Novel unsteady temperature/heat transfer instrumentation and measurements in the presence of combustor instabilities

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ABSTRACT

Lower NO\textsubscript{x} emission from gas turbine combustion systems can be achieved through reducing the equivalence ratio of the main reaction zone and/or increasing the burner pressure drop. This strategy however takes pressure drop and/or air away from the combustor cooling, thereby compromising the combustor life. In order to achieve an optimum design that is a good compromise between low emissions and long component life, accurate heat transfer prediction is essential.

It is well known that free stream turbulence can influence wall heat transfer characteristics. However the impact of combustion induced pressure dynamics, and the associated unsteady fluid dynamics, upon combustor wall heat transfer has not been adequately investigated.

This paper reports on combustion tests conducted at gas turbine operating conditions, where pressure dynamics have been controlled by altering combustor operating conditions and through the use of a siren placed in the upstream air flow. Combustor wall temperatures were measured using standard thermocouples and QinetiQ’s “True Surface Thermocouples” (TST). The latter, which were mounted on the hot gas surface of the wall, are capable of a fast response and are capable of indicating the temperature fluctuations experienced by the metal surface.

Fourier analysis of the TSTs showed no particular peaks associated with the pressure dynamics. This suggests that any coherence is damped within the boundary layer or by the thermal inertia of the metal. However temperature fluctuations of up to ca. 100°C were detected.

INTRODUCTION

The increasing global interest in reducing pollution has led to the establishment of legislative limits on gas turbine exhaust emissions. Guarantees of <25 ppmv NO\textsubscript{x} (@15% O\textsubscript{2}) emissions are now commonplace for land-based gas turbines operating with natural gas. Furthermore, there is an increasing trend towards yet lower emissions, for example, some US states are legislating <3ppmv NO\textsubscript{x} emission, which gives a design target of <2ppmv. Presently, such low emissions are commercially achieved with post gas turbine cleanup systems, with the associated increase in capital and operational cost. Such costs are proportionately large in the case of small industrial gas turbines and prohibit the degree to which low emission legislation can be set for such machines.

After initially controlling industrial gas turbine NO\textsubscript{x} levels by water or steam injection, advances in combustion technology have allowed the application of lean premixed technology for industrial engines (Dry Low Emissions, DLE). Currently, safety and practicality issues do not allow the application of DLE combustion technology to aero-engines. However, the steady tightening of aircraft emissions legislation has forced the engine manufacturers to run the combustion systems leaner to avoid the production of NO\textsubscript{x} at high temperatures.

Unfortunately, DLE gas turbine combustion systems have an increased tendency to suffer from combustion generated noise and acoustic phenomena – commonly known as ‘humming’. Combustion-driven oscillations cause substantial pressure fluctuations at discrete frequencies that, particularly with systems characterised by high power densities, may reach levels leading to mechanical failure of the combustion chamber, or of other engine/plant components. The engine manufacturers employ a number of approaches to control the problem, but these generally are only able to minimise the pressure fluctuations to avoid physical damage. Although modern aero-engine combustors are not DLE, the trend towards leaner combustion has resulted in the emergence of combustion-induced pressure oscillations. Combustion ‘rumble’ traditionally had only been an issue at idle conditions, but pressure fluctuations are becoming an issue at higher power levels for ‘low NO\textsubscript{x}’ aero-combustors.

Gas turbine ‘hot end’ component (combustor, nozzle guide vanes & turbine blades) lives are a very important factor when considering the Cost of Ownership of a gas turbine. Life and integrity are dependent on a number of factors:—
• material selection;
• material coatings;
• heat transfer;
• engine rating;
• engine usage – hours & cycles;
• combustion generated noise.

It is well known that heat transfer rates can be enhanced by increased turbulence levels and oscillating flow. The prediction of convective heat transfer rates to gas turbine combustor walls is difficult since the gasside boundary conditions are not generally well known. Measurements are difficult due to the relatively hostile conditions, so engine manufacturers rely on a mixture of experience, CFD predictions and rig test measurements (thermocouples & thermally-sensitive paint). The relatively recent emergence of combustion-induced pressure oscillations at higher engine powers has added more uncertainty to the calculation of combustor wall temperatures.

This paper describes combustion tests which were conducted at gas turbine operating conditions and focused on the impact of combustor pressure oscillations on wall heat transfer. The pressure dynamics were controlled by modifying the combustion generated noise through altering the operating conditions and through the use of a siren. Dynamic temperatures were measured using fast response thermocouples mounted on the hot gas surface of the combustor transition duct. The fast response temperature data were then used to deduce wall surface heat rates. The siren capability was developed at QinetiQ as part of earlier research, funded by the UK DTI, where flame transfer functions were measured.

The next section describes the combustion system that forms the focus of the present work. Subsequently the combustion rig and instrumentation are described. Sample results of pressure dynamics and the transient temperature measurements are presented and discussed.

THE DLE COMBUSTOR

The combustor used in the present work is the dual fuel dry low emissions (DLE) combustor of Siemens Industrial Turbomachinery (the company) [1-3]. The combustor is applied across the company’s range of small industrial gas turbines, from the SGT100 (Typhoon) at ca. 5MW to the SGT400 (Cyclone) at 13.4MW, and which has now accumulated >3 million hours of experience. In gas operation, the newest machines, the SGT300 (Tempest) and the SGT400, are offered commercially for certain markets at <10ppm NOₓ (@15% O₂).

In order to cover the power range from 5 to 13.4MW, rather than having a single combustor design and applying different numbers of combustors to each engine type, the combustors have been scaled, see Figure 1. The SGT100, SGT300 and SGT400 have 6 combustors per engine and the SGT200 (Tornado) has 8.

Figure 1 The DLE combustor family.

The combustor consists of three main sections (Figure 2):

i. the pilot burner, which houses the pilot fuel galleries and injectors for both gaseous and liquid fuel;
ii. the main burner, which houses the main air swirler and main gas and liquid fuel systems;
iii. the combustor, which includes a narrow inlet duct, called the prechamber.

The combustor is of a double skin construction and is cooled through impingement cooling. The cooling air is then exhausted into the combustor through dilution holes downstream of the main reaction zone. A transition duct, located downstream of the combustor, conditions the flow from the circular combustor exit to a sector of the turbine entry annulus.

Figure 2 The DLE combustor construction.
Reaction supported by internal and external recirculation zones

Main fuel
Pilot fuel
Combustion air
Combustion air

Figure 3 DLE combustor concept

Figure 3 shows a schematic of the combustion concept. The main combustion air enters through a single radial swirler at the head of the combustor. The flow then turns through a right angle into the prechamber followed by a sudden expansion into the combustion chamber. The swirl number is sufficiently high to induce a vortex breakdown reverse flow zone along the axis. This is termed the internal reverse flow zone. In the concept, this reverse flow zone remains attached to the back surface of the combustor, thereby establishing a firm aerodynamic base for flame stabilisation. In the wake of the sudden expansion, an external reverse flow zone is established. The flame is stabilised in the shear layers around the internal and external reverse flow zones.

The fuel, both gas and liquid, is introduced, in two stages: the main, which results in a high degree of premixedness and hence low NOx emissions, and the pilot, which is steadily increased as the load demand decreases in order to ensure flame stability. The pilot is arranged, such that as the pilot fuel split increases, the fuel is biased towards the axis of the combustor.

EXPERIMENTAL FACILITY

The Siemens Industrial Turbomachinery combustor was successfully installed on the QinetiQ High Pressure Combustor Rig. Figure 4 shows a general arrangement of the combustor mounted in a pressure casing with the inlet air being supplied via a radially-fed plenum chamber. A siren was installed in the inlet air duct to induce cyclic perturbations in the airflow into the combustor by modulating the projected flow area by approximately 30%. A radial inflow design was selected to minimise dynamic axial loads on the siren motor shaft. Experience with a siren used as a flow modulator shows that the siren can behave as a turbine and deliver electrical power to the drive circuitry causing damage. To prevent such damage in the present application, electronics were fitted to the controller to absorb any generated power. The siren assembly consisted of an electrically driven rotor that was situated immediately downstream of twelve equi-spaced holes. The edge of the rotor was shaped with twelve equi-spaced cutouts to produce ±15% area modulation.

Gaseous fuel (99.95% purity methane) was supplied from a gas trailer at an initial pressure of 200bar. Gas was passed through a coil immersed in hot water (363K max) to avoid ice formation on the pressure regulator and isolation valves. The pilot and main fuel was metered using separate Coriolis meters that were installed in series with two existing orifice plate flow meters. The pilot and main Coriolis meters were scaled 0-10 and 0-60 g/s.

INSTRUMENTATION

Dynamic pressure

Dynamic pressure transducers were fitted at four different places in the test set-up:

1. siren exit duct;
2. combustor inlet pressure casing volume;
3. pilot burner face inside the combustor;
4. at 2 dilution holes inside the combustor.

The signal from the pilot burner face was used as the primary on-line assessment of combustor ‘humming’ - the signal being connected to a loudspeaker in the rig test control room to provide a continuous on-line audible warning. The dynamic pressures from all tapping points were measured using piezo-electric pressure transducers (Piezotronics 102M206) connected to semi-infinite tubes consisting of 30 metre coils of 0.25 inch copper tubing. Figure 5
is a photograph of the tappings positioned over two of the combustor dilution holes.

**Figure 5 Combustor barrel**

**Temperature**

A plain un-cooled transition duct was run at the nominal design conditions with thermally sensitive paint at Siemens Industrial Turbomachinery. These results were used to decide the positions for 15 QinetiQ true surface thermocouples (TST) to be applied to the inner wall of the transition duct. An equal number of Type-K reference thermocouples were also fitted at similar positions, but to the outer wall. In addition 3 total gas temperatures thermocouples were installed close to the inner wall of the transition duct.

Prior to the duct being instrumented with the TSTs, laboratory trials were conducted to establish the best method of attachment to the relatively thin-walled transition duct. Various arrangements were tested on sample plates of the same material as the duct and checked for frequency response and robustness. The samples were thermally cycled to temperatures exceeding 1000°C.

The 1mm diameter ‘reference’ thermocouples were attached by spot-welding the sheath close to the grounded junction to the external surface of the transition duct. These were also tested by temperature cycling test pieces as with the TSTs. Figure 6 is a schematic showing the arrangement of a TST sensor and a ‘reference’ thermocouple on the transition duct inner and outer walls. Figure 7 shows a photograph of the instrumented transition duct immediately prior to installation in the rig.

**Figure 6 Schematic details of TST & 'Reference' thermocouples**

**Figure 7 Outboard view of instrumented transition duct**

Figure 8 is a photograph of the internal surface of the outboard transition duct wall – a close-up is included of two TSTs and one total gas thermocouple.
EXPERIMENTAL RESULTS

Siren performance

Large amounts of acoustic data were obtained from the dynamic pressure transducers over a number of combustor operating conditions and different siren frequencies.

Figure 9 is an example showing the sound pressure spectra from the siren and pilot burner face transducers at a siren frequency of 200 Hz. The siren spectrum indicates a remarkably pure siren tone with some 90% of the tone energy being contained in the fundamental.

Figure 10 is another example showing the siren generated frequency as well as activity at about 330Hz, which is generated by the combustion system itself. Since pilot and plenum spectra are not available without combustion, it is not possible to say whether the pilot sound pressures at the siren frequencies are due to siren driven combustion oscillations or due to plenum-pilot feed-through.

Temperature measurements

Initially air from the compressor was blown through the system and datum data were taken to check all the thermocouples for functionality and noise levels. Figure 11 gives typical TST and reference thermocouple temperatures against time recorded during this period. Notably the temperature levels are around 665 °C which corresponds well with the compressor delivery temperature, the electrical interference on the thermocouples is also notably low.
Figures 11 and 12 show some typical temperature traces from the outer wall reference thermocouples and the inner gas total thermocouples, after the combustor had been lit and reached a relatively stable conditions at 8bar and 671K inlet temperature.

Figures 14 and 15 show similar data at higher inlet conditions of 14 bar and 724K inlet temperature.

Figures 13 and 15 show some typical temperature traces from the outer wall reference thermocouples and the inner gas total thermocouples, after the combustor had been lit and reached a relatively stable conditions at 8bar and 671K inlet temperature.

Figures 12 and 13 show some typical temperature traces from the outer wall reference thermocouples and the inner gas total thermocouples, after the combustor had been lit and reached a relatively stable conditions at 8bar and 671K inlet temperature.

Inner wall TST temperatures show large temperature fluctuations in comparison to the outer reference wall temperatures. TST measurements indicate transient excursions of up to ca. 100°C (fig. 15) whereas on the outer wall there is almost no variation (fig. 14). Although the absolute levels of the outer ‘reference’ thermocouples looked reasonable, further inspection of the results and the instrumented duct post-test revealed that some had become detached from the duct. It is presumed this may have occurred as a result of thermal cycling during the commissioning. Hence the accuracy on some of the outer thermocouple temperature measurements is considered to be questionable. However the inner wall True Surface thermocouples did not suffer from this effect and measured accurate fluctuating temperatures. The outer wall temperature results presented in figures 12 and 14
are for thermocouples that had not become visibly detached.

The TST results presented in figures 13 and 15 indicate that the temperature probabilities do not exhibit a Gaussian behaviour, but have a tail towards higher values. This may be due to intermittent penetration of higher temperature hot gas into the boundary layer.

Figure 16 shows the form of the TST temperature fluctuations zoomed in. The biasing of the fluctuations to higher temperatures is evident here also. FFT analyses of the TST temperature data did not show any peaks associated with the applied siren frequency or the natural combustion generated peaks (see also fig. 21). This may be due to any coherence decaying within the boundary layer and/or to the thermal inertia of the wall itself.

Gas total temperature measurements (Figures 12 and 14) show only a small variation between the three thermocouples - these data have not been corrected for radiation effects.

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**Heat transfer rate**

Fluctuating heat transfer rates were evaluated using the inner surface temperature measurements alone. This is possible because the time period over which the temperature fluctuations occur would not allow the heat pulse to penetrate the duct wall thickness. Details of the method used are given by Ainsworth et. al. [4]. These calculated heat transfer rates are restricted to the surface. The heat transfer rates were computed using an unsteady semi-infinite and an impulse response method and these gave very similar results.

Figures 17-19 show typical heat transfer rate fluctuations for three different locations. Figure 20 shows the data zoomed in, giving more details of the fluctuations.

On further inspection the levels of heat transfer fluctuations are large (of order of $10^7$), however, similar levels of heat transfer rate fluctuations have been measured previously in a combustor at QinetiQ using a different type of sensor (thin film gauge) [5].
Figure 20 Heat rate fluctuations (expanded timescale)

Figure 21 gives the power spectral density of the computed heat transfer results. Unlike the pressure measurement spectra these data do not show peaks related to the siren frequency or the natural combustion generated sound. As stated earlier, this may be due to damping within the boundary layer or to the thermal inertia of the wall.

Figure 21 Spectra of heat rate measurements

These data are being further analysed in conjunction with fluid dynamic analysis and transient thermal analysis of the combustor wall to develop models for the fluctuating heat transfer. It may be necessary to compensate the TST data for thermal inertia, in order to get a true representation of the heat transfer coefficient. Although the TSTs are arranged such that they should give a good representation of the temperature fluctuations in the metal surface, the deduced near wall gas properties may be in error due to thermal inertia effects.

Clearly the temperature fluctuations will have an effect on the combustor material, and hence may impact component life. For example, the large temperature fluctuations measured may not have a discernible impact on crack initiation, but may accelerate crack propagation once a crack has formed. Additionally the temperature fluctuations and the resultant fluctuations in thermal stresses induced close to the surface may influence material aging properties.

CONCLUSIONS

The Siemens Industrial Turbomachinery combustor was successfully installed on the QinetiQ High Pressure Combustor Rig with specialist temperature sensors on the transition duct. The combustor was run over a range of conditions on methane fuel whilst monitoring the temperature and acoustic sensors.

The siren operated successfully with inlet air conditions up to 14 bar and 673K. The siren tone could be detected on the pressure dynamics transducers within the combustor, where an amplitude of the order of the natural combustion generated sound was detected.

The method of attachment for the TST thermocouples on the hot-side wall of the transition duct proved to be successful. The majority of these TST sensors were still operating properly at the end of the trial.

Calculations from the TST data showed that the heat rates to the inner hot-side wall of the transition duct were in the order of $10^7$ W/m².

The high frequency traces of temperature from the TSTs show that the fluctuations are biased to higher temperatures.

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REFERENCES