho_{fl,2}q_{V,fl,2} - \rho_{tr}q_{V,tr}$$

= $\rho_{fl,2}q_{V,fl,2} \left(1 - \frac{\rho_{tr}}{\rho_{fl,2}}\frac{q_{V,tr}}{q_{V,fl,2}}\right)$ (A.12)

 $q_{V,fl,2}$ and $q_{V,tr}$ are unknowns in the equation, however, their ratio can be determine in function of $\chi_{tr,2}$ of Eq. A.9.

$$\frac{q_{V,tr}}{q_{V,fl,2}} = \frac{q_{V,tr}}{q_{V,fl,2} + q_{V,tr} - q_{V,tr}} = \frac{1}{\frac{1}{\chi_{tr,2}} - 1}$$
(A.13)

 $q_{V,fl,2}$ is obtain introducing the expression of Eq. A.13 into Eq. A.12. Then, $q_{V,tr}$ is consequently determined directly from Eq. A.13.

$$q_{V,fl,2} = \frac{q_{m,2}}{\rho_{fl,2} \left(1 - \frac{\rho_{tr}}{\rho_{fl,2}} \frac{\chi_{tr,2}}{1 - \chi_{tr,2}}\right)}$$
(A.14)

$$q_{V,tr} = q_{V,fl,2} \frac{\chi_{tr,2}}{1 - \chi_{tr,2}}$$
(A.15)

At this point Eq. A.10 will provide the estimated concentration of the tracer passing through the test section.

Chapter A. Labview script for real time control of the *Reynolds number* and the tracer 98 concentration



Figure A.1: Front panel of the LabView script interface.

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Figure A.2: Raw signal panel and calibration constants interface.



Figure A.3: Block Diagram of the LabView script.

Chapter A. Labview script for real time control of the $\it Reynolds\ number$ and the tracer 100 concentration



Figure A.4: Notation for the branches of the facility and location of the pressure and temperature measured during the experiments.

Appendix B

Instantaneous velocity/temperature images

In this section some examples of the instantaneous flow field and temperature fields are shown (Fig. B.1). An observation is that there are images and areas where the temperature is higher than the bottom wall or lower than the flow. This is due to the large uncertainty on the instantaneous value of the temperature. High and low temperature spots do not appear to be correlated with the velocity field. A similar decrease of the temperature close to the bottom wall detected in Fig. 5.16 is also visible in the 2D field. Furthermore, in all the picture the temperature on the left always higher than on the right. This gradient was not taken into account in the temperature calibration since only the position close to the heater was considered. The difference in the laser fluence might be the reason.



Figure B.1: Examples of the instantaneous vector fields (white arrows) from *PIV* coupled with the temperature field (colored contours) by means of one-color air-toluene LIF.

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