

# Fuel Gallery Residence Time & Heat Transfer Experimental Technique Development for Gas Turbine Fuel Injectors

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**Abstract** Two experimental techniques are presented in this paper looking at flows in complicated passages such as those of internal fuel galleries in modern fuel spray nozzles. The first relates to residence time measurement using a dye wash-out technique and the second to surface heat transfer measurement using thermochromic liquid crystals.

Dye concentration can be sufficiently calibrated making this technique easily and successfully applicable to residence time measurement within the chosen geometry. This experiment highlighted areas within the geometry where fuel is likely to become trapped in a recirculation and so leading to high residence times.

The liquid crystal method proved more challenging due to the susceptibility of the crystals to fail under water. One set of measurements was gathered and showed that areas of high fuel residence time also correspond to low heat transfer coefficient. Small volumes of slow or stagnant fuel will be susceptible to soaking more heat increasing the risk of coke formation.

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## 1. Introduction

Modern gas turbine engines are developed to operate at increasingly high temperatures in order to improve their thermal efficiency. Yet a hot cycle is also accompanied by increased levels of oxides of Nitrogen ( $\text{NO}_x$ ) emissions which are stringently regulated due to their effects on health and the environment. One additional implication of high temperature combustion is the chemical stressing of the fuel which is used to cool some aircraft parts (avionics, oil etc.). Such chemical processes may cause the deposition of carbonaceous materials within the fuel nozzle; the term coking is generally used to describe this phenomenon.

The occurrence of blockages caused by coke formation may result in uneven fuel sprays or localised burning (high temperature spots) which in turn will lead to high  $\text{NO}_x$  emissions. In some cases it may lead to mechanical failure and may cause detrimental effects to the turbine and the engine.

In an effort to comply with future emissions legislations and improving the efficiency of a gas turbine engine, research in this area is currently facing major challenges in the overall design of the engine cycles and components such as the combustion system.

One such area of research looks at lean combustion systems where the aim is to burn at lean air to fuel ratios (AFRs) in order to reduce hot spots and ultimately reduce  $\text{NO}_x$  emissions. In this system most of the combustion air is passed through the fuel injector and the fuel is delivered in a split pilot/mains strategy such that: at low fuel flows, all the fuel is supplied through the pilot injector. This ensures efficient burning at start up and idle. At higher power settings, a control logic is employed to allow fuel into both the pilot and the main injectors. A typical architecture of a lean burn fuel nozzle is shown in figure 1 (left) and a portion of the internal geometry of the fuel passages (right). In this example the pilot fuel circuit (item 60) is in proximity to the mains fuel circuit (item 70); pilot fuel has the added function of cooling mains fuel passages in order to maintain any stagnant fuel pockets in the mains passages at a temperature below that of autoxidation (Thomson 2012).

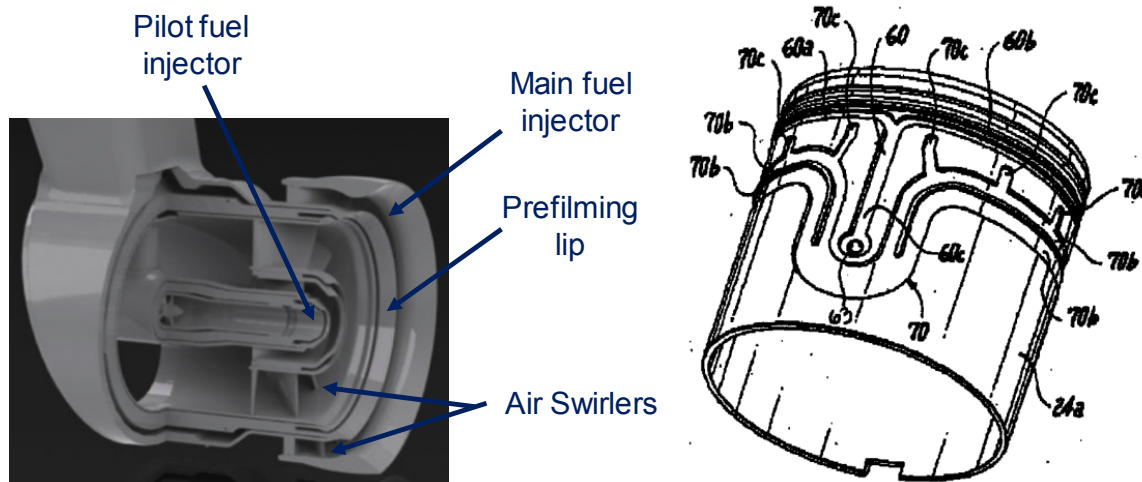


Fig. 1 Cut-away lean burn fuel injector (Meier et al. 2012) & fuel passage geometry (Thomson 2012)

Fuel stability studies are widely documented in the literature, it is known that temperature is the main contributor to fuel's chemical degradation and therefore increased risk of deposit or coke formation as was shown by the work of Chin and Lefebvre (1993) and Spadaccini et al. (2001). Work by the former authors also showed that at low Reynolds numbers and at locations of high residence time and temperature (for example at the walls) the rate of coke build up is higher. At high Reynolds numbers (increased mass flow rate), residence time is lowered and so is the rate of coke build up. An analytical model studied by Stickles et al. (1993) looked at methods of reducing wetted wall temperature within fuel passages to prevent fuel deposition. The work confirmed that increasing fuel velocity by reducing passage area would reduce residence time, increase heat transfer and so lead to reduced wetted wall temperature. Other design rules were also investigated such as improving the surface finish and the reduction of bends and steps (areas where fuel is likely to become stagnant) and were found to aid the reduction of wetted wall temperature.

Experimental techniques relating to flow measurement within fuel passages are scarce however dye wash in/out techniques have been used in various guises in many studies. In combustion, Cheng and Spencer (2010) used a combined PIV/PLIF set up to determine spatially and temporally resolved measurements of residence time in a high swirl fuel injector. PLIF methods give an effective way of determining residence time however one of their drawbacks is their complicated and often lengthy calibration process.

In environmental engineering, Weitbrech (2004) used Planar Concentration Analysis (PCA) to determine the decay rate of a pollutant in dead water zones (in rivers). Unlike LIF where the concentration is determined by the intensity of a fluorescent dye excited by a laser, this technique uses the effect of light absorption such that a fluid marked by a high concentration of a given dye would appear dark when viewed by imaging equipment whereas with zero concentration all the light would be reflected.

In the field of industrial coal furnaces, van der Lans et al. (1997) attempted the measurement of residence time distribution in a combustion chamber using the decay rate or wash-out of a tracer, Helium. Residence time was measured at three discrete locations within the combustor using a fast response probe and the results were complemented by velocity field measurements using LDA (Laser Doppler Anemometry). The experimental results were used to validate CFD models and to understand the chemical processes which influence the formation of pollutants in furnaces.

For surface temperature measurements, liquid crystal materials are usually sprayed as a thin coating into the surface with a dense black paint backing to ensure good contrast in colour. A method widely applied in the literature, for example the investigation of turbine blade film cooling effectiveness by Mayhew et al. (2003) and the investigation of effusion cooling performance in combustor representative flow conditions by Kakade et al. (2012). Where the working fluid is water, Zhong et al. (1999) developed a method to visualise turbulent spots (localised turbulent regions) in an otherwise laminar boundary layer over a heated surface.

In the current work scalar tracking technique is used to investigate its applicability to flows in narrow passages namely those of fuel galleries within modern fuel spray nozzles. Surface temperature measurements are also important; thermochromic liquid crystals are chosen for their relatively low cost compared to infra-red imaging, ease of calibration and repeatability of the results.

## 2. Experimental methods

Two methods were investigated, residence time using a partially calibrated dye wash-out technique and a liquid crystal heat transfer method applicable to a fluid environment. Measurement access to the internal passages of a metal injector is difficult and therefore a Perspex 15:1 scale model of a generic branch of the internal passages has been made. The curvature of the body of the injector has been ignored since its radius is between one and two orders of magnitude greater than the channel depth. This simplified model was used for both techniques investigated and is shown in figure 2.

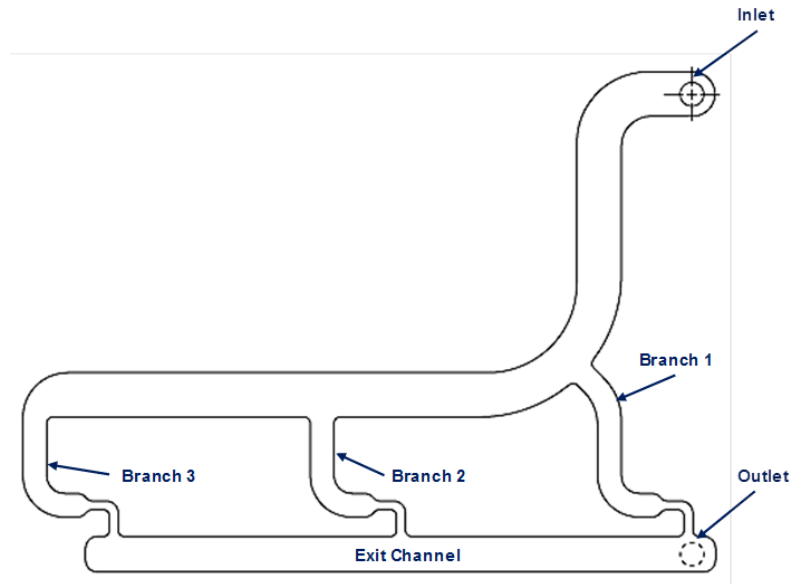


Fig. 2 Generic internal fuel passage geometry

### 2.1. Dynamic scaling

Appropriate dynamic scaling was performed to ensure the water used in this experiment produced representative Reynolds and Prandtl numbers. The range of fuel flow rates per fuel injector varies considerably within a flight envelope. Varying temperatures will also affect the fluid's density and viscosity and so Reynolds and Prandtl numbers as per equation 1:

$$Re = \frac{\rho u D_h}{\mu} ; Pr = \frac{C_p \mu}{k} \quad (1)$$

where  $\rho$ ,  $u$ ,  $\mu$ ,  $C_p$  and  $k$  are the fuel density, velocity, viscosity, specific heat and thermal conductivity.  $D_h$  is the passage hydraulic diameter defined by the ratio of 4 cross sectional areas to the wetted perimeter.

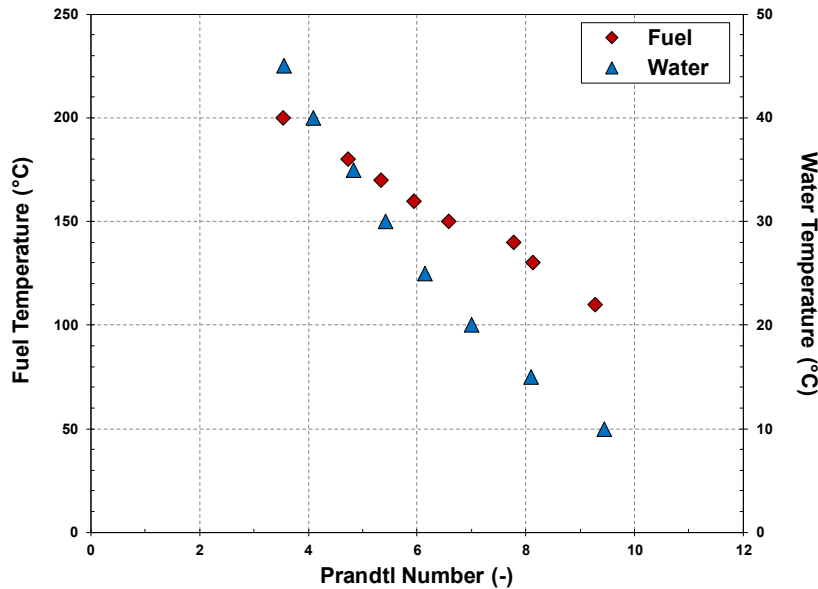
Data corresponding to cruise fuel consumption of a jet engine, Rolls-Royce Trent772-60, Airbus A330 (jet-engine.net 2014) was used to calculate typical mass flow rates of fuel in one of the branches. Exact fuel temperatures are not published however it is possible for temperatures to span between 100°C at high fuel flows and 180°C at lower fuel flows. Table 1 shows the properties of a typical Jet A-1 fuel used to calculate Reynolds and Prandtl numbers.

Temperature (C)	Density (kg/m <sup>3</sup> )	Kinematic Viscosity (cSt)	Specific Heat (J/kg.C)	Thermal Conductivity (W/m.C)
10	815.00	2.000	1.900	0.1171
30	800.00	1.375	2.000	0.1136
50	786.00	1.025	2.056	0.1101
70	772.00	0.800	2.170	0.1066
90	758.00	0.580	2.255	0.1030
110	743.60	0.530	2.342	0.0995
130	729.40	0.440	2.430	0.0960
140	722.30	0.410	2.475	0.0942
150	715.20	0.337	2.525	0.0925
160	708.10	0.297	2.560	0.0907
170	701.00	0.260	2.605	0.0889
180	693.90	0.224	2.650	0.0872
200	679.70	0.159	2.736	0.0837

**Table 1** Fuel properties\*

\* Values reproduced from published data (CRC Aviation Handbook Advisory Group 1983). Values in red were interpolated

Figure 3 was produced from the above data table and properties of water (Cengel 2003). It gives a comparison between Prandtl numbers of fuel at temperature to those of water at lab conditions. If fuel temperature is between 100°C and 200°C then its Pr may be matched to that of water by varying the temperature between 10 and 45°C.



**Fig. 3** Comparison between fuel & water Pr

## 2.2. Dye calibration and experimental set up

In this experiment dye concentration will be averaged through the thickness of the passage, allowing a back lighting to be used and the attenuated light signal to be calibrated against the dye concentration through which it has passed. A two-dimensional distribution of the fuel residence time in the passage will hence be produced. Several calibration tests were conducted, each through a range of 10 concentrations and it was found the dye concentration was linearly proportional to the log of the recorded light intensity. These calibration curves are shown in Figure 4, and performed on a pixel by pixel basis to eliminate any spatial non-uniformity in illumination or optical paths.

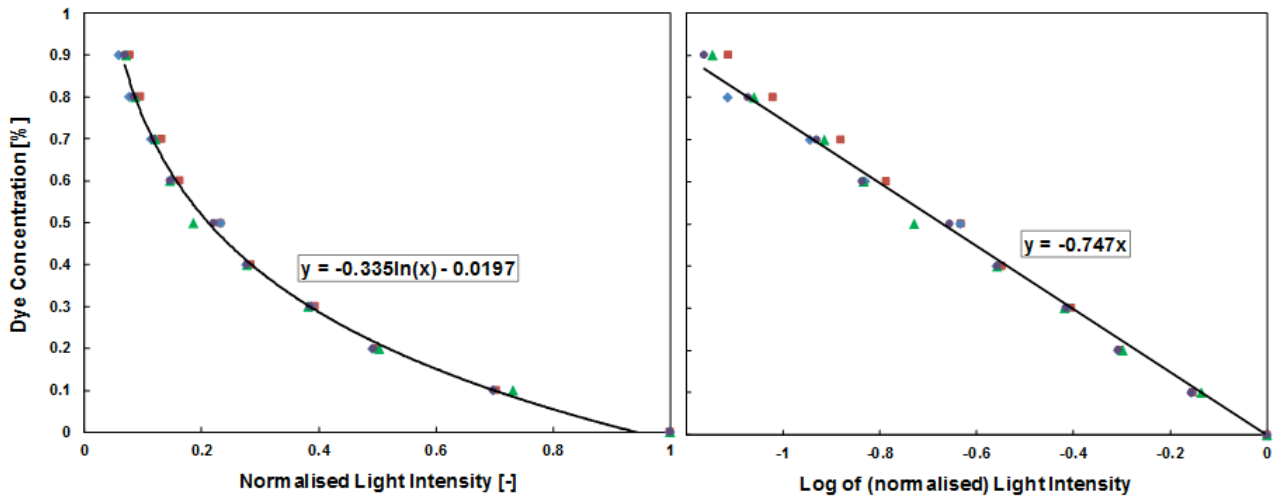


Fig. 4 Dye concentration calibration against light signal

A LaVision HSS-5 camera (1024x1024pixel) was used at a frame rate of 250Hz to capture the necessary dynamic range for the experiment. Again, at each pixel location the light signal response to a step dye wash out was recorded and an exponential decay curve fitted to this time history. It allowed for a delay time to be determined for the convection of the step to a particular location, then the rate of decay to also be determined, which could be significant in regions of recirculation.

### 2.3. Experimental set up for the heat transfer measurement

A number of modifications were required to the rig to perform the heat transfer analysis. The bottom Perspex plate was replaced by a heated aluminium plate, insulated on the test-cell side and coated with a Hallcrest SLN40/R30C1W liquid crystal slurry. This sandwich is shown in figure 5.

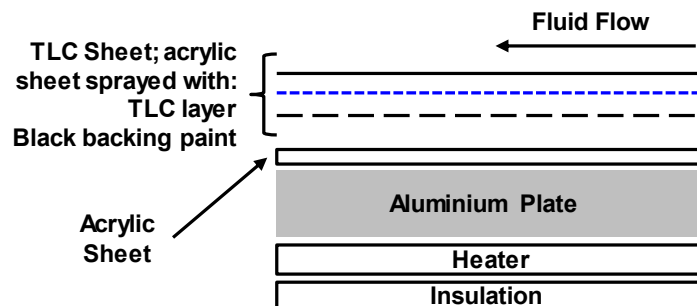


Fig. 5 Schematic of the heated surface

The aluminium plate was chosen for its high heat capacity allowing for uniform spreading of the temperature across the surface. The acrylic sheet of known thickness and thermal conductivity was used to create a uniform temperature drop to a measurable level captured by the liquid crystal sheet.

The peak reflected green light intensity from the liquid crystal is found to be 31.3°C, determined from submersion of a similarly prepared sample in a calibration water bath. An experiment can then be performed in which the heater power is varied slowly, changing the aluminium plate temperature. This allows the surface temperature to be known where the liquid crystal response is at a maximum and then a local HTC can be established for these points by balancing the surface heat transfer with the conductive heat transfer using equation 2:

$$\dot{q} = -k_f \left. \frac{\partial t}{\partial y} \right|_{y=0} = h (T_w - T_f) \quad (2)$$

where  $h$  is the convection heat transfer coefficient and  $k_f$  the thermal conductivity of the fluid.

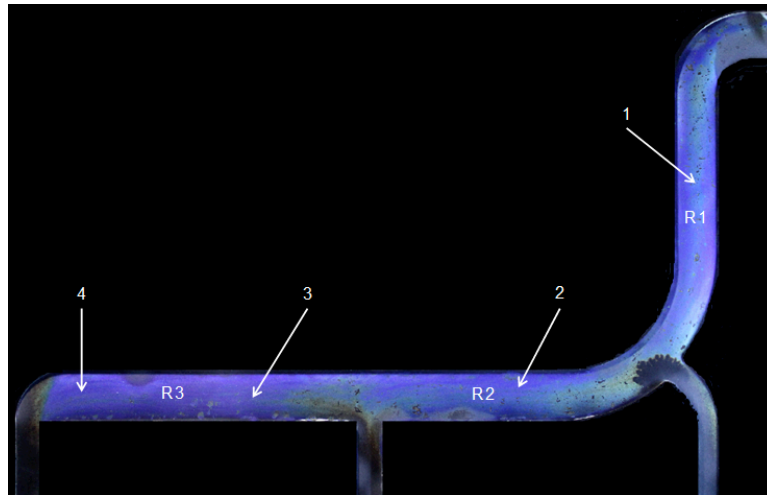


Fig. 6 Example image of the liquid crystal response

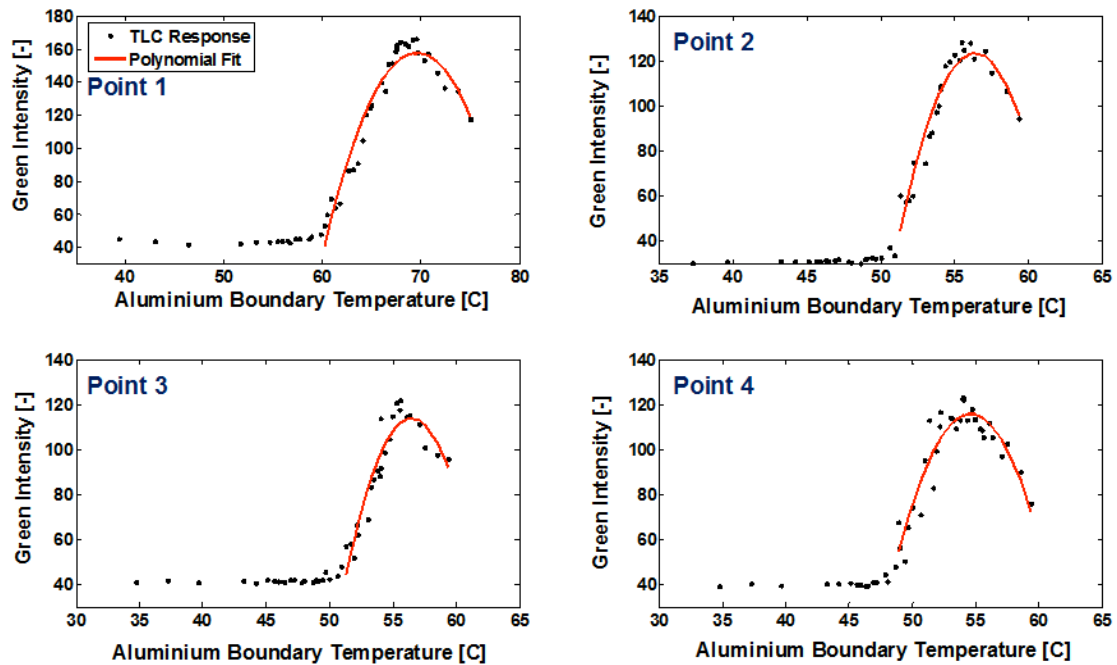


Fig. 7 Local green intensity response vs aluminium temperature

With a sweep in heater power, the surface HTC distribution can be built up, as shown in Figure 6. With the water and aluminium temperatures known at each heater power setting it is possible to determine the local heat transfer coefficient at points where the surface temperature is known through equation 3:

$$h(T_{water} - T_{TLC}) = \left(\frac{k}{x}\right)_{perspex} (T_{TLC} - T_{Al}) \quad (3)$$

assuming one-dimensional heat transfer, in which  $(k/x)$  is the acrylic sheet thermal conductivity per thickness, and  $h$  is the unknown HTC. The surface temperature is known to be 31.3°C at the peak green response locations. Details of this technique may be seen in the work of Zhong et al. (1999) for example.

### 3. Results

The dye wash-out technique proved to be a simple, easy and successful way to map out the residence time within the chosen geometry. This experiment highlighted areas within the geometry where fuel is likely to become trapped in a recirculation and thus leading to undesirable high residence times. The response can be split into a convection time: the time it takes for the step dye change at rig inlet to be noticed at any particular location in the test section, and then a half-life time: how quickly the concentration falls to half of its initial value. Conventionally for combustor flows residence time is the sum of these two quantities.

A reference time ( $t_{d-ref}$ ) was defined at inlet as the time it takes the light intensity to reach a certain threshold. Similarly  $t_d$  was defined for every other location within the geometry as shown in figure 8. The calibration curves were then used to convert intensity into dye concentration starting at  $t_d$ . The method used by Cheng & Spencer [6] whereby an exponential function is fitted to the experimental decay of tracer concentration was adopted in the current test in order to determine half-life time.

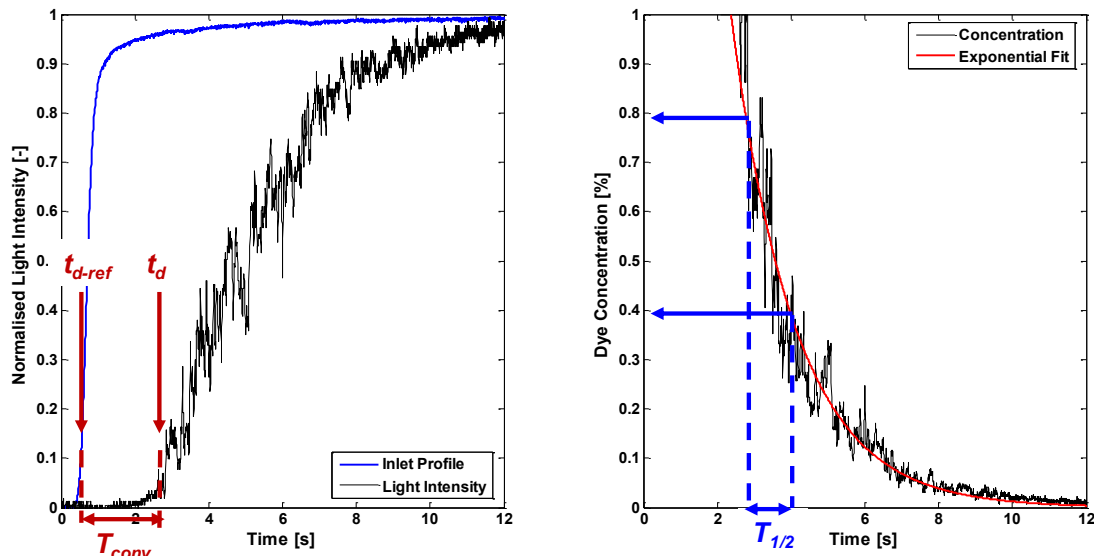


Fig. 8 Definition of convection & half-life times

The above calculations were repeated pixel by pixel for 3 test runs: test 1, 2 and 3 are at Reynolds numbers of 10200, 9750 and 5700 respectively to give the combined residence time map shown in figure 9. Tests 1 and 2 show a good level of repeatability. Because results have units of time, the values are not particularly sensitive to non-linearity in the dye concentration calibration for example. As the Re is reduced some increase in residence time is seen as may be expected. However 'Region 3' shows some discrepancy due to what appears transitional behaviour, originating from the separation point, opposite the second flow off-take branch. When the values are properly normalised by the channel mass flow rate it is seen that the nature of the recirculation in the upper part of region 3 has changed. The mixing of the recirculating fluid with that of the main flow stream is increased with Re.



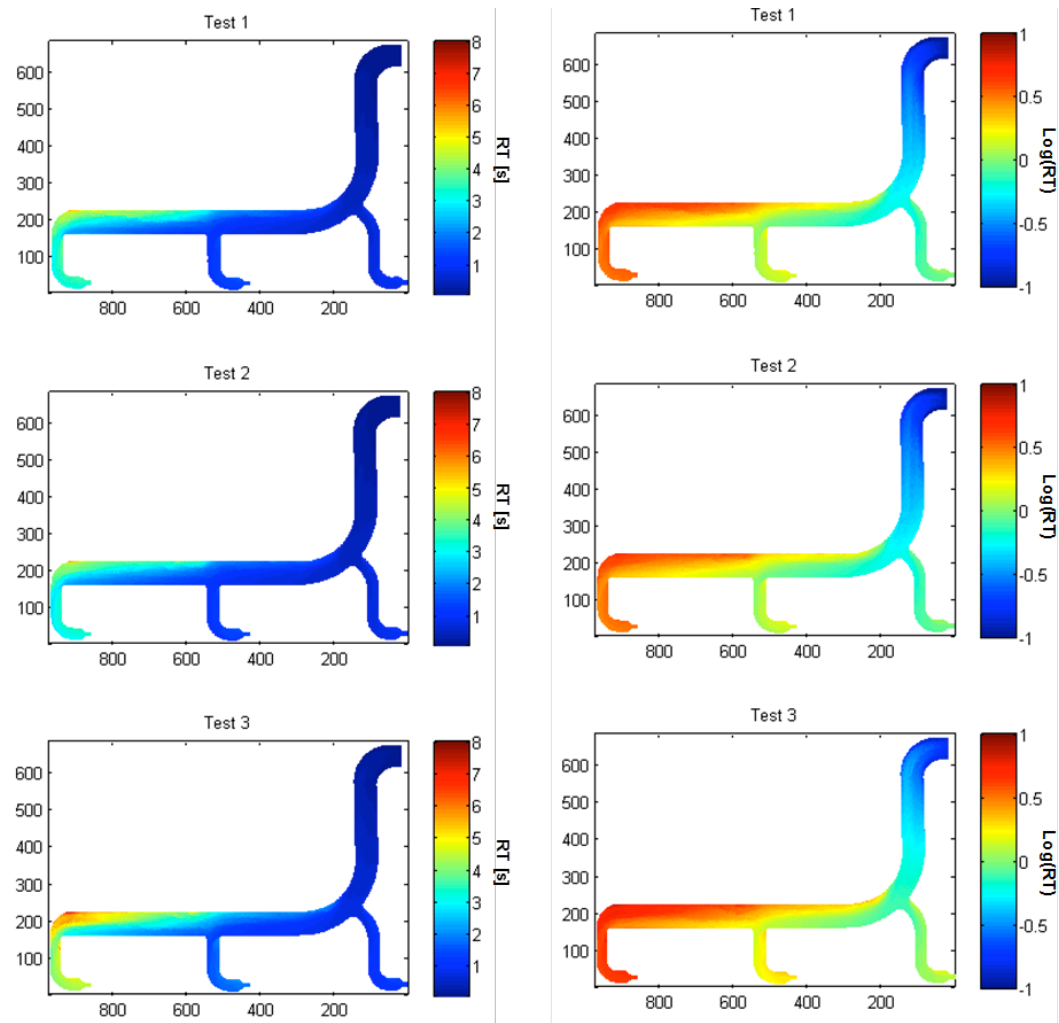


Fig. 9 Residence time distribution

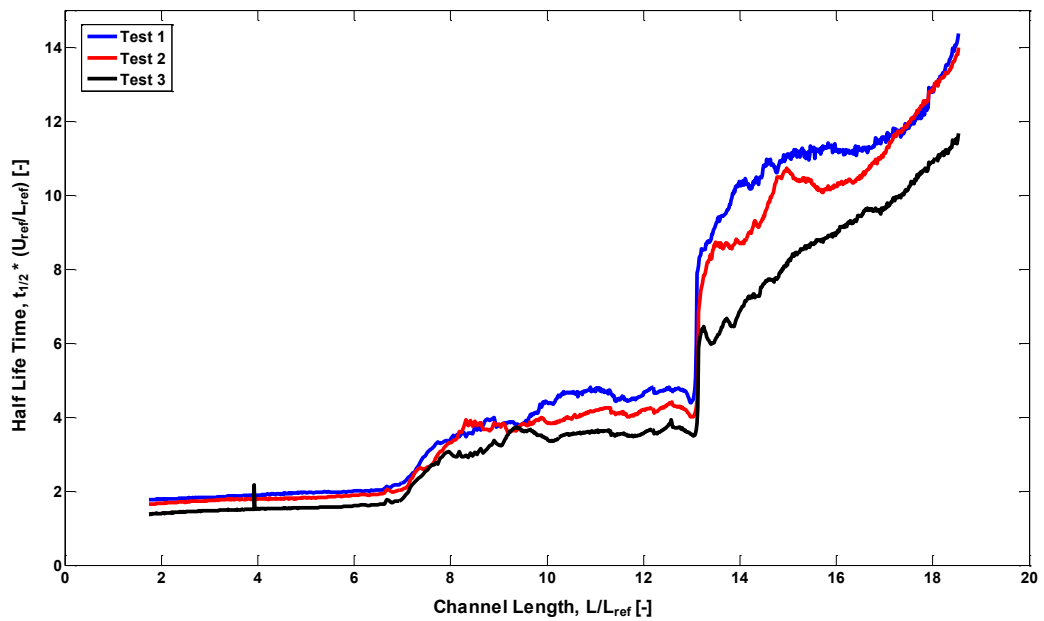


Fig. 10 Non-dimensional half-life times, averaged across channel width



The liquid crystal method proved more challenging due to the susceptibility of the crystals to fail under water. One set of measurements was gathered and showed that areas of high fuel residence time also correspond to low heat transfer coefficient. In these regions, small volumes of slow or stagnant fuel will be susceptible to soaking more heat increasing the risk of coke formation.

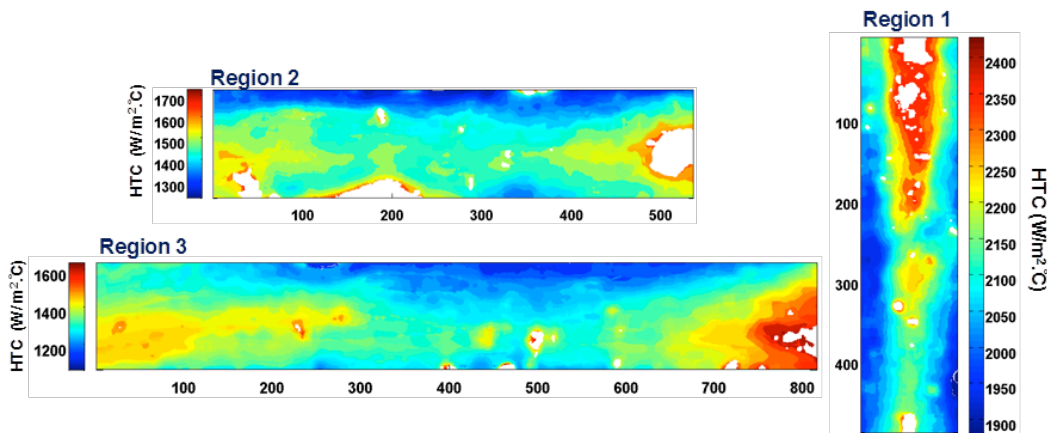


Fig. 11 Heat transfer distribution (refer to Fig. 6 for regions definition)

In general, regions of low fluid flow and velocity correspond to lower values of heat transfer coefficient. In other words, the fluids ability to cool the surface is lowered as the fluid goes from region 1 to 2 then 3. By analysing the results region by region however there is an apparent tendency for the fluid to be accelerated in the centre of the cavity and slowed near the walls leading to even lowered values of heat transfer coefficient. Areas near the top walls in region 2 and more so region 3 were also highlighted in the residence time experiment to be areas of high recirculation and high residence time. Although the current experiment was not completed to show a complete heat transfer map throughout the whole geometry and further testing was not possible the above results may be used as a qualitative measurement highlighting areas of reduced fuel thermal management capability and the importance of further experimentation.

#### 4. Conclusions

With new designs driving towards high temperatures and low fuel flows, the thermal management of fuel becomes a challenge even at normal operating conditions. The worst case scenario is found to be in those flight regimes where fuel flow is low and still used to cool aircraft oil which is still very hot. High temperature conditions are favorable for the formation of coke especially in areas of high residence time.

Residence time and heat transfer measurements were performed on a scaled geometry representative of fuel gallery of a typical lean burn fuel injector. Areas of high residence times were found to be in regions where fuel is trapped in a recirculation especially at low fuel flows. Those same areas also correspond to regions of low heat transfer coefficient as expected. The diagnostics developed here have indicated an area of concern for this particular flow geometry.

Dye wash out experiments proved to be a quick, easy and effective method for the measurement of residence time in complicated passages. With careful choice of dyes, an appropriate calibration and effective image processing this method could be applied over a range of applications. The current work on residence time would benefit from a classic LIF experiment in order to validate the results.

At the time of testing, TLCs were thought to be the best tool available to the measurement of heat transfer coefficient in a fluid environment. The challenges faced suggest that this method could either be improved by further investment in higher heating power in order to achieve the test faster or by scaling into air where liquid crystal is more robust. The first suggestion may provide more information quicker however the problem of liquid crystal layers delaminating under water remains a risk from test to test. The second option is also possible although scaling fuel properties at temperature (matching Prandtl number) to those of air in a lab environment may also prove challenging. Other methods such as infra-red imaging could be suitable for heat transfer work where water is the working fluid. The calibration of infra-red cameras is difficult to achieve however this method may provide quicker and more accurate results.

## References

- Cengel YA (2010) Heat Transfer, a Practical Approach (2nd Edition). McGraw-Hill, New York.
- Cheng L and Spencer A (2010) Residence Time Measurement of an Isothermal Combustor Flow Field. *Experiments in Fluids*, pp. 1-15.
- Chin JS, Lefebvre AH (1993) Influence of Flow Conditions on Deposits from Heated Hydrocarbon Fuels. *Journal of Engineering for Gas Turbines and Power*, vol. 115, pp. 433-437.
- CRC Aviation Handbook Advisory Group (1983) Handbook of Aviation Fuel Properties. Coordinating Research Council, Inc.
- Jet engine.net (accessed 25 May 2014) <http://www.jet-engine.net/civtfspec.html>
- Kakade VU, Thorpe SJ, Gerendas M (2012) Effusion Cooling Performance at Gas Turbine Combustor Representative Flow Conditions. *Proceedings of ASME Turbo Expo GT2012-68115*.
- Mayhew JE, Baughn JW, Byerley AR (2003) The Effect of Freestream Turbulence on Film Cooling Adiabatic Effectiveness. *International Journal of Heat and Fluid Flow*, vol. 24, no. 5, pp. 669-679.
- Meier U, Heinze J, Lange L, Hassa C, Rackwitz L, Doerr T (2012) Characterisation of the Combustion Performance of Low Emission Fuel Injectors with Laser Measurements. *CEAS Aeronaut J* 3:45-53, DOI 10.1007/s13272-012-0042-z.
- Spadaccini LJ, Sobel DR, Huang H (2001) Deposit Formation and Mitigation in Aircraft Fuels. *Journal of Engineering for Gas Turbines and Power*, vol. 123, pp. 741.
- Stickles RW, Dodds WJ, Koblish TR, Sager J, Clouser S (1993) Innovative High Temperature Aircraft Engine Fuel Nozzle Design. *Transaction of the ASME Journal of Gas Turbines and Power*, vol. 115, pp. 439-446.
- Thomson N (2012) Systems and Methods for Cooling a Staged Airblast Fuel Injector. Patent no EP 2 497 922 A2, European Patent Office.
- vab der Lans RP, Glarborg P, Dam-Johansen K, Larsen PS (1997) Residence Time Distribution in a Cold, Confined Swirl Flow: Implications for Chemical Engineering Combustion Modelling. *Chemical Engineering Science*, vol. 52, Iss. 16, pp. 2743-2756.
- Weitbrecht V (2004) Influence of Dead-Water Zones on the Dispersive Mass Transport in Rivers. PhD Thesis, Universitat Karlsruhe, Germany.
- Zhong S, Kittichaikan C, Hodson HP, Ireland PT (1999) Visualization of Turbulent Spots and Unsteady Wake-Induced Boundary-Layer Transition with Thermo-chromic Liquid Crystals. *Optics & Laser Technology*, vol. 31, no. 1, pp. 33-39.