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UNSTEADY PRESSURE MEASUREMENT IN A HIGH TEMPERATURE ENVIRONMENT USING WATER COOLED FAST RESPONSE PRESSURE TRANSDUCERS

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ABSTRACT

Measurement of unsteady pressure is a requirement in many proposed aero-engine active control systems. In the high temperature environment associated with the engine, thermally unprotected transducers may not measure accurately or even survive. This paper reports an examination of two water cooled, commercially available unsteady pressure transducers, which assesses the ability of the transducer to accurately measure unsteady pressure when mounted in a water cooling adapter and the effectiveness of the thermal protection at high temperatures.

Mounting the transducer in a cooling adapter was shown to have no adverse effect upon its ability to measure dynamic pressure. Deliberately recessing the adapter back from the flow provided the most stable and predictable output at all flow conditions tested. Thermal protection allowed the transducer to survive at flow temperatures of up to 500°C with a potential to survive at higher temperatures. No reduction in performance is shown at elevated temperatures relative to performance at ambient conditions.

INTRODUCTION

Unsteady pressure has been measured successfully at relatively low temperatures since the late 1940's using the strain gauge principle and since the early 1960's using the piezoelectric principle; both principles use internal sensing elements that are inherently highly temperature sensitive. At elevated temperature the measurement accuracy degrades and at temperatures typical of those associated with the gas turbine environment (500-1200°C), the integrity of the transducer is at risk.

Existing, reliably proven, high temperature strain gauge and piezoelectric technology indicate that operating temperatures are limited to 275°C (Kulite) and 350°C (Kistler) respectively. Despite advances in materials technology to reduce the temperature sensitivity of the transducer, the operating limit of the transducers remain at this low level due to other, as yet unresolved, design constraints in the transducer structure (Allocca and Stuart, 1984).

Thermally protecting the transducer and/or mounting the transducer remote from the environment are two approaches that have shown promise. However, mounting the transducer remote of the environment is often impractical and has yet to produce wholly accurate measurement of unsteady pressure.

Ashby (1988) used a piezoelectric transducer mounted in a Pitot probe to measure total pressure in temperatures of 260°C, and Lagen et al (1991) mounted static pressure tappings in the side of a probe connected to transducers by a lead out tube and reported survival in environments up to 1370°C: both studies used water to provide thermal protection. Ashby (1992) also patented a water cooled pressure measuring system that measured total pressure using a probe inserted into the flow with a transducer and cooling system mounted entirely remote from the flow.

Larguier (1985) presented a scheme where a miniature transducer was mounted flush on the side of the wall of a water cooled probe. The measurement accuracy of dynamic pressure is good because of the flush mount, but the integrity of the diaphragm, exposed to the flow, is in doubt. However, a similar configuration is presented by Moore (1977) reporting survival at 977°C.

From a critical review of the open literature, three

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specific strategies for measurement of unsteady pressures in high temperature environments are identified. These are the development of very high temperature transducers, the remote mounting of the transducer and the provision of thermal protection. The following conclusions can be drawn: (i) the development of reliable high temperature pressure sensing devices has yet to be achieved, (ii) the validity of remotely locating the transducer has yet to be proven, and (iii) thermal protection is the basis of the majority of successful solutions to the problem.

Suppliers of transducers were canvassed and two were identified as providing water cooling. Objectives of the examination reported in this paper were to understand the effect of assembling a transducer in a cooling adapter on the ability to accurately measure unsteady pressure, to evaluate the effect of a high temperature environment on the measurement of unsteady pressure using such an assembly, and finally, to identify the implications of recessed and protruded installation.

EXPERIMENTAL APPARATUS

Isothermal Facility

The apparatus consisted of a pipe three metres in length and 100mm in diameter with a plenum chamber at the inlet, see Figure (1). Between the plenum chamber and the pipe was a pressure pulse generator consisting of a D.C. motor connected to a circular disc with four slots in it. This disc rotated in front of an identical fixed disc and flow through these generated an oscillatory pressure waveform in the flow downstream of the plenum. The frequency of the oscillatory wave generated was changed by adjusting the speed of the motor.

Downstream of the pulse generator were two instrument installations located at the same distance along the pipe but mounted directly opposite each other. One installation was for a reference transducer mounted flush with the inside wall of the pipe. The other was a threaded hole suitable for the screw threads on both of the transducer cooling adapters. This apparatus was also used to assess the implications that recessed and protruded installation had for measurement accuracy.

The capacity of the apparatus was as follows; maximum mass flow rate 1.13 kg/sec, mean velocity 41m/sec, maximum plenum pressure 138.1 kPa, frequency of pressure pulse in the range 0 to 200 Hz and temperature 19-23°C.

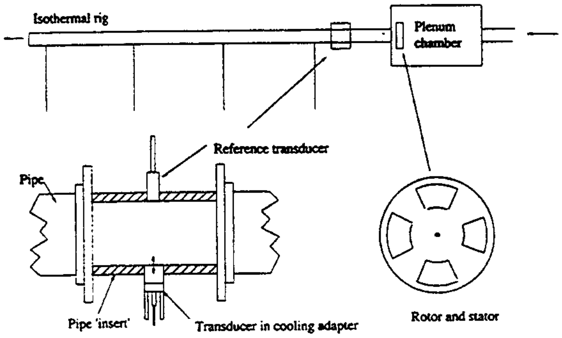

Figure 1 - Schematic showing the isothermal facility

Heat-Transfer Facility

Air from a compressed air source passed through an in-line combustor and subsequently along the working length of pipe before exiting to atmosphere, see Figure (2). A 'paddle-wheel' (90% of pipe diameter) rotated inside of the pipe downstream of the heater producing a pressure pulse in the flow. To reduce the 'background' unsteadiness in the flow caused by the combustor, this generator was situated ten diameters downstream of the combustor exit. Three instrument locations were a further 100mm (~ 1 dia.) downstream of the generator: one was for a thermocouple to measure the temperature of the flow, one had a threaded hole suitable for the screw threads of both of the cooling adapters and the other (directly opposite) was designed to suit a reference transducer detailed below.

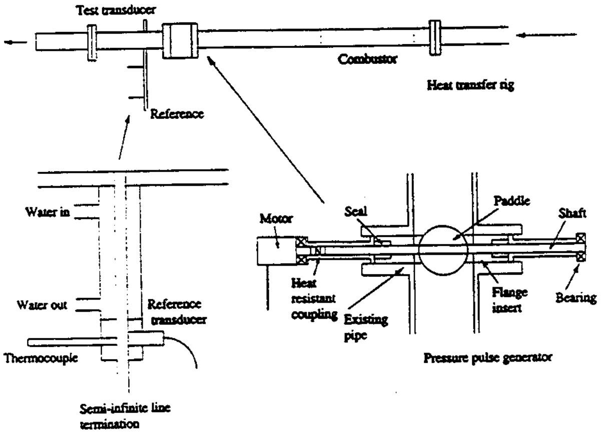

Figure 2 - Schematic showing the heat transfer facility

The reference transducer for this study used a semi-infinite line probe configuration. The short section of tube between the flow and the reference transducer was water cooled to prevent overheating of this remote transducer. The inside diameter of the tube was 3mm, equivalent to that of the reference transducer diaphragm. The termination tube (downstream of the transducer location) was 27m of plastic tubing with 3mm inside diameter. These tube dimensions were based upon recommendations made by Wilhelm (1988). The rig capacity was as follows; maximum mass flow rate 1.5 kg/sec, maximum pressure 317.2 kPa g, and flow temperatures in the range of ambient to 600°C

Data Collection

Pressure measured by the transducers was saved to disk on a P.C. via an Analogue to Digital Converter (ADC) which itself sequentially digitised the amplified transducer output voltage and held it in a Sample and Hold (S/H) device. The sample and hold device held 300 readings, taking one sample every time an optical switch on the rotor of the pulse generator was triggered. Voltage protection was provided between the sample and hold device and the ADC.

The analogue voltage from the Kulite XTE-190 piezoresistive pressure transducer was amplified by the data acquisition system. The Kistler 6121A piezoelectric pressure transducer signal was amplified by an additional Endevco 2375 Charge Amplifier.

EXPERIMENTS

At each installation condition (between 1.25mm protruded and 3.75mm recessed), pressures were measured at two pressure pulse frequencies and at two mass flow rates. The adapter installed flush with the pipe provided an indication of the inherent misalignment, between pipe inner surface and transducer, of mounting the transducer in a cooling adapter; the other tests showed if further 'engineered' misalignment of the adapter installation compounded any error.

Initial measurements using both transducer/adapter assemblies showed a consistently higher indicated pressure than that measured by a flush mounted Kulite XCQ-093 reference transducer. Whilst this phenomena had been observed in previous studies, see Gaudet (1978) and Wittler and Frizell (1990), a mechanism responsible for this effect could not be identified. As a consequence, an additional series of experiments were conducted using the isothermal facility to assess the validity of the reference transducer used, and the effect of the circumferential position of the instrumentation in the pipe.

Part of the experimental program from the isothermal facility was repeated on the heat-transfer facility at progressively increasing temperatures. Flow temperatures of 20°C (Ambient), 350°C, 400°C and 500°C were generated. It was evident from the isothermal experiments that trends found at one mass flow rate and one frequency of pressure pulse, and at the extreme recessed and protruded condition could be applied to all flow characteristics and further, interpolated for all misalignment conditions.

Additional tests were conducted to measure the temperature of the diaphragm of the piezoresistive transducer (Kulite) in high temperature operation. This was achieved by exciting the transducer bridge circuit with a constant voltage as reported by Cherrett and Bryce (1993).

RESULTS

Measurements were analysed to examine specific characteristics of the transducer output. These were (i) to assess the extent to which the output waveform 'followed' the reference waveform (shape and amplitude), (ii) the effect of protruding and recessing the cooling adapter, and (iii) the effect of flow temperature on the above.

Transducer outputs were simultaneously measured over 225ms. For a better comparison of the indicated dynamic pressure waveform, the AC component from test and reference transducers were normalised by the time average indicated pressure measured by each transducer, and then superimposed onto each other by equating the two time averages. This clearly highlighted any differences in measurement. Any difference in amplitude between the two waveforms was indicated by the RMS values for the positive and negative parts of the dynamic waveform, calculated relative to the time average value derived from the whole sampling period.

Figure (3) shows waveforms measured by two identical Kulite XTE-190 transducers: one transducer was mounted flush with the wall of the pipe of the isothermal facility, and the other was mounted in it's cooling adapter.

It can be seen that no significant or consistent amplification of the indicated pressure is measured. (Whilst this finding is not consistent with previous work by other researchers referenced above, no mechanism for *increasing* the amplitude of the measured signal has been previously presented.)

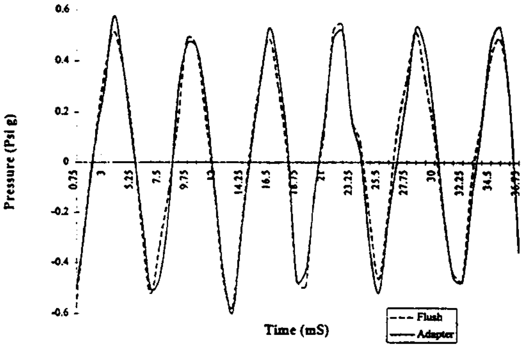

Figure 3 - Kulite XTE-190 in cooling adapter and Kulite XTE-190 mounted flush with wall of pipe

The Helmholtz resonant frequency of the Kulite XTE-190 transducer and adapter was calculated to be between 4 and 6 kHz over the transducers operating temperature range exceeding the frequency generated in either facility for this investigation. It is believed that the minor inconsistencies between the two waveforms are caused by calibration errors due to linearisation and averaging. (It is estimated that the calibration error could be +/-5% at worst case.)

Significantly, the amplitude of signal indicated in Figure (3) is similar to those measured using the transducer/adapter assemblies initially referenced against the Kulite XCQ-093 transducer; this similarity raises doubt concerning the validity of the initial reference transducer. The matching of measured amplitude was subsequently shown to be independent of which Kulite XTE-190 transducer was under test and relative circumferential position. In addition there is no measurable phase shift between the two measurements shown in figure (3).

The reference transducer for the Heat-Transfer facility was mounted remote from the hot air in the pipe in an semi-infinite line configuration. Using such a configuration the amplitude of the signal is attenuated due to friction in the tapping pipe, and the signal experiences a phase shift due to viscous forces in the tapping pipe. Compensation for amplitude is possible, see Bergh and Tidjeman (1965), and the relative level of attenuation of this particular configuration was calculated and a correction applied to the reference transducer signal before analysis began.

The phase shift between the Kulite XTE-190 transducer on test and the reference transducer measurements due to remote mounting the reference transducer can be seen from Figure (4).

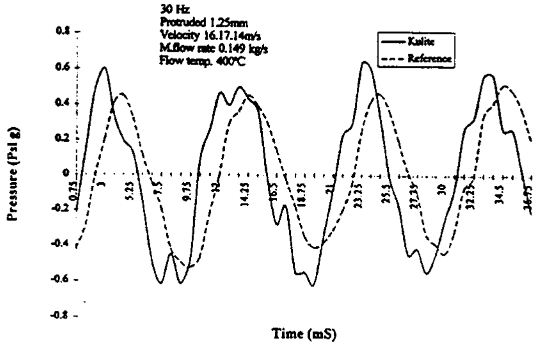

Figure 4 - Example of Kulite XTE-190 and reference transducer waveforms

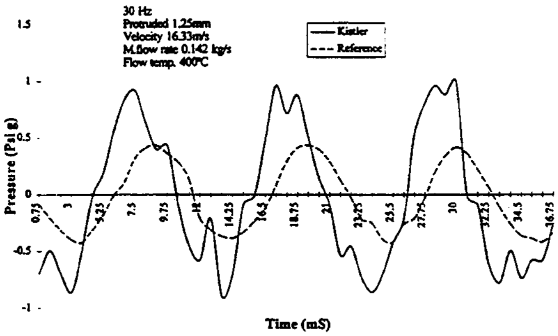

Figure 5 - Example of Kistler 6121A and reference transducer waveforms

From discussions above the amplification of the test signal indicated in this figure is not believed to be physical, but due to the questionable validity of the reference transducer used. Figure (5) shows a similar result but for the Kistler 6121A transducer. Given the discussion above no other inconsistencies between the two waveforms may be conclusively identified.

Figure (6) shows the effect of Kulite XTE-190 transducer/adapter assembly installation on the measurement of a pressure waveform for two values of frequency and mass flow rate.

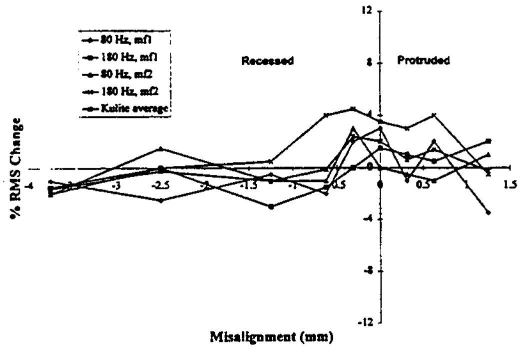

Figure 6 - Percentage change in amplitude from reference due to misalignment of installation (Kulite XTE-190)

Measurements stability improves and appears less effected by either frequency change or mass flow rate variations when the assembly is recessed back from the 'flush' position. This result is in agreement with the findings of Hanly (1975). The most stable position is at full recess available, where the deviation due to changes in frequency of pressure pulse and rate of mass flow is only 2% of the measured value. Protruding the assembly into the flow is shown to decrease measurement stability.

This study was repeated using the Kistler 6121A transducer and the results, whilst showing a similar trend, were far more erratic. A possible explanation for this feature is found in figure (7).

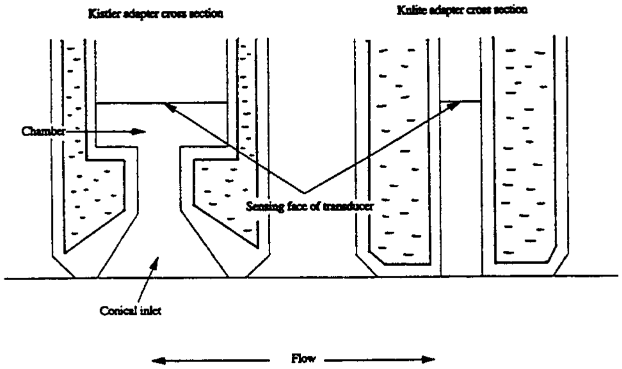

Figure 7 - Differing cooling adapter designs

The Kulite cooling adapter has a straight cylindrical recess between transducer diaphragm and the flow, whereas the Kistler adapter has a conical inlet, a small diameter cylindrical section, which opens to a larger diameter chamber at the sensing face of the transducer. Such a conical inlet has been shown to effect the measurement of pressure (Benedict, 1984), and a chamber at the face of the transducer has also been shown to contribute to measurement error.(Bergh and Tijdeman, 1965)

At all the misalignment conditions, differing mass flow rates and frequencies of pressure pulse examined, measurements showed no delay or phase shift. However, greater contamination of the waveform is anticipated if the frequency of pressure pulsation were higher.

The Kulite transducer was shielded from ambient cooling air to reduce any 'natural' cooling effect and the flow temperature was incrementally increased. Figure (8) shows transducer temperature resulting from each incremental rise in flow temperature; the lower measurements are the initial temperatures of the back (transducer) and the front (diaphragm) of the transducer at the time when the temperature of the flow stabilised, the higher are the transducer temperatures after five minutes at constant flow temperature when the indicated front and back transducer temperatures reached thermal equilibrium.

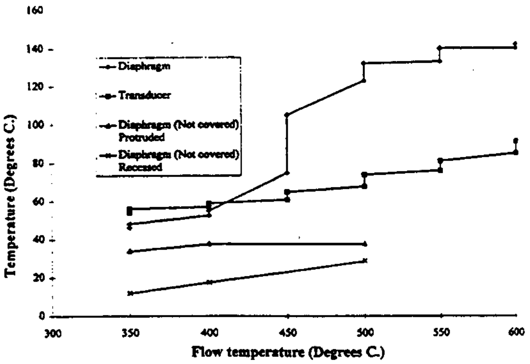

Figure 8 - Temperature of the front and back of a Kulite XTE-190 transducer at elevated flow temperatures

The temperature of the diaphragm is shown to remain relatively constant at 40 to 50°C at flow temperatures between 350 and 400°C, then to rise sharply to 120°C before levelling off again at approximately 140°C at flow temperatures between 500 and 600°C. The temperature of the back of the transducer rises steadily from 55 to 90°C as the flow temperature increases from 350 to 600°C, and remains below that of the diaphragm temperature as the flow temperature rises above about 410°C. During these incremental increases in flow temperature no significant increase in temperature with time is shown.

By way of comparison, the temperature of the diaphragm of the Kulite transducer at full recess and full protruded conditions, is also shown with the transducer exposed to ambient air and as a consequence experiencing any 'background' cooling. The diaphragm temperature remains relatively constant for flow temperatures increasing to 500°C.

At the extreme misalignment conditions no effect upon the indicated waveform from either transducer was identified confirming measurements obtained on the isothermal facility. Increasing flow temperature had no additional effect upon the shape of the waveforms for either transducer.

CONCLUSIONS

The conclusions from the experiments conducted on unsteady pressure transducers mounted in cooling adapters are as follows :

- The Kulite transducer has a more stable response than the Kistler transducer over the entire range of misalignment conditions, rates of mass flow and frequency of pressure pulse when mounted in a cooling adapter.
- The least deviation from the pressure indicated by the flush mounted reference transducer, due to changes in rate of mass flow and frequency of pressure pulse, has been shown to be when the transducer/cooling adapter assembly is deliberately recessed back from the flow. Deviation measured using the Kulite transducer is much less than that measured by the Kistler transducer.
- Both transducers show no consistent contamination of the output in the form of amplification, attenuation or delay of the waveform, relative to the flush mounted reference.
- An increase in flow temperature up to 500°C has been shown to have no marked effect upon the performance of both the water cooled transducers.
- Effective thermal protection of both the water cooled transducers has been proven for flow temperatures up to 500°C. The measured temperature of the Kulite transducer diaphragm at 500°C strongly suggests the potential for survival at very much higher flow temperatures.

The work reported in this paper has confirmed the use of water cooling of standard transducers as a solution to the problem of obtaining an accurate measure of unsteady pressure in a high temperature environment. The use of water cooled, standard unsteady pressure transducers on test bed engines for the development of future active control system technology has been justified.

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