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Effects of Thermal Shock Protection Methods on Pressure Measurements in a Rapid Compression Machine

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ABSTRACT

The study investigates the impact of thermal shock protection methods on pressure measurements in Rapid Compression Machines (RCMs). It focuses on the performance of various pressure transducers, specifically 601A, 701A, 6061B, and 7005, under atmospheric initial conditions. The research emphasizes the importance of mounting techniques and coatings, revealing their significant effects on pressure trace accuracy. Special mounting adaptors for the pressure transducers were designed and manufactured, this enabled simultaneous measurements for all transducers to be made in a single compression stroke. Instantaneous pressure within combustion chamber was measured when air was compressed in RCM from initial pressure and temperatures of 0.1 MPa and 293K respectively, compression ratio was fixed at 13.58. Pressure traces revealed that all pressure values measured using the selected transducers were affected by thermal shock effect, this led into significant deduced end of compression temperature error of up to 8.7 K. Different temperature protection measures were tested and their effectiveness in reducing thermal shock effect was studied. A combination of recessed mounting and silicon coating provided the best thermal shock protection for the pressure transducers tested in this work. The insights gained from this study are crucial for optimizing accuracy of pressure measurements and interpretation in combustion testing rigs.

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INTRODUCTION

Rapid Compression Machine (RCM) is, essentially, a piston inside a cylinder which mimics a single piston internal combustion engine. It compresses a mixture of liquid fuel and air rapidly to ensure adiabatic compression without losing mixture temperature and pressure. The machines are essentially used to study the autoignition properties of liquid fuels by measuring ignition delay times. The compressed mixture of air and fuel is left in the combustion chamber and the time it takes to auto ignite is measured. Details of such machines are found elsewhere in (Afleck *et al*., 1968; Carlier *et al*., 1991; Griffiths *et al*., 1992; Mittal, 2007)

The measurements of ignition delay times for fuels in RCM are reported for a given end of compression temperature. However, due to the fast transient nature of the compression process, direct temperature measurement of fuel-air mixture is not possible and instead pressure measurements are used to derive the temperature in the combustion chamber using the common method of adiabatic core hypothesis (Mittal *et al.*, 2007; Goldsborough *et. al*, 2017). Therefore, accurate measurement of pressure in the RCM cannot be over-emphasised.

Measurements of pressure histories during and after compression for the RCM usually use dynamic pressure transducers, their preference comes from high frequency response, accuracy, durability and repeatability. The Leeds RCM, which this work is based upon, uses a piezoelectric dynamic pressure transducer, this type of transducer uses special piezoelectric crystals which generate charge when force is applied, the charge obtained is then amplified and converted into voltage using a charge amplifier. The crystals are properly packed in the stainless-steel housing and use a thin stretched diaphragm as its sensing face.

In a steady thermal condition, the sensitivity to thermal change of these transducers is less than 0.0001%/K as shown in table 1, but when exposed to very high rates of temperature change the accuracy is highly degraded. The sudden change of temperature imposes thermal stresses on the transducer diaphragm and its housing, and in response it results in momentary deformation/expansion which eventually lessens the preload force on the crystals, causing a negative signal output and hence gives an erroneous pressure signal (Krause *et al.*, 2021).

Previous experiments from RCMs by (Mittal *et al.*, 2013) have shown that a thermal shock error of 0.34 MPa was experienced at the end of compression when nitrogen was compressed. This is about an 12.5% reduction in pressure from when the transducer was protected from thermal shock. This pressure drop is equivalent to 27 K drop from derived mixture temperature using adiabatic core hypothesis. In ignition delay times scales, the 27K error in end of compression temperature is a substantial value. If this temperature error is assumed to be constant throughout the temperature range, ignition delay time measurements reported by (Materego *et al.*, 2023) would shift from a solid line to a new dashed line as shown in Figure 1.

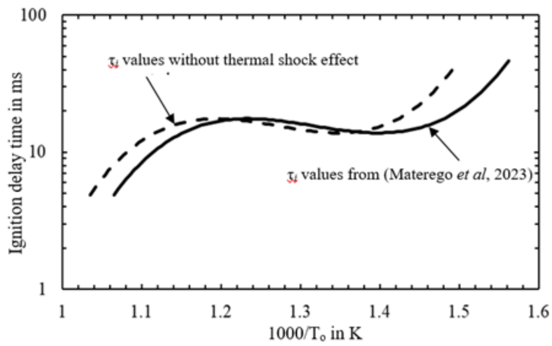

Figure 1: Effect of pressure error due to thermal shock on ignition delay times (τi) curves.

Similar effects have been reported in engines (Davis *et al*, 2022; Lee *et al*, 2005; Randolph, 2010; Rosseel *et al*, 1999) and combustion bombs (Dibbern *et al*., 2009). Most of the published studies conducted in combustion rigs such as Rapid Compression Machines have not reported on how they have handled thermal shock effect; it can be assumed that some have not considered this effect at all. This would potentially be one of the reasons for some discrepancies in the reported ignition delay times of same fuels tested at same conditions in different RCM rigs such as that reported in (Bradley *et al*., 2015).

Several methods have been suggested to protect pressure sensors against this thermal shock from both manufacturers (PCB piezotronic, 2015) and researchers (Soltis *et al.*, 2005; Gejji *et al.*, 2018; Krause *et al.*, 2021; Shi *et al.*, 2023). These methods can be mainly classified into two main groups which are mounting positions and sensor surface coatings. Pressure transducers mounting position can either be flush with the combustion chamber surface or recessed leaving a passage in front of the diaphragm. Recess mounting helps to physically isolates the sensitive sensor diaphragm from direct exposure to extreme temperature fluctuations. By placing the transducer slightly recessed within a cavity or housing, the thermal gradients are dampened, reducing the effect of rapid temperature changes on the sensor. Surface coatings methods include application of silicone grease (Shi *et al.*, 2023), room temperature vulcanizing (RTV) silicon rubber, vinyl tape and metallic foils (Krause *et al.*, 2021), these coatings either act as high temperature resistance flexible seal or thermal insulator which eventually dampen rapid temperature fluctuations and prevent damage to sensitive piezoelectric elements. Combination of recess mounting and silicon filling in a recess volume is also another technique that can be used to try to reduce the effects of thermal shock in pressure measurements (PCB piezotronic, 2015; Davis *et al.*, 2022).

Very little work/research has been done in RCMs not only to evaluate the effects of thermal shock on pressure measurements but also to assess the effectiveness of proposed thermal protection methods proposed by manufacturers and researchers. This work therefore is aiming at conducting experiments to quantify the amount of thermal shock errors in pressure measurements and measure effectiveness of different thermal shock protections on pressure measurements...

MATERIAL AND METHODS

Study approach

The study was based on first measuring the quantity of thermal shock in pressure measurements in RCM. This was then followed by evaluating different thermal shock protection measures which are suggested by pressure transducers manufacturers and evaluate their effectiveness. The protection techniques used in this work were grouped in two categories; surface coating a flush mounted transducers and recess mounting with and without silicon filling. Each pressure transducer was tested for these different protection techniques and effects on measurements were recorded.

Experimental set up

Experiments were conducted in RCM by compressing air from atmospheric initial conditions of 0.1 MPa pressure and temperature of 293K, with compression ratio fixed at 13.58. For these conditions, temperature gradients of up to 110 K/ms were achieved during compression. This temperature gradient is enough to give a thermal shock effect to the pressure transducers. Six different common techniques for thermal shock protection were tested at these conditions. These are; application of vinyl tape on flush mounted transducer, application of 1mm coating of Loctite 5399 room temperature vulcanizing (RTV) rubber on flush mounted transducer, recess mounting transducer without any filling, recess mounting transducer with silicon grease filling, recess mounting transducer with Loctite 5399 RTV rubber and recess mounting transducer with 2 pack RTV silicon rubber.

To obtain accurate results and ensure that changes in pressure measurements are indeed from thermal shock effect, pressure transducers to be tested were first calibrated using two reference pressure transducers 6052C and 6045A obtained from the manufacturer (Kistler), these transducers have very low thermal shock error of less than +/- 1%. The charge amplifier (Kistler 5015) was also calibrated by the manufacturer using a dedicated calibration unit that generates precise charge signals, allowing direct comparison between the amplifier's output voltage and a known reference charge. This way the amplifier's sensitivity setting can be adjusted to ensure accurate measurements. A total of four different Kistler pressure transducers (601A, 701A, 7005 and 6061B) were tested. These are commonly used pressure transducers in different combustion studies rigs such as shock tubes, engines, RCMs and combustion bombs. 6061B is a water-cooled transducer designed to minimize the thermal shock error by cooling the crystal housing during measurements, a 7005 has a reinforced diaphragm to enable measuring higher pressures of up to 60 MPa, 601A has very high natural frequency making it suitable for applications where vibrations are high and 701A has high sensitivity for increased accuracy. Table 1 summarizes selected technical specifications of the pressure transducer types used in this study. These were tested simultaneously using specially designed end plugs in which they were mounted. Two types of end plugs (mounting adapters) were designed and manufactured, one for flush mounting and the other was for recess mounting as shown in Figures 2 and 3 respectively. Dimensions of the slots are based on the size and shape of the transducers tested. Figure 4 shows experimental set up for simultaneous pressure measurements of four (4) pressure transducers in RCM.

Table 1: Technical Specifications of pressure transducers tested in this work, (Kistler group).

Transducer model name	Pressure range (MPa)	Sensitivity (pC/MPa)	Natural Frequency (kHz)	Temperature sensitivity (%/K)
Kistler 601A	0 - 25	≈ –160	≈ 150	$<10^{-4}$
Kistler 7005	0 - 60	≈ –500	≈70	$<10^{-4}$
Kistler 701A	0 - 25	≈ –800	≈70	$<10^{-4}$
Kistler 6061B	0 - 25	≈–250	≈90	$<10^{-2}$

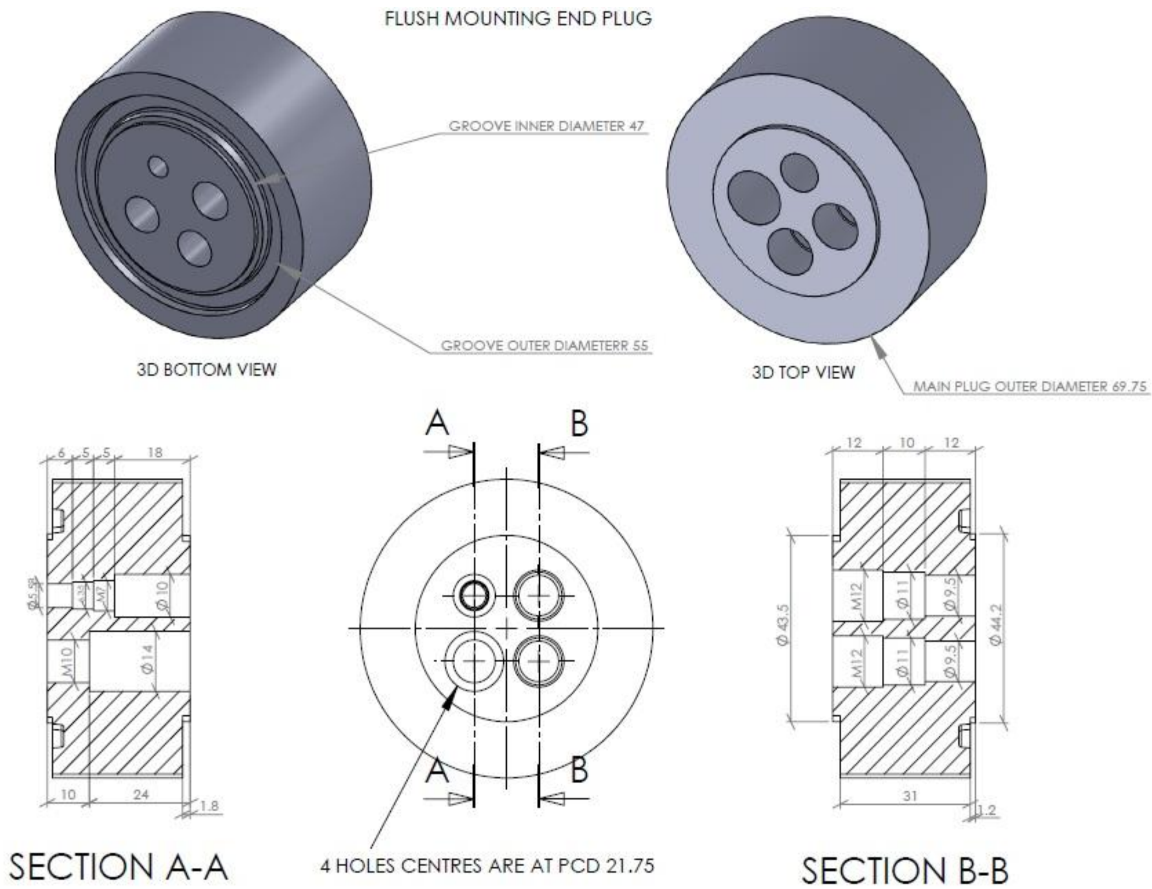

Figure 1: End plug for flush mount pressure transducers.

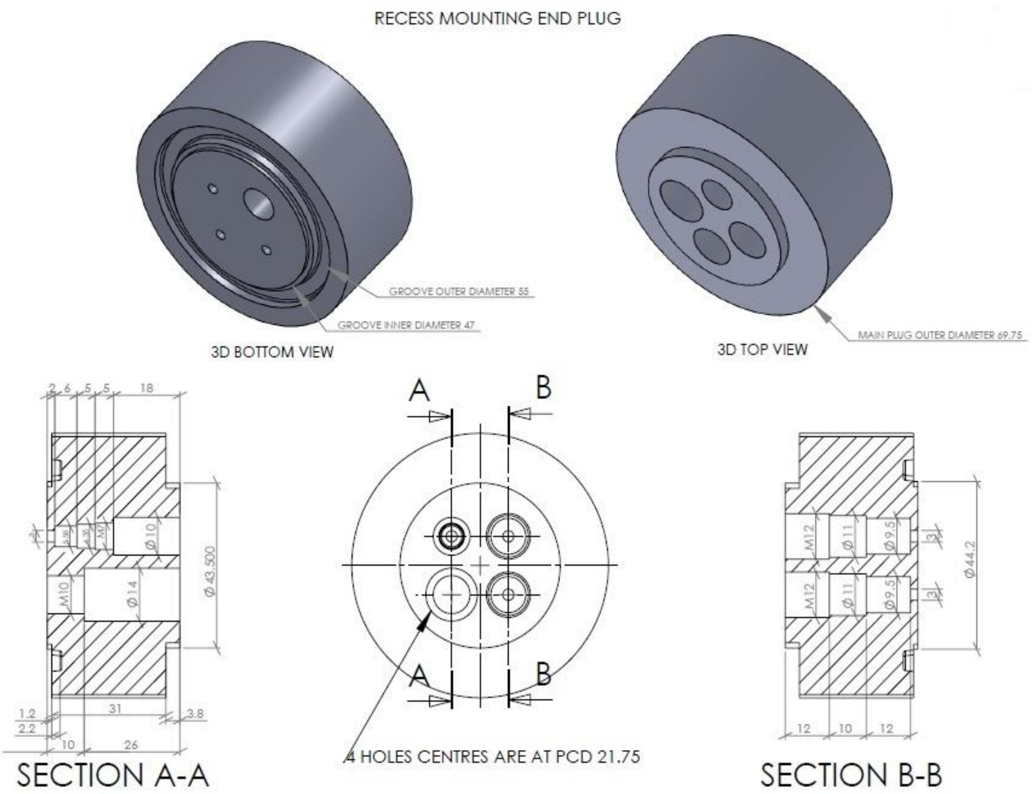

Figure 2: End plug for recess mounted pressure transducers.

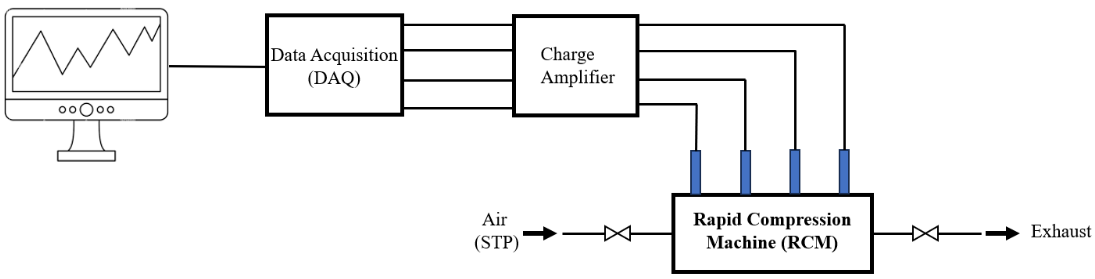

Figure 3: Experimental setup for simultaneous pressure measurements in RCM.

RESULTS AND DISCUSSION

Thermal shock test

Shown in Figure 5 are the pressure readings for the five transducers (including reference transducer 6045A). The time zero in Figure 5, and for all other similar plots, denotes the time when the piston reached the end of compression (EOC). In this test, the magnitude of thermal shock error was measured by the pressure difference between the measurements with the reference transducer (6045A) and the one being compared. Values are shown in Figure 6.

Transducers 601A and 701A show the maximum effect to the thermal shock, they record the lowest end of compression pressures of all the transducers tested, a difference of 0.11 MPa (3.6%) is seen at the end of compression. Using adiabatic core hypothesis, this pressure drop is equivalent to end of compression temperature drop of about 8.3 K which is considerable temperature error in ignition delay times scales. In autoignition studies, Bradley, 1996 had shown that it is normal for autoignition to be triggered by a hot spot, particularly at high temperatures. Even a slight increase in hot spot temperature, on the order of 1 K, can significantly alter the reactivity of the bulk fuel/air mixture. The reactivity gradient at the hot spot can induce localized velocities substantial enough to initiate autoignition (Gu *et al*, 2003). Therefore, the deduced temperature difference of 8.3 K from pressure error measurements could introduce a significant error in the presentation and interpretation of RCM results. The water cooled 6061B shows the least deviation of 0.01 MPa from the reference transducer 6045A. Transducer 7005 recorded less pressure drop at the end of compression than 601A and 701A. However, a sharp pressure drop of 0.106 MPa was seen 3 ms after the end of compression, this could be due to the lower thermal response of its reinforced diaphragm which momentarily delays its thermal expansion. All transducers showed reduced pressure difference after the compression which indicates their recovery from the thermal shock effect as time progressed.

With the exception of the water-cooled transducer 6061B, all other pressure transducers were noticeably affected by the thermal shock due to the very rapid temperature rise during compression. The rate of temperature rise within the combustion chamber was high enough to cause temporary expansion of pressure sensors diaphragm and housing which led to recording less pressure signals than what was recorded by the reference sensor. Different methods commonly used for thermal shock protection were therefore investigated and are reported in the following section.

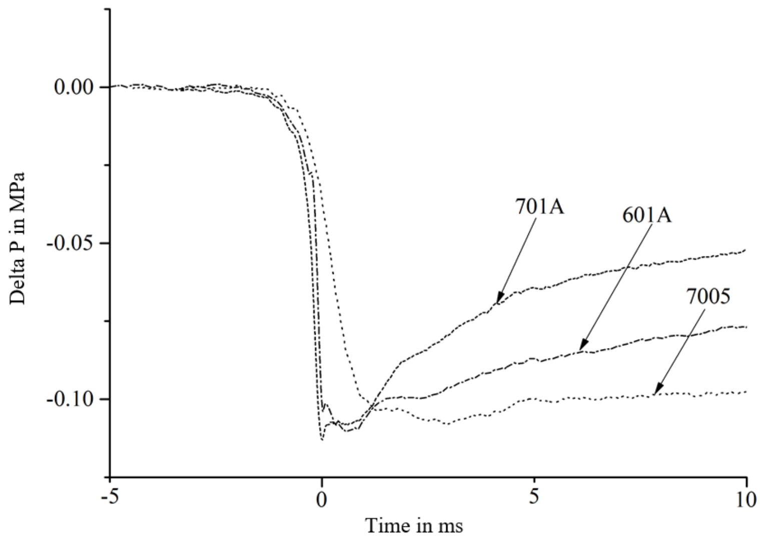

Figure 4: Magnitude of thermal shock error for different pressure transducers.

Flush mounting and surface coating method.

Shown in Figures 7 to 10 are pressure traces for the different transducers when mounted flush with the chamber walls, with and without the protective coatings over the transducer diaphragm. The effect of the vinyl tape is minimal for the 601A and 701A transducers in Figures 7 and 9. However, results for the 7005 in Figure 10 shows a slight increase in pressure at the end of compression when the tape is present, this effect is due to the delay effect that was seen and discussed in Figure 7, protection of thermal shock by vinyl tape is evident but only momentarily due to the thermal expansion delay. Interestingly, the vinyl taped water-cooled transducer 6061B recorded lower pressure at and after the end of compression compared to its corresponding non-taped measurements. This suggests that, although vinyl tape can protect the transducer diaphragm against thermal shock, it also makes transducers less sensitive to rapid pressure change as seen in Figure 9 for the 6061B. This effect negates the thermal shock protection advantage. There was no change in recorded pressure for 601A and 701A when a coating of Loctite 5399 was applied whilst for 7005 there was a slightly higher pressure reading with the surface coating. Therefore, with the current RCM set up, using flush mounted transducers tested in this work, a vinyl tape and Loctite 5399 coatings have very minimal effect in protecting transducers 601A, 701A and 6061B against thermal shock. Transducer 7005 was well protected when coated with vinyl tape, a pressure increase of 0.12 MPa from its non-protected recordings was obtained at the end of compression. However, an abrupt pressure drop within 3 ms after the end of compression was seen, this is due to the same effect discussed in Figures 5 and 6, where the reinforced diaphragm of transducer 7005 results into lower thermal response. The vinyl tape could therefore only delay the heat flux reaching the transducer for a very short time and cause only a temporary thermal protection.

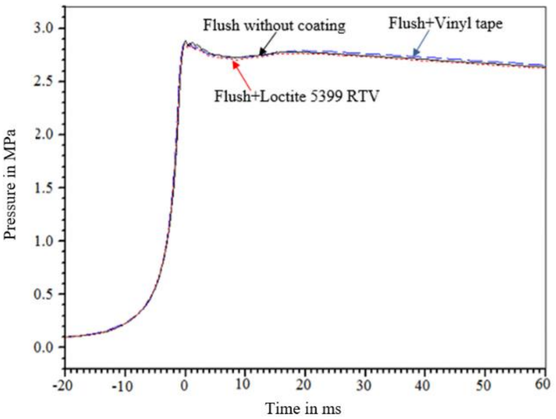

Figure 5: Air pressure traces using transducer 601A flush mounted, with and without coatings

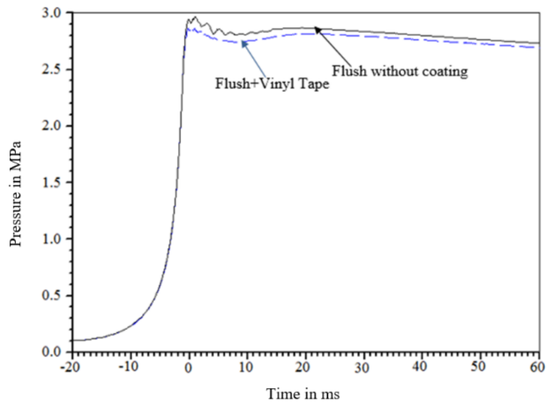

Figure 6: Air pressure traces using transducer 6061B flush mounted, with and without coatings.

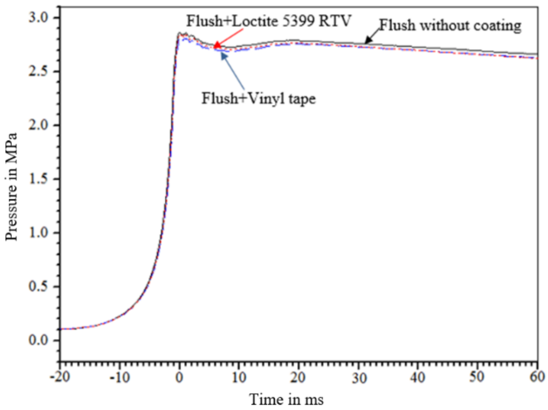

Figure 7: Air pressure traces using transducer 701A flush mounted, with and without coatings

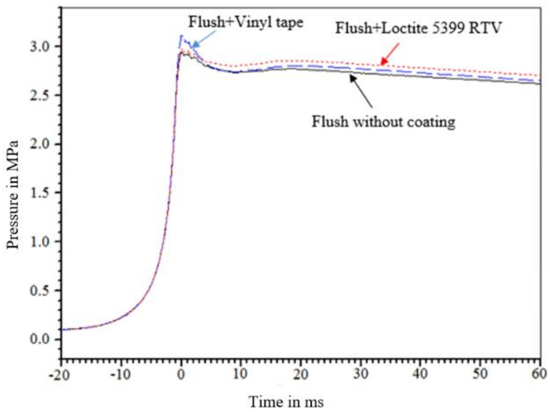

Figure 8: Air pressure traces using transducer 7005 flush mounted, with and without coatings

Recess mounting and silicon filling method.

In this work, tests were conducted with three pressure transducers; 601A, 701A and 7005, using the recess mounted end plug shown in Figure 3. Three types of silicon fillings were tested, these were 2 pack RTV, Loctite 5399 RTV and silicon grease. Shown in Figures 11-13 are the pressure traces for recessed mounted transducers when with and without RTV coatings. Also, for comparison, pressure records for flush mounted transducers without coating are included.

For all transducers tested, the recess mounted measurements, with or without coatings, recorded lower pressures compared to when flush mounted. Application of both RTV coatings in the recess mounted transducers reduced the transducer's sensitivity and lead to measurements that were significantly lower than those measured without coating. However, when silicone grease was applied, and pressure records were compared with those of recess without coatings, a pressure increase of 0.1483 MPa for 601A and 0.19 MPa for 7005 was obtained. This increase is equivalent to about 55% recovery from pressure drop caused by thermal shock as was shown in Figure 6. There was a slight pressure increase for 701A compared to when recessed and non-coated.

Therefore, with the RCM set up used in this work, transducers 601A and 7005 can be fairly protected from thermal shock effects using recess mounting technique together with the silicon grease, while other methods are either less effective or make the measurements errors much worse.

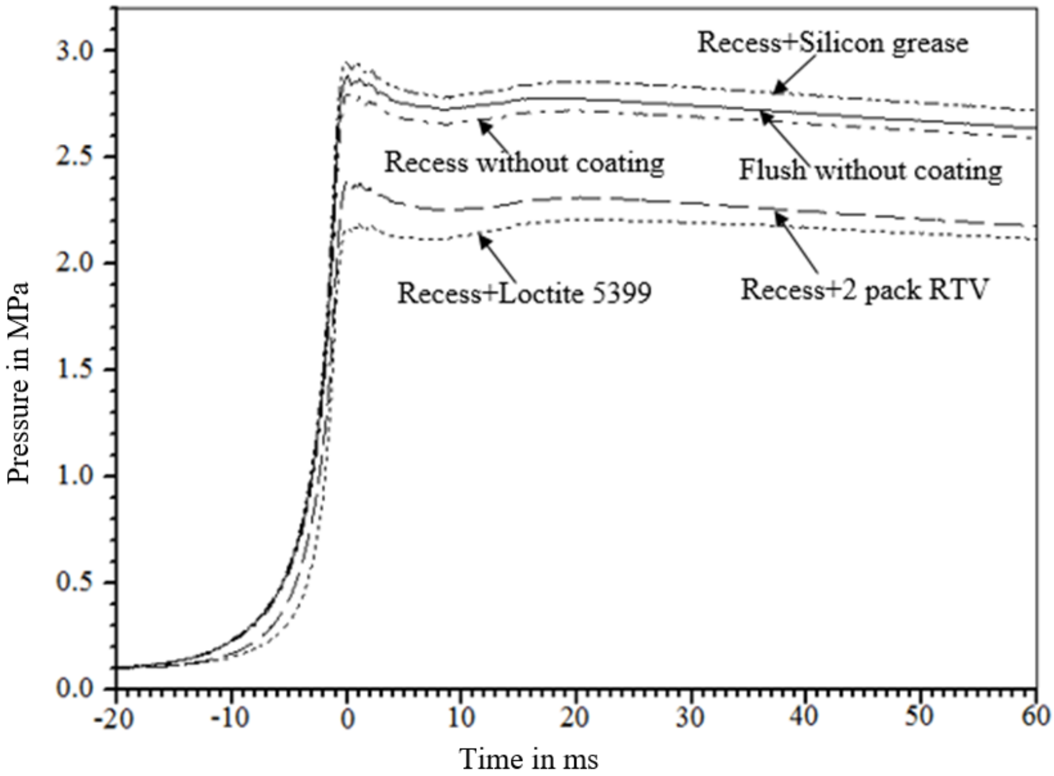

Figure 9: Air pressure traces using transducer 601A when recess mounted with and without coating, and when flush mounted without coating.

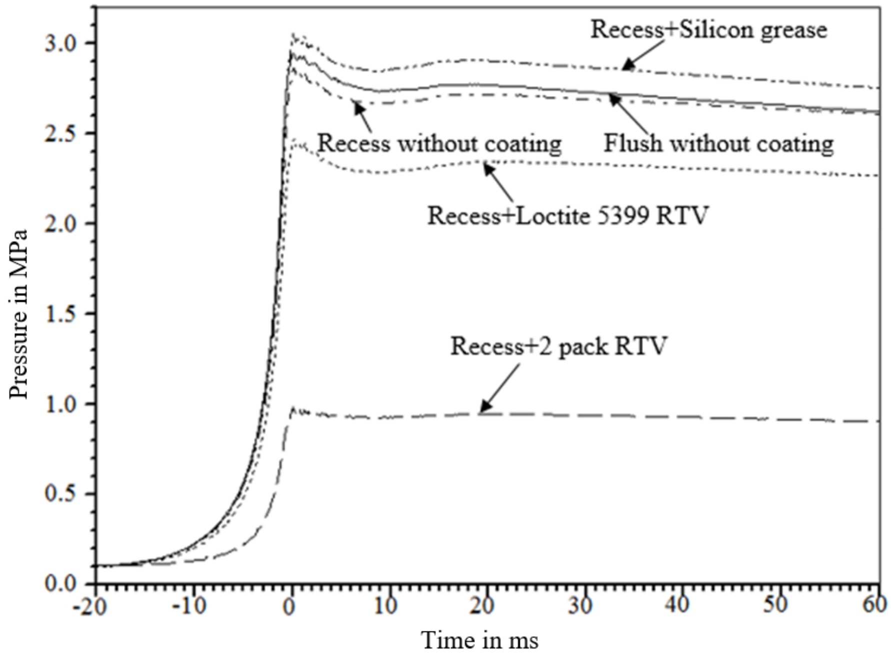

Figure 10: Air pressure traces using transducer 7005 when recess mounted with and without coating, and when flush mounted without coating.

CONCLUSION AND RECOMMENDATIONS

Pressure measurements in explosion rigs such as RCM are indeed affected by the thermal shock from high rates of temperature increase. This makes the pressure measurements to deviate from the actual true values due to expansion of the transducer case. In this work, end of compression pressure error of up to 3.6% was observed due to thermal shock effect, this is equivalent to corresponding temperature error of 8.3 K which is substantial in ignition delay time scale.

A number of protection methods have been proposed by manufacturers and they have been tried in this work. These techniques included application of face coating on a flush mounted transducers and silicon filling on recessed mounted transducers. While most of these techniques showed some kind of protection to the pressure sensors but the best method was found to be recessed mounting technique together with the application of silicon grease, this produced the least pressure error of only 0.5% from the reference pressure.

This therefore warrants further studies to understand and interpret published previous measurements that were made using pressure transducers with no any form of thermal shock protection. Introduction of temperature rate dependent model specifically for each rig depending on their design which would compensate for measurement errors due to transducer case expansion would be an ideal scenario. Several researchers have made an attempt with some degree of success (Lee *et al*, 2015 and Shi *et al*, 2023). Moreover, since manufacturer now produce pressure transducers with better thermal shock resistance, it is recommended to make it mandatory to use these transducers to ensure pressure results are accurate and free from thermal shock effects.

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