CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

MASTER'S THESIS ASSIGNMENT

TITLE:	Crank angle resolved piston temperature measurement
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DEPARTMENT:	Dept. of Automotive, Combustion Engine and Railway Engineering
STUDY PROGRAM:	Master of Automotive Engineering
BRANCH OF STUDY:	Advanced Powertrains
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GUIDELINES:

Perform a detailed research of the known piston temperature measurement methods and compare these methods with the existing Scania piston temperature measurement system. Focus mainly on measurement uncertainty, required engine/piston design modification for each method, field of usage, durability, financial aspect etc.,

Perform piston temperature measurement using existing system and evaluate the results.

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Master's Thesis

Crank angle resolved piston temperature measurement

Thesis project in association with SCANIA CV AB, Sodertalje, Sweden

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Date: 20/08/2018

Czech Technical University In Prague

Declaration

I, Prathik.S.Neelavara declare that this thesis work is completely written by myself as a result of my own research. All the external sources used directly or indirectly are clearly marked and quoted. The sources are all acknowledged in the right manner.

This work has neither been submitted in part or full to any institute or authority for other qualification, nor has it been published elsewhere.

Södertälje, 20/08/2018

Prathik.S.Neelavara

Abstract

During the course of this research work, piston temperature measurements were successfully conducted using a microwave telemetry system at Scania CV AB engine laboratory.

In the age of increasing emission regulations and advent of electric vehicle technology, researchers are striving for better efficiency and power output from the internal combustion engines. Pistons are the heart of engine and are constantly under high thermal and mechanical loads. Information regarding the piston temperature are vital when discussing heat transfer and combustion phenomenon. As part of the study, brief discussions about the various piston temperature measurement techniques and their comparison on various significant parameters are made. Advantages and drawbacks of different measurement methods are listed in detail. Effect of various engine parameters on the piston temperature are explained. Study into the future possibility of piston surface temperature measurement with temperature sensitive paints, their advantages and downsides are discussed. Thorough study of various piston temperature measurement equipment's in Scania's inventory are done and they are compared based on technical specification. Detailed measurement plan was devised and piston temperature measurement system was setup on a single cylinder test engine. Procedure to obtain the accurate piston temperature data is explained. The results obtained were evaluated to understand the piston behaviour towards varying engine conditions. Decent agreement between the hypothesis planned from the literature study and measurement data was obtained. The correlation of piston temperatures with engine parameters like load, speed, oil temperature and intake pressure are described in detail. Fascinating temperature variation over piston surface is explained.

Keywords: Piston temperature measurement, Telemetry, IR Telemetrics.

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Table of Contents

List of Figures

List of Tables

Abbreviation

CA – Crank Angle

FE – Finite Element

WOT – Wide open throttle

DOHC – Double overhead camshaft

BMEP – Break mean effective pressure

A/F – Air fuel ratio

MBT – Maximum brake torque

TDC – Top dead centre

BTDC – Before top dead centre

BDC – Bottom dead centre

UHC – Unburnt hydrocarbon

EMF – Electromotive force

MW – Microwave

VCO – Voltage controlled oscillator

NTC – Negative temperature coefficient

EMI – Electromagnetic Induction

LED – Light emitting diode

ICCD – Intensified charge coupled device

S/N – Signal to Noise ratio

IR – Infrared

PCM – Pulse code modulation

RF – Radio frequency

FS – Full Scale

DAQ – Data Acquisition

TSP – Temperature Sensitive Paint

SOI – Start of Injection

TC – Thermocouple

RPM – Rotation per minute

1. Introduction

Many physical properties and processes are dependent on temperature and its measurement is critical to many aspects of human activity from the thermodynamic improvement of internal combustion engines to process control and health applications. Temperature is a fundamental unit of measurement and current estimates of the value of the temperature measurement market run at approximately 80% of the sensor market [1].

It is a common experience that heat transfer will occur between a hot and a cold object. Temperature can be viewed accordingly as a potential for heat transfer, and temperature difference as a force that impels heat transfer from one object or system to another at lower temperature by conduction, convection or radiation. Engine combustion is inevitably linked to tremendous increase in pressure and temperature in the combustion chamber, which places severe mechanical and thermal stress on the piston. Mechanical stresses on the piston are primarily caused by the gas pressure acting on the piston crown, the movable part of the combustion chamber, inertia force and side load. Thermal stress starts with the exposure of the combustion chamber side of the piston crown to hot combustion gases. Heat then flows from the combustion chamber through the piston to the piston rings, particularly the compression ring to the cylinder walls and from there to the surrounding coolant. Another portion of the heat is carried off by the engine oil in engines with piston cooling [2].

In past few years the mechanical power output and engine efficiency have increased significantly, also the emissions have reduced considerably. In particular for a car engine, the specific power has increased from 34 kW/litre in 1992 to 63 kW/litre in 2010 [3]. Furthermore, the peak pressure of combustion chamber and the fuel injection pressures have been increased to aim at reduced emission and higher efficiencies. Also, the idea of engine downsizing is being focused. These development implies high thermal loads and thermal risks on engine components, particularly on the piston.

Piston performance and life are profoundly influenced by thermal conditions in the engine combustion chamber. Thus, it is important to understand how such conditions affect the piston temperature levels and their profiles during the engine cycle. In addition, the piston temperature distributions are fundamental factors in the determination of piston stress, piston material requirements, expansion and distortion, friction, carbon deposit formation and oil consumption. Piston temperature effects the efficiency of the combustion process and hence engine performance and emissions [4].

From analysis standpoint, measurement of piston surface temperature plays a key role. Temperatures measured at various positions on the piston are needed as initial values for the FE computation of temperature fields, majorly when developing a highly stressed diesel engine. Extensive temperature measurements are also required to optimize systems with controlled cooling.

The range of methods and devices available for temperature measurement are extensive. Temperature cannot be measured directly, effects on some other physical property must be observed and related to temperature. Few physical phenomenon that are dependent on the temperature are resistance, volumetric expansion, vapour pressure and spectral characteristics. Critical to measurement of temperature is calibration, as this provides the quantitative validation for the uncertainty of measurement. Indication of temperature can be worthless without information on calibration [1]. A typical chain for industrial measurement system might be calibration against a system that itself has been calibrated by standard laboratory which in turn was calibrated by a national standards laboratory.

Piston temperature measurements have always been difficult or expensive to obtain in a reciprocating engine. The system mounted on the piston must be able to withstand harsh conditions such as inertial forces about 2000 g's at 6000 RPM and temperatures above 150°C [5]. The measurement options include invasive or contact methods such as thermocouples and resistance thermometers or non-invasive techniques like infrared detectors. In addition, recent developments in optical methods and micro manufacturing have resulted in the wide spread availability and use of advanced techniques such as coherent anti-Stokes Raman scattering and thin film transducers.

This thesis work will majorly focus on the crank angle resolved temperature measurements. Instantaneous surface temperature provides more detailed knowledge about the temperature distributions and swings in the piston during the combustion cycles. These measurements would further assist with the heat flux and piston cooling concepts. In the coming sections various measurement techniques are evaluated and compared based on various criteria such as, robustness, design modification, uncertainty and financial aspect.

We need to constantly look into newer possibilities as ” Measurement once made with a device may now be more appropriate and feasible with other systems “

2. Literature Review

Before going into the details regarding piston temperature measurement techniques and systems, let us discuss about the dependency of piston temperature in relation to the major engine parameters.

2.1 Effects of various engine parameters on piston temperature

Comparison with major engine parameters always gives a clear idea about the importance of performing a particular experiment or measurement on the engine.

Engine speed

Ishibashi *et al.*, (2014) [6] conducted experiment on an in-line 4 stroke 4 cylinder naturally aspirated engine with maximum speed of 6900 rpm. The engine speed was varied from 1500 to 6500 rpm at intervals of 500 rpm or 1000rpm. The results showed that the temperature increased with increasing engine speed. The highest temperature recorded was 571 K at the centre of the crown at 6500 rpm.

The Figure 2.10 depicts the piston temperature distribution at the crown at different engine speeds and the trend established is in correlation with the findings of Ishibashi *et al.*, (2014) [6]

The results of Zhang *et al.*, (2011) [13] show that when engine speed is increased from 1000 rpm to 2100 rpm with WOT, the piston temperature increases quickly when the speed increases from 1000 rpm to 1300 rpm. The measured temperature reaches a peak at 1600 rpm.

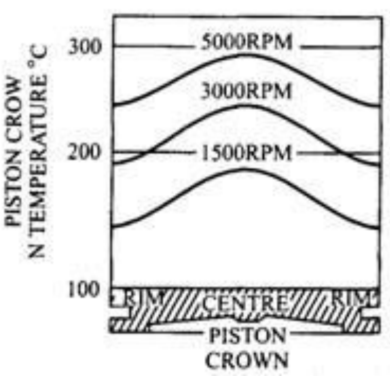


Figure 2.10: Piston temperature distribution according to engine speed [39]

Ignition and Injection timing

Suzuki *et al.*, (2006) [7] conducted measurements on a DOHC 4-stroke 4-cylinder gasoline motorcycle engine with maximum speed of 15,300 rpm. They come to a conclusion that the piston temperatures increase along with spark advance at middle engine speeds of about 11,700 rpm. At high speed operations close to 15,000 rpm, there is no noticeable rise in piston temperature with spark advance as the temperatures are already high.

Ladommatos *et al.*, (2004) [8] performed tests on an in-line, 4-cylinder turbocharged direct injection engine with compression ratio of 19:1. Their main aim was to isolate the effect of piston surface temperature on exhaust pollutant emissions. During their discussion they write about the relation between injection timing and piston temperature. The engine was run at 2000 rpm and 80 Nm load, both the engine head and block coolant temperatures were held constant at 90˚C and 95˚C respectively. A linear relationship between the injection timing and piston temperatures was noted. Advancing the injection timing resulted in the raise in piston temperatures, this is mainly due to increase in chamber peak pressures and temperatures. Also, they stated that the piston temperature increase was between 0.9˚C and 1.9˚C for each 1˚ crank angle of injection timing advance.

Air/Fuel Ratio

Air-fuel ratio is the ratio between the mass of air and the mass of fuel in the fuel-air mixture at any given moment. The normal operating range for a conventional SI engine using gasoline fuel is $12 \leq A/F \geq 18$; for CI engines with diesel fuel, it is $18 \leq A/F \geq 70$ [9]. For gasoline engines the stoichiometric A/F ratio is somewhere around 14.7:1 and 14.5:1 for diesel engines. Fuel mixtures below the stoichiometric ratios are considered as rich mixture and if they are greater than stoichiometric they are called as lean mixture.

Ishibashi *et al.*, (2014) [6] have described the effect of A/F ratio on piston temperature in their paper. In their tests the air/fuel ratio was varied in the range of 10 to 12.5 at an engine speed of 6000 rpm. The deviation of target BMEP was fixed within ±5% overall operating conditions. They observed that enriching the A/F ratio led to the lower temperatures at the piston crown face.

Suzuki *et al.*, (2006) [7] have discussed about the cooling effect obtained by the fuel in their experiment conducted on the motorcycle gasoline engine. They say that there is an experimental means to lower the piston temperatures by latent heat of vaporization of extra fuel that does not contribute to the combustion but makes the air-fuel ratio richer than stoichiometric level. The authors have also come to a conclusion that the piston temperature is significantly affected at middle speeds of 11,700 rpm by the change of air-fuel ratio. At higher speeds of about 15,000 rpm the piston temperature becomes less sensitive to the changes in air-fuel ratios.

Kato *et al.*, (2001) [10] conducted test on two in-line gasoline engines, one was 2.0 litre 4 cylinder D4 and the other was 2.5 litre 6 cylinder D4 engine. They compared the difference between stratified and homogenous combustion based on piston temperature. Measurements of piston temperature during the change of combustion from stratified to homogenous with engine torque 30 Nm at 1200 rpm, 2400 rpm and 60 Nm at 2400 rpm were tabulated at different piston locations. They concluded that the piston temperature was lower during stratified combustion indicating lean-burn effect.

The researchers [10] also conducted study on piston temperature lowering at high load conditions. Under 6000 rpm, full load conditions piston temperatures were noted for varying fuel injection mass. They were able to define such a fuel injection mass that can lower the piston temperature by 10°C while only reducing the engine torque by 4 Nm.

Therefore, by altering the air-fuel ratio and fuel injection volume the piston temperatures are affected. This parameter can be used in prevention of seizure, piston damage from knocking and increase the piston life in racing conditions [7].

Piston cooling

As specific power output increase in modern combustion engines, the pistons are subjected to increasing thermal loads and rising maximum component temperatures. Efficient piston cooling is therefore required in order to ensure operational safety and reduce the degradation of piston material properties and lubricants [2] [11]. Various popular methods implemented for piston cooling are (1) Spray jet cooling, (2) Oil gallery cooling and (3) Oil jet cooling.

Thiel *et al.*, (2007) [11] talks about the different types of gallery cooling concepts with one or two cooling nozzles and how efficient they in comparision. They conduct experiment on a passenger diesel engine operating at full load conditions at 2800 rpm and 4200 rpm. From their experimental values it is clearly visible that the piston cooling efficiency has been improved in comparison to reference configuration. The best concept was the one with dual nozzle and dual arm gallery design, at bowl rim a temperature reduction of 22°C at 2800 rpm was observed and 26°C at 4200 rpm. The top groove temperature decreased by 13°C and 18°C at 2800 rpm and 4200 rpm respectively in comparison to the reference configuration.

Suzuki *et al.*, (2006) [7] the authors explain the effectiveness of piston cooling oil jet in relation to the piston temperature by conducting experiment on a 4-stroke, 4-cylinder (max speed of 15, 300 rpm) gasoline engine with piston cooling jet diameter of 0.9mm and oil pressure of 590 kPa. Temperature measurements were done with and without cooling oil jet at various engine speeds, the engine was set at MBT – Maximum brake torque and A/F – Air fuel ratio of 13 was maintained. After evaluation of the results a remarkable difference of approximately 50°C in the middle engine speed was observed. In high engine speed the gap narrows and gradually the effectiveness of the cooling oil jet is lost.

Kato *et al.*, (2001) [10] in their paper verify the effectiveness of piston cooling methods by measurement of piston temperature. Piston temperature of a 1.364 litre, in-line 4-cylinder turbocharged diesel engine was obtained. The oil gallery of the piston lowered the cavity edge and piston ring temperature by approximately 30°C. Drop in piston temperatures with increase in oil jet flow was observed. This was later used to calculate the appropriate amount of oil jet flow.

Ladommatos *et al.*, (2004) [8] talk about the relation between the block coolant temperature and piston temperature. Measurement were conducted on a diesel engine at 2000 rpm and 80 Nm. Linear relationship between the piston and coolant temperature were noticed, approximately 1°C rise in coolant temperature shows 0.6°C rise in piston temperature.

It is clear from all the research conducted that the piston temperature is of importance when designing, simulating and evaluating the cooling systems. It is valuable to have a high accuracy instantaneous temperature measurement system and a lot of efforts are being made to come up with new techniques having low uncertainty levels.

Intake pressure and temperature

Volumetric efficiency of the engine is directly related to the intake pressure. It is defined as the volume flow rate of air into the intake system divided by the rate at which the volume is displaced [9]. If the inducted air is compressed to a higher pressure than the ambient, the volume of air inducted will be more and it would increase the volumetric efficiency as well as engine power.

Luo *et al.*, (2015) [12] conducted piston temperature measurements and discuss the effect of intake pressure and temperature on the piston. Measurements were done on a single cylinder 4-stroke diesel engine. They varied the inlet pressures while the intake gas temperature was kept constant at 60°C. Observations were made that the average surface temperature of the piston increased with inlet pressure. For a Thermocouple measurement system average temperature rise of 13°C was noted when the inlet pressure was increased from 1.1 bar to 1.5 bar. This is mainly because the convective heat transfer coefficient increases as the pressure increases.

During the next set of measurements [12], the inlet temperature was varied while the intake mass flow rate was kept at 6.45 g/s (19 kg/m^3 charge density at TDC) and the coolant temperature was also help constant. The average surface temperature of the piston increased with inlet temperature, as the steady flux component increase as the inlet temperature is raised. This result was expected in accordance to the Woschni correlation.

Therefore, whenever it is intended to boost the intake pressure, piston temperature rise must be taken into account to avoid future piston related issues.

Influence of Piston temperature on exhaust emissions

Increasing importance is being given to the emission reduction and control in engines due to the stringent rules being implemented. Piston temperature has a direct impact on the exhaust emissions, lot of studies have been made to relate the two parameters.

Experimental results by Ladommatos *et al.*, (2004) [8] shows the effect of piston temperatures on UHC, NOx and smoke emissions.

Rise in piston temperatures had substantial effect in reducing the exhaust UHC. With injection timing at 1° CA BTDC raised the piston temperature by 38°C this in turn reduced the HC emissions by an average of 27%. Sudden increase in load caused sharp increase in HC emissions, but if the piston temperature was raised by 40°C the UHC decreased by at least 29%. Effects on NOx was a bit different, raise in piston temperature of 38°C had no significant effect on NOx emissions. But during high loads steady state conditions, 40°C raise in piston temperature showed significant increase in NOx emissions. This study also showed that the smoke emissions increased by an average of 25% when the piston temperature was increased by 38°C, mostly due to the fuel spray interaction with the hot piston bowl region.

By maintaining and controlling the piston temperatures over different engine operating conditions, we are able to gain slight control over the exhaust emissions. Kato *et al.*, (2001) [10] says quick increase in piston temperature in the starting conditions is an effective means to reduce HC emissions.

2.2 Piston Temperature Measurement Methods

As seen from the previous study and comparison, importance of piston temperature to designing of an engine is clear. By attaining trustworthy accurate results, it is possible to obtain a better efficient engine with minimal emissions. But the measurement conditions for the sensors and equipment are very harsh, they need to sustain high thermal and mechanical loads. In the following section brief discussion about the various piston temperature measurement techniques used in the industry, their accuracy, durability, financial cost, modifications required etc., are done.

Fusible Plugs

Fusible plugs are used to determine the temperature of the piston during steady state engine operations. They are usually made of a threaded metal cylinder of gunmetal, bronze or brass with a hole drilled in them. This hole is filled with suitable metal as per temperature measurement requirement. The melting points of the plugs are selected to cover the expected temperature range in the measurement locations. The melting points are spaced over a range of 10°C to 15°C [2].

Once the plugs are fit in the measurement locations, the engine is run at steady state conditions for a set duration and the fusible plugs are examined to see if they have started to melt. Thus the temperature at the location is estimated as it must be between the one that has melted and the one that has not yet started melting.

The main benefits of this measurement technique is that it is cost effective, simple and requires less equipment, has low setup and measurement time. The reason it's not used in modern days, is due to its high uncertainty and precision of measurement, it can measure only one operating condition. Also the temperature range of the plugs must be expected in advance, which increases the uncertainty of the system.

Templugs

Templugs are small, hardened temperature sensitive pins made of steel alloys, mainly used for determining the average maximum temperature at a particular location. They function on relative simple principle of thermal tempering (thermal softening) of hardened steel [14]. The average temperature during the measurement run is determined by the decrease of hardness of the templug and the run duration, the measurement must be run at constant conditions. This evaluation is done once the templug is removed from its location.

For a particular material, calibration curves are obtained prior to the experiment. Once the experiment is completed, the hardness is evaluated and compared to the calibration curves to obtain the temperature correlation. Below figure 2.20 shows an example of calibration curve.

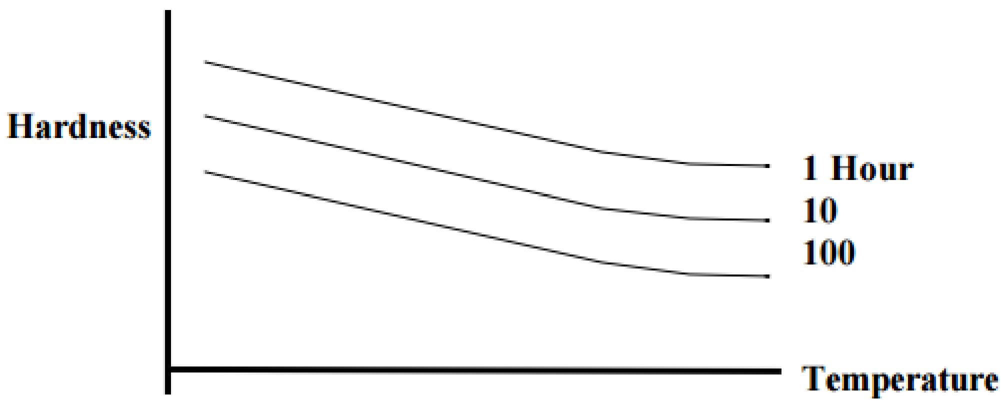


Figure 2.20: Hardness vs Temperature calibration curve [14]

Templugs are available in various sizes depending on their application. The figures in 2.21 [a],[b],[c] show standard templug design with dimensions.

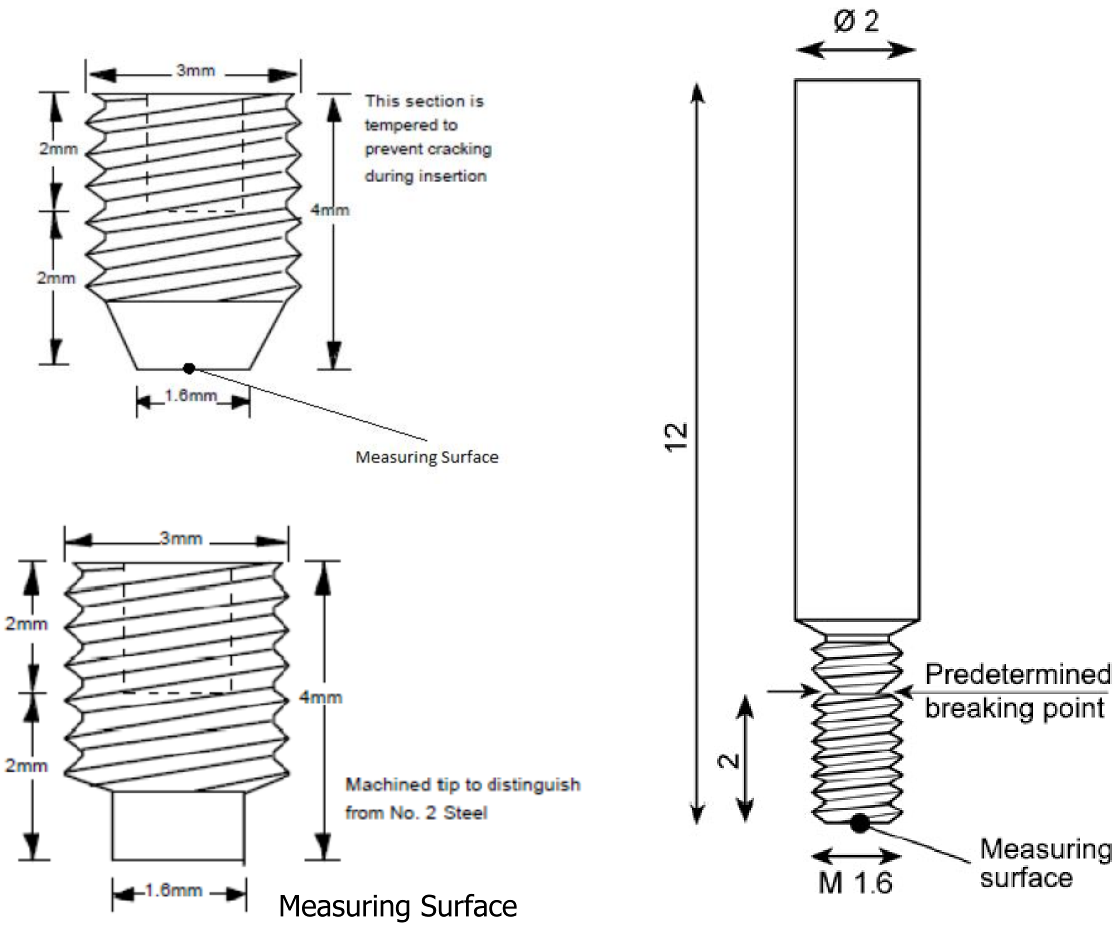


Figure 2.21: [a] [b] standard templug with Allen socket, [c] templug with predetermined breaking point

The templugs have replaced the fusible plugs in the temperature measurement methods. The main advantages of templugs are that they have relatively high precision, accuracy of about 3% - 5% [14]. Large number of measurement locations (up to 15 [2]) can be obtained due to small size of templugs. These plugs are usually corrosion resistant and can be used in harsh conditions. They also require minimal equipment alteration and measuring equipment. On a financial note they are cheap and durable.

The main drawbacks of templugs are that they are only usable for one operating engine condition as each templug return only a single value. Transient and instantaneous measurement are not possible. To gain high accuracy of temperature measurement the setup must be run for a long duration typically about 10 hours [2]. The hardness analysis is externally done, so the setup must be dismantled and this consumes a lot of time.

Mancaruso *et al.*, (2018) [15] in their research have used templugs measurements for calibration purpose. They state that " templugs have the advantage to be easy to use and to provide a reliable measure of temperature. On the other hand, they completely miss the possibility of sequential measurements, due to their simple technology they save only the value of the maximum reached temperature ".

Thermocouples

A thermocouple consists of two dissimilar metal wires connected together to form a junction at one end and the free ends are connected to a voltage measurement device [Figure 2.22]. The junction is where the temperature is measured. When the junction experiences a change in temperature, a voltage is created. The net EMF indicated by the voltmeter is a function of temperature difference between the join and the voltmeter connections. The temperature can be calculated from the voltage using reference tables. Thermocouples are common choice for temperature measurement due to their low cost, robust nature, self-energization and wide temperature range [1].

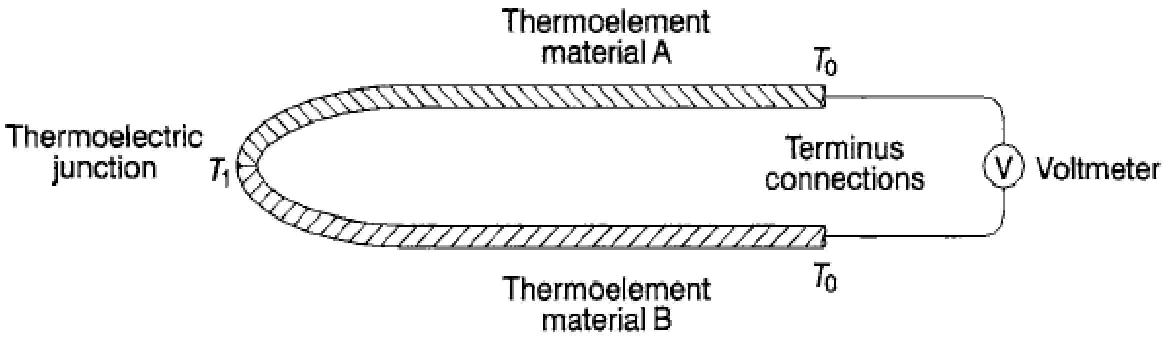


Figure 2.22: Thermocouple circuit. T_1 – Temperature at the junction; T_0 – Temperature at the terminus connections

There are many types of thermocouple depending on the different junction formation. They have different temperature ranges, accuracy and durability. The below table 2.21 [1][16] lists down the different types of thermocouple and their characteristics. But they are majorly classified as

- Rare-metal thermocouples (types B, R and S)
- Nickel-based thermocouples (types K and N)
- Constantan negative thermocouples (types E, J and T)

Thermocouple Type	**Junction**	**Temperature Range**	**Accuracy**
Type K	Nickel-Chromium/Nickel-Alumel	-250°C to 1100°C	+/- 2.2°C
Type J	Iron/Constantan	-196°C to 800°C	+/- 2.2°C
Type T	Copper/Constantan	-262°C to 850°C	+/- 1°C
Type E	Nickel-Chromium/Constantan	-268°C to 800°C	+/- 1.7°C
Type N	Nicrosil/Nisil	0°C to 1250°C	+/- 2.2°C
Type S	Platinum Rhodium-10%/Platinum	0°C to 1500°C	+/- 1.5°C
Type R	Platinum Rhodium-13%/Platinum	0°C to 1600°C	+/- 1.5°C
Type B	Platinum Rhodium-30%/ Platinum Rhodium-6%	100°C to 1750°C	+/- 0.5°C

Table 2.21: Thermocouple classification.

Temperature measurement is rarely taken with bare thermocouple wire. The wire is usually electrically isolated and protected from the environment. The K type thermocouple is the most common type and is widely used due to its low cost, accuracy, wide range and reliable results. Many researchers have used K type thermocouples in piston temperature measurements [6][8][12]. The thermocouples are placed at required locations by usually drilling small precise holes through the underside of the piston. The thermocouples are usually held in position with the help of high temperature epoxy. The nickel based thermocouples [Figure 2.23] are well suited for measuring large temperature amplitudes in transient test run programs, also they can be used over the entire temperature range that can occur in a combustion engine [2].

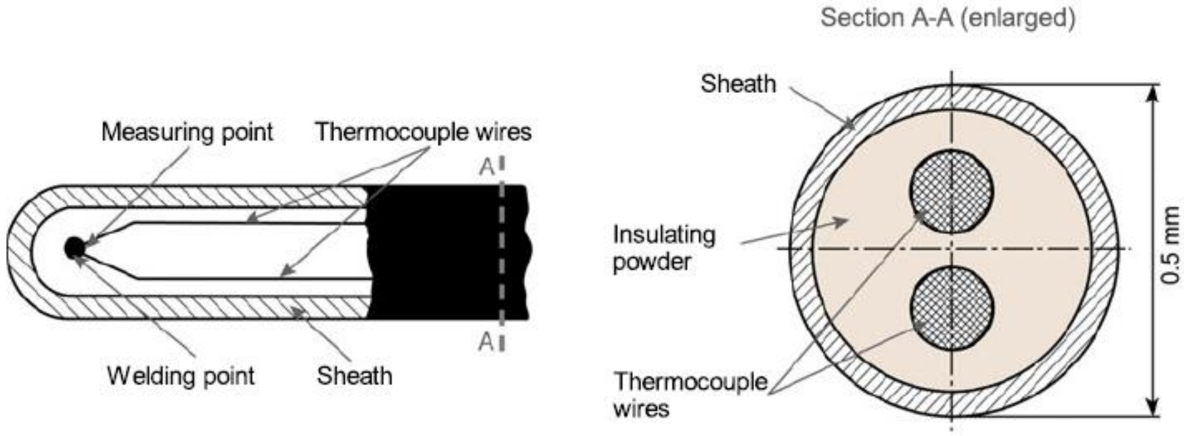


Figure 2.23: Schematic of NiCr-Ni Thermocouple [2]

The next step would be to link the thermocouple wires to the data acquisition system outside the engine. The main challenge is to make least modifications to the engine, to obtain a reliable output and to be able to use the system for long duration. The main techniques employed for this purpose and their practical application are discussed in the below section.

Temperature measurements from thermocouples with linkage construction

The signals or values of temperature from the thermocouple in the piston are transmitted out through measuring lines supported by a linkage construction, one approach is to use a "grasshopper linkage". The system can be made durable by having the wires run parallel to the axis of each linkage join, so that the wires twist instead of bending. The designs of various linkage are often different depending on the constructions and geometries of the test engines. A technique that is used most often, involves routeing of the signal wires down the piston connecting rod to the moving big-end bearing cap. A hinged linkage system is used to support the wires between the moving big-end cap and a stationary point on the engine crankcase [8]. The figure 2.24 shows a measuring system with a linkage construction.

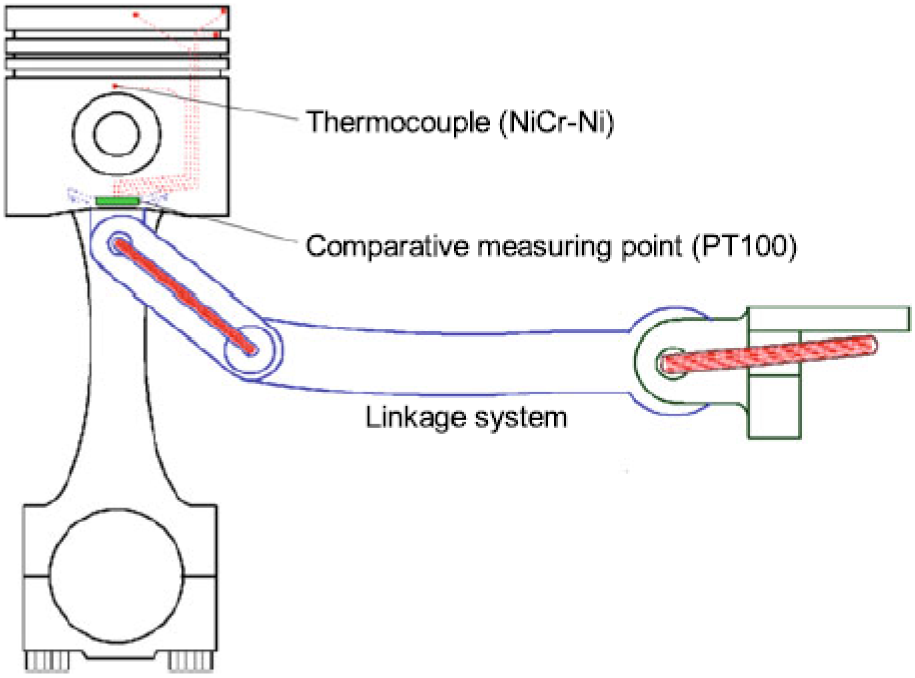


Figure 2.24: Schematic of a linkage system [2]

The main positives of this technique are its ability to measure both steady state and transient conditions, it can capture rapid temperature changes which enables us to obtain crank angle resolved data, numerous measurement points depending on the design constraints, the obtained data is highly reliable as the issue of noise is not pronounced and there is no issue of power supply to the amplifiers.

The main drawbacks which limits the use of this technique are the high requirement of design modification to the engine, the application is usually done only to single cylinder systems, the measurements are constrained by the speed of the engine (not suitable at high rpm) and the measurement duration is limited due to the cyclic bending of the wires at various locations which leads to wire fatigue and breakage.

Assanis *et al.*, (1991) [4] describes the development of a two-beam mechanical linkage system, from concept to construction. They have discussed the design details, wire linkage and routing paths, and also conducted dynamic simulations of the linkage to evaluate the component stresses. The design was done for a modified single cylinder AVL 520 DI, Diesel engine with displacement 1.5 litres. The links were made of Aluminium 6061-T6 due to its good strength to weight ratio and easy machinability. The links were connected together with the help of pin joints and the electrical continuity was maintained by passing the wires through the hollow pivot pins. Using a special adapter the beam linkage was connected to the connecting rod. To maintain the electrical connectivity between the con-rod and the piston a steel strap looping over the con-rod is fixed to the piston skirt using a flexible hollow pin. After the complex design and connections were completed the piston temperature measurements were conducted successfully for 15 hours run duration with varying conditions and maximum speeds of 1900 rpm were reached.

Huegel *et al.*, (2015) [17] during their investigations on heat flux profiles measured crank angle resolved piston surface temperatures using a grasshopper linkage for data acquisition [Figure 2.25 (Left)]. The experiment was done on a single cylinder research engine with lot of design modifications. K-type thermocouples with 0.5mm diameter were used as temperature sensors. The thermocouple wires were attached to the reference junction at the bottom of the piston skirt. After the reference junction, copper wires were used for electrical connectivity. Teflon coated 0.3 mm diameter copper wiring from the reference junction on the piston to the customized grasshopper linkage runs along a flexible thin sheet of metal. The design was robust and was able to carry out measurements successfully with accurate final results.

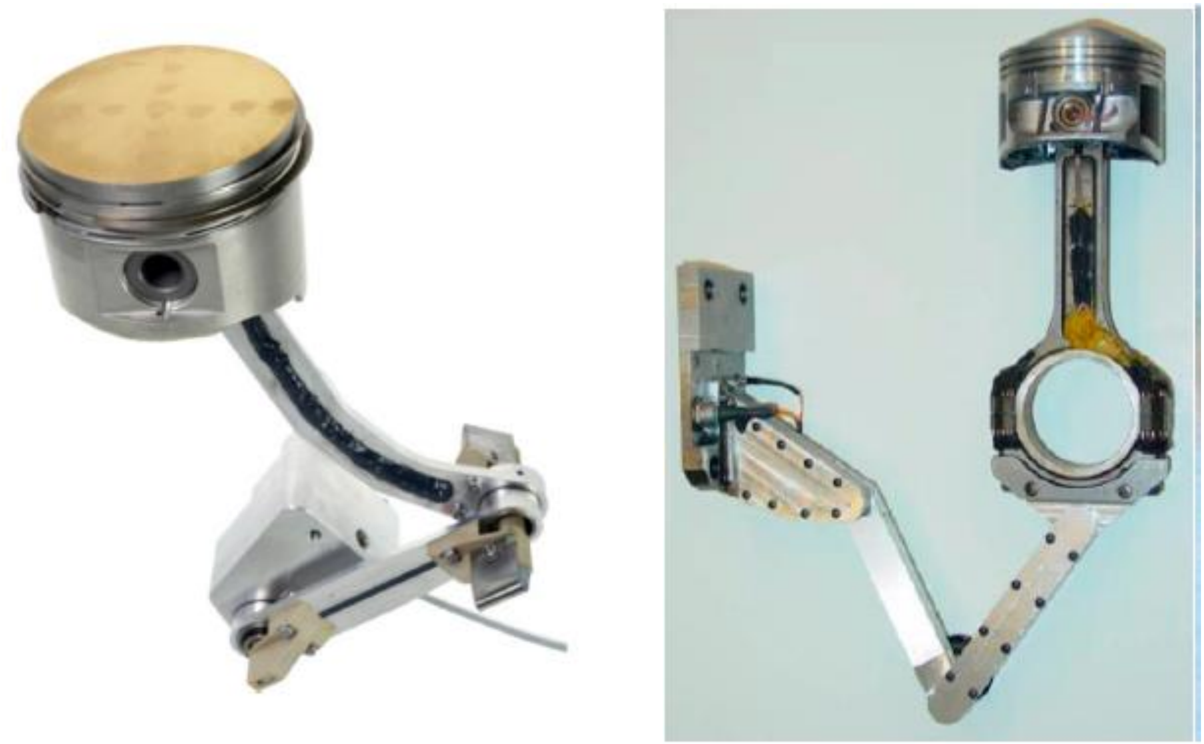


Figure 2.25: (Left) Grasshopper Linkage [17]; (Right) Mechanical Telemetry System [27]

Temperature measurements from thermocouples through telemetry

Telemetry can be defined as an automatic measurement and recording of data from remote, inaccessible locations and transmitting them to monitoring equipment. Creating mechanical linkage for data transmission is a huge design task and has its limitations, so telemetry system using contact and non-contact methods have been designed.

The contact technique is a simple method which transmits continuous temperature signals out of the engine by maintaining a sliding contact between the movable connector on the piston and stationary connector on the engine crankcase. The contact usually takes place at the BDC for a short duration which is sufficient for the data transfer. The main downside of this technique is the short limited lifetime due to the high wear and fatigue effects on the sliding connectors [5][8].

The non-contact methods have no contact between the piston and the data monitoring system. The sensor signals are transferred without contact points. A general schematic of the non-contact technique is shown in the figure 2.26.

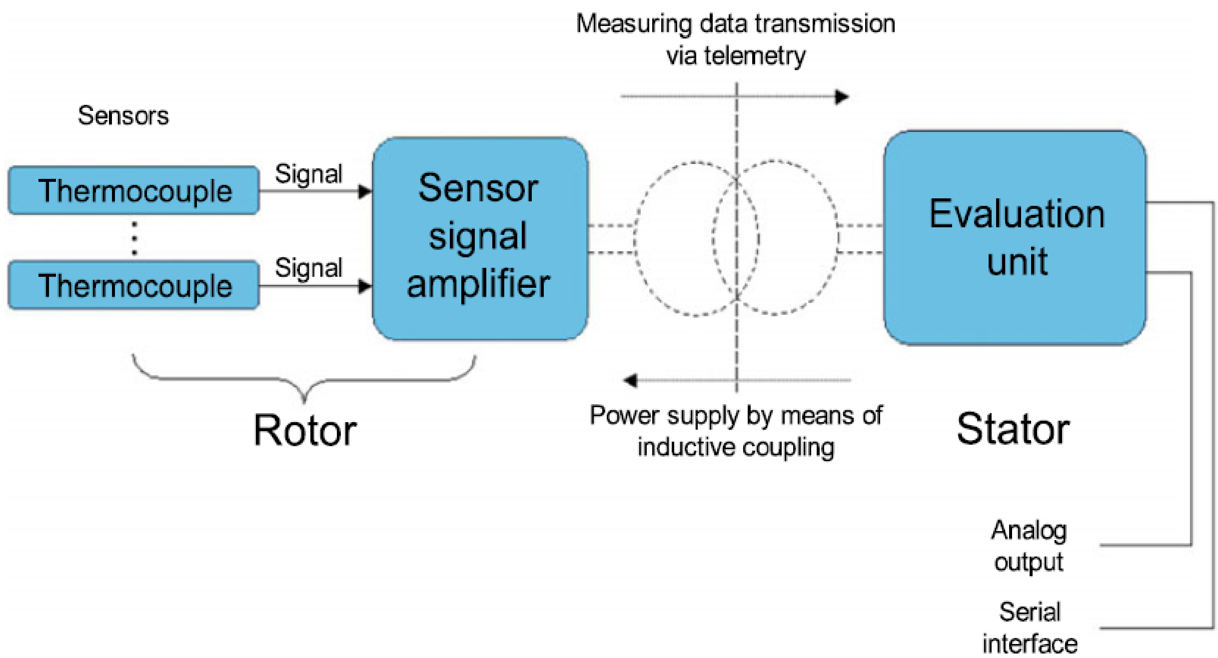


Figure 2.26: Scheme of non-contact telemetry system for temperature measurement [2]

The thermocouples are drilled into the measurement locations as per requirement and the wires are guided through the underside of the piston to a convenient position. The temperature signals are usually conditioned and multiplexed at the piston location before the data transmission out of the engine. The signal transfer happens in two main ways (I). Inductive transfer, (II). MV transmission

Inductive transfer of temperature signals

This method makes use of a moving secondary coil, mounted on the piston and a stationary primary coil in the crankcase. The strength of the inductive coupling between the two coils at the piston BDC can be related to the piston temperature. When the two coils couple a current is induced in the secondary coil and the signal transfer occurs only when the coils are coupled. The primary coil is usually powered with high frequency generator and the load on the secondary coil is from the sensor signal [5][8].

Ishibashi *et al.*, (2014) [6] in their task to obtain piston temperatures from a gasoline engine have used telemetry method using electromagnetic induction [Figure 2.27 (a)]. This approach enabled them to obtain real-time and transitional measurements at high engine speeds of 6500 rpm. Non-ground K-type thermocouples were affixed to six pre-decided locations at 0.5mm from the piston surface. The signal transmission system consists of a rotor antenna on a holder fixed to the piston [Figure 2.27 (b)] The sensor signal are amplified, digitized and transmitted to the rotor antenna (hollow cylinder shaped). The receiver unit affixed on the cylinder block comprises of a stator antenna (rod like) [Figure 2.27 (c)], holder and a transmission cable. This stator antenna is wound with induction coil, the data transfer occurs when inductive coupling occurs between the rotor and the stator at BDC. At this point, in addition to signal transfer the rotor also receives power to run amplifiers from stator antenna. The data processor unit extracts the actual temperature values from the transmitted signal and provides high frequency power to the complete system.

Schäfer *el al.*, (2007), Koppel *et al.*, (2014) [18][19] in their papers, explain about the inductive telemetry setup in piston temperature measurement [Figure 2.28]. The overall basic concept of signal transfer remains almost similar with cylindrical rotor antenna (transmitter) on the piston and the pin like (receiver) at BDC on the cylinder block. Depending on the accuracy, financial availability and quantity to be measured the signal modulating and processing unit are acquired.

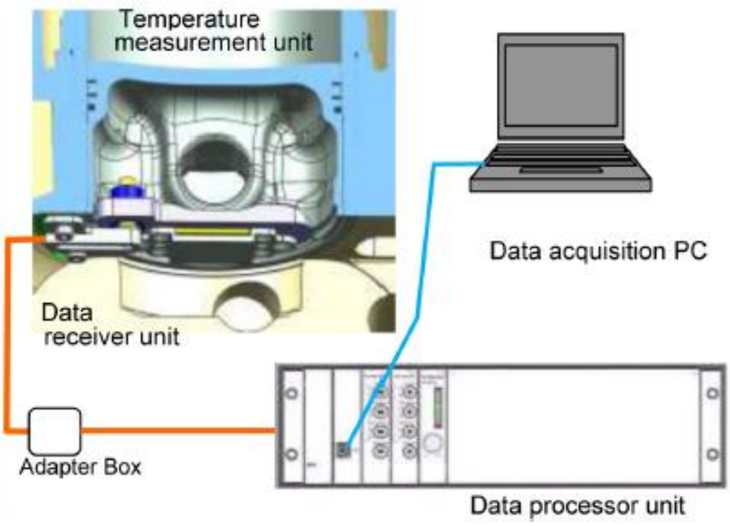


Figure 2.27(a): Inductive transfer telemetry system[6]

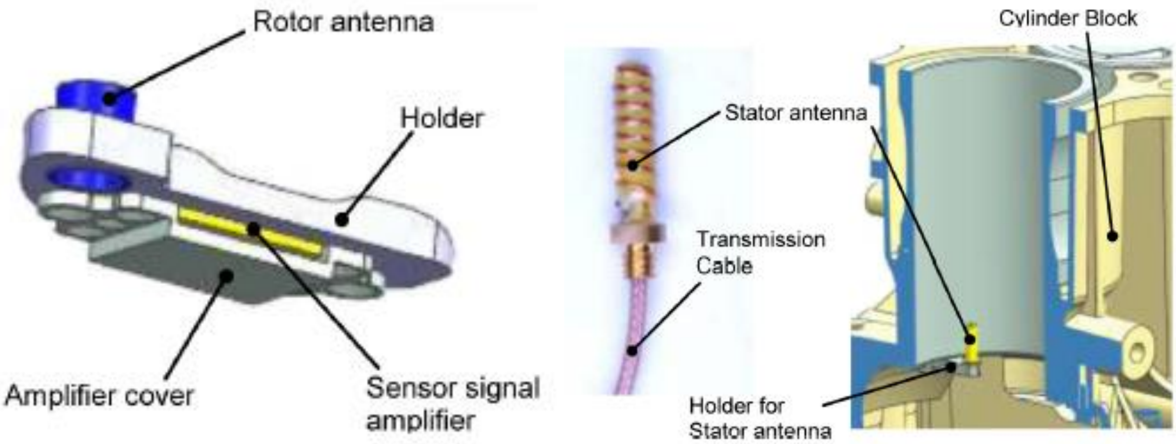


Figure 2.27: (b) Rotor antenna [6]; (c) Stator antenna [6] used by Ishibashi et al., (2014)

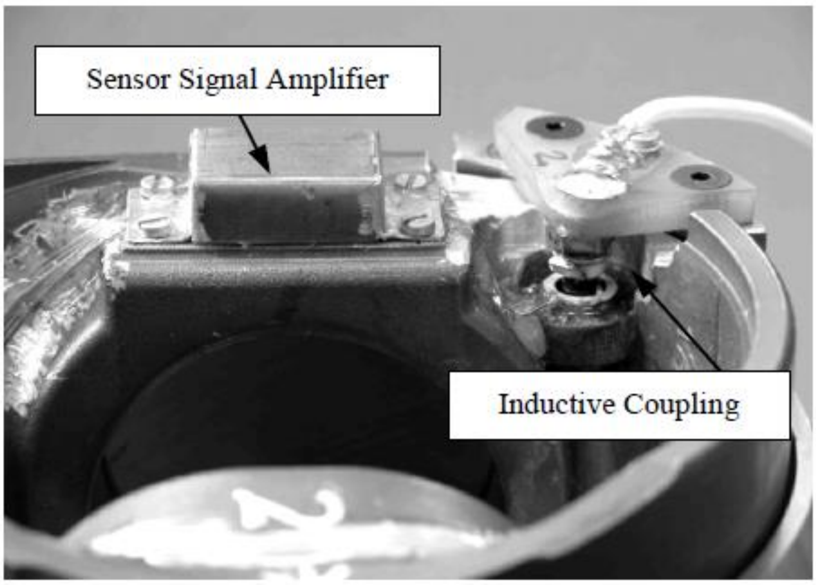


Figure 2.28: Image of the modified piston used by Schäfer el al., (2007) [18]

Microwave transfer of the temperature signals

This technique employs a transmitter on the piston skirt which transmits continuous signal from the sensor to an receiver on a stationary point on the engine crankcase. The signal from the thermocouples are conditioned and converted to frequency before being transmitted. The receiver then conditions and converts the frequency to temperature measurement.

Gingrich *et al.*, (2016), Miers *et al.*, (2005) [20][21] during their research have made use of wireless microwave telemetry for piston temperature measurements [Figure 2.29]. The sensor signals from the thermocouples is input to a voltage to frequency convertor. The EMF is converted to frequency modulated square wave over the range of 10-50kHz. A voltage controlled oscillator (VCO) converts this wave to microwave signal and then amplified. The microwave signal is transmitted from the piston location with the help of a transmitter attached at the bottom of the piston. The antennas mounted at the crankcase receive these signals and demodulate them back to the original thermocouple signal, which is later interpreted to temperature values. An inductive power supply at the BDC is used to power the electronics in the system. This system is light weight (80 grams) and can be run at high speeds.

The advantages of the wireless telemetry technique due to which they are frequently used nowadays are, the low level of modifications requirement on the engine block, service life is much greater when compared to other techniques, measurements can be done for high engine speeds and the temperature variations are captured quickly, overall the system is light weight and has the ability to measure numerous locations [2].

The major disadvantage of this technique is the high cost of system installation to the piston and the need for appropriate software to modulate and demodulate the signals.

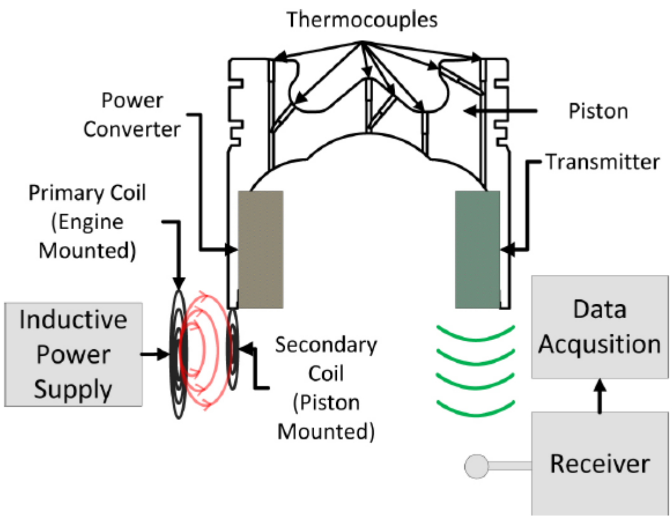


Figure 2.29: Schematic of Wireless microwave telemetry system [20]

Temperature measurements using thermistor with telemetry

Thermocouples are not the only available temperature sensors, NTC thermistors can be used effectively to measure temperatures. NTC thermistors/resistors exhibit property where in their electrical resistance decreases with the increase in temperature. Making use of this functional property and measuring the change in resistance offered by the thermistor, the temperature of the system can be estimated.

The positives of this technique is the possibility to run the measurements at high speed and easy set up. The system can be highly durable if they are within the temperature limitations [2].

The drawback of using a thermistor instead of thermocouple is the limited temperature range (400˚C) over which they can be used, before implementing the thermistors the maximum temperature must be predicted to avoid failure.

Kato *et al.*, (2001) [10] explain the principle for temperature measurement by thermistor and EMI very well in their paper. The system basically consists of a transmitter, receiver coil installed at the lower region of cylinder bore and a resonator coil mounted on the piston. The embedded thermistors are wired to a resonator coil, which is designed to cross over the receiver coil at BDC. AC applied to the transmitter results in a current generated at the receiver coil. When the piston is at BDC the current flows to the resonator coil due to EMI and in turn current in the receiver coil is lowered. Higher the temperature of the piston, higher the current generated at the resonator coil due to reduced resistance offered by the thermistor which results in reduced current at the receiver coils. By appropriate numerical relationships the value of current at receiver coil can be related to temperature. The accuracy of measurement can be improved by providing a constant frequency and voltage to the transmitter, minimising signal noise and acquiring the values at maximum EMI.

Thiel *et al.*, (2007) [11] decided to use NTC temperature measurement technique as it was the best compromise between complexity of application and measurement accuracy. By this statement they wanted to say that NTC technique is easy to setup but the accuracy is a bit lower in comparison with thermocouples. Suzuki *et al.*, (2006) [7] also decided to use the NTC thermistor technique for temperature measurement of their motorcycle piston due to its ability to withstand high speed. The measurements were conducted successfully for over 10 hours at maximum speeds of 15,300 rpm with satisfactory accuracy.

Temperature measurement with telemetry using LED transmitter and photodetector

The temperature signals from the sensors in the piston are transmitted to the data acquisition system with the help of LED. The voltage signals from the thermistors/thermocouple are converted to frequency and are transmitted off the piston as pulses emitted by a LED transmitter. A photodetector located in line with the LED at the bottom of the crank case collects the infrared carrier wave. The signal is then conditioned and converted back to voltage by the receiver unit and expressed as temperature with help of appropriate conversion factors. Figure 2.30 depicts such a telemetry system.

Researchers [5][22] have made use of this method to obtain piston temperatures in their experiments. Accurate, stable measurements were obtained at speeds of 5000 rpm, using a Gallium-Aluminium-Arsenide (GaAlAs) LED and a silicon phototransistor [22].

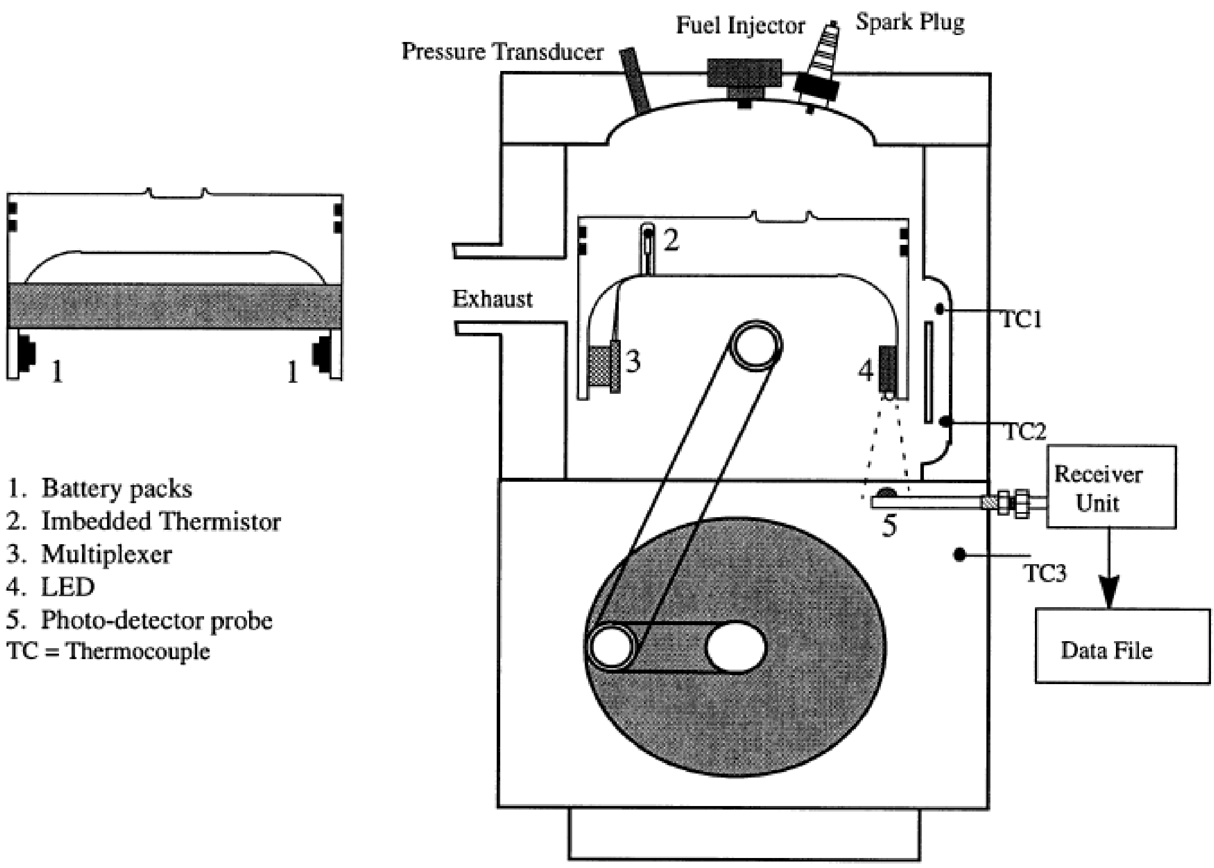


Figure 2.30: Telemetry system using LED transmitter [22]

Surface Thermography

In the recent past a lot of research has been done on piston surface thermography for temperature and heat flux measurements. Surface thermography is mainly divided into two types based on their principle of operation. In the coming section a brief description of their theory and practical application to measurements are discussed.

Phosphor Thermometry or Laser-induced phosphorescence

The basis for this non-contact measurement technique is a large class of materials made up of inorganic oxides, oxysulfides, orthophosphates, and vanadate of rare metals. By adding small concentration of rare earth dopant material, these compounds fluoresce when excited by certain wavelength of light. This fluorescence/phosphorescence is temperature dependent [23]. Phosphor thermometry is of two kinds: one is lifetime method, the other is intensity method.

Intensity based temperature measurement:

On excitation of the phosphor coated surface by a laser pulse results in phosphorescence. The intensity of phosphorescence exhibits exponential decay, the signal intensity decreases with increasing temperature. This phosphorescence is captured by a high speed camera (usually ICCD). Temperature of the test surface can be obtained by calculating the ratio of phosphorescence signal intensity at measured temperature to the intensity at a reference temperature. This method is mostly suitable for two-dimensional measurements [24][25]. Takada *et al.*, (2009) [25] have made use of this technique to estimate local two dimensional temperature fields in diesel piston bowl in an optical engine. Two different phosphor coating were experimented on (I) $Y_3Al_5O_{12}$:Dy [YAG:Dy] (II) $BaMg_2Al_{10}O_{17}$:Eu [BAM], the excitation was provided by Nd:YAG laser for both cases. The signal intensity of desired spectral region was captured by two CCD cameras and the temperature was evaluated. Though a lot of factors had to be overcome the final deductions of this research are truly satisfactory.

Lifetime based temperature measurement:

Due to limitations with high speed cameras and S/N ratio the intensity based technique is not always feasible. By measuring the phosphorescence decay time of the emitted spectral signal from the excited phosphor coated surface, surface temperatures can be calculated [25]. The evaluation of the temperature from the decay time is done by comparing the values to a previously obtained calibration curve for the employed phosphor [26].

Researchers [23][24][25][26] have made use of lifetime method to evaluate the piston temperatures in their various experiments using different phosphor coatings and exciters. Figure 2.31 show a general set up of Phosphor thermometry.

The positives of this technology is its highly responsive nature, if needed the temperature measurements can be made in microsecond timescale and the temperature data can be resolved in crank angle basis. With the use of appropriate filters the measurement can also be made during the combustion phase. This method is non-contact and does not have any wiring, drilling or mechanical linkage adjoining the piston. There is no speed limitation on the engine during the measurement.

The chief issues related with phosphor thermometry are the need to bond the measurement surface with phosphor material and they may alter the thermal environment. This technique requires an optical access to capture the spectral signals. Formation of soot may hinder the measurement continuity. The signal strength is also an issue with increasing temperatures.

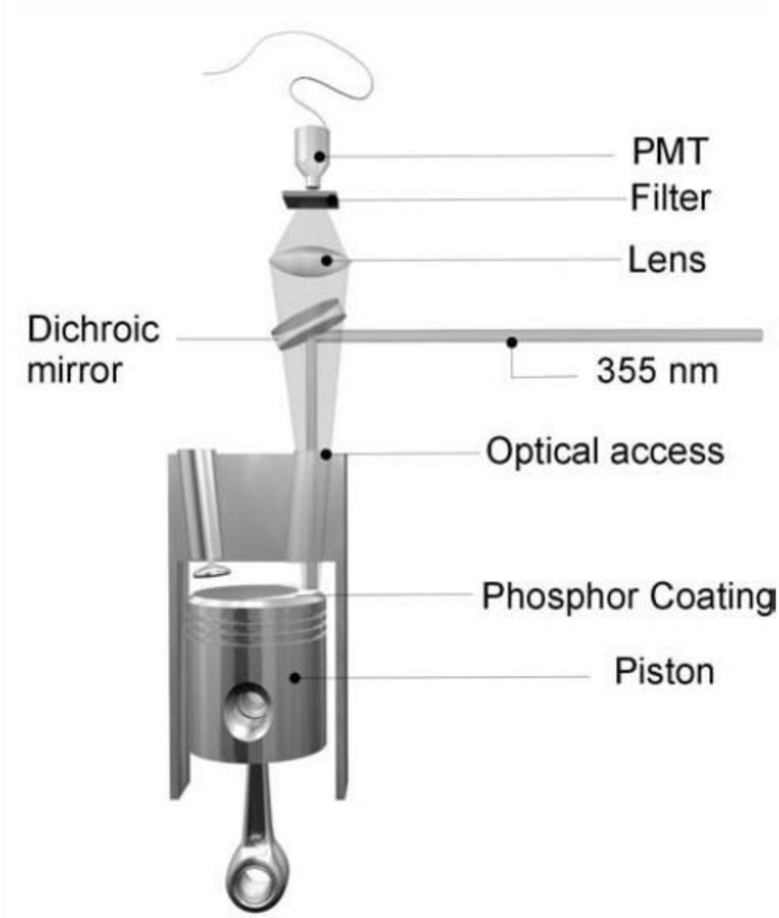


Figure 2.31: Piston temperature measurement system using Thermographic Phosphors [28]

Infrared Temperature Measurement

Infrared radiation is emitted from all objects whose temperature is above absolute zero, hence it can be used to measure temperature. Infrared radiation is emitted from the piston surface which is picked up by photovoltaic diodes which generates proportional current. This can be related to the surface temperatures using calibrated values.

Luo *et al.*, (2015) [12] explains about duel wavelength infrared diagnostic for surface temperature measurement of optical engine. The temperature is evaluated measuring the emission intensity of a single known wavelength. Indium antimonide (InSb) sensors were used to detect the IR emissions. Appropriate IR range was selected and two filters were used, so as to avoid interference created from combustion species.

Buono *et al.*, (2011) [3] conducts full scale experiments on IR piston temperature measurement system [Figure 2.32]. They implemented the detector (InGaAs) in a special spark plug and conducted measurements. Calibration process and analysis on various interference possibilities were discussed. Mancaruso *et al.*, (2018) [15] also performed thermal imaging and detection of sapphire in-cylinder surface temperature.

The notable benefit of this process is its fast response time and ability to capture fluctuating temperature changes [12], the effort needed in modifying the engine parts is comparably low and the obtained signal strength is high. The major disadvantage related to this method is the background interference produced by combustion products.

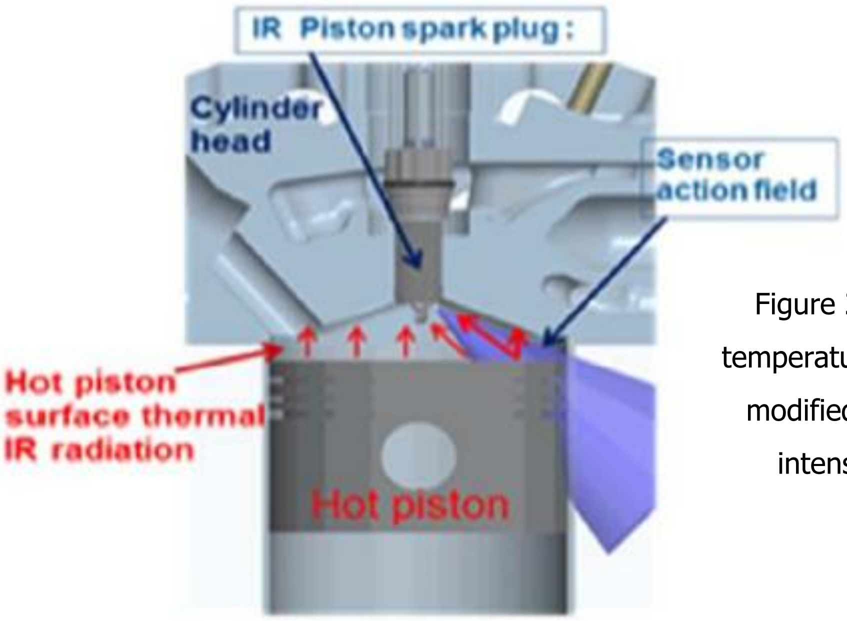


Figure 2.32: Infrared Piston temperature measurement using modified spark slug to detect intensity of radiation [3]

Thermographic Paints

Thermographic paints are heat sensitive paints that change colour when exposed to certain temperature limits. These products are either irreversible and designed for one-time use providing evidence of attained temperature or are reversible and can change back and forth to provide an indication of current temperatures [33]. The colour change can be single or multi-change depending on the type of paints being used. Multi-change paints can have from 2 to 15 colour changes [34].

A thin layer of irreversible temperature sensitive paint is applied on the experimental surface (Piston) and allowed to stabilize. Then the piston is run under steady state condition for a set duration. Once the piston is cooled to atmospheric condition, it is examined and compared with calibrated colour range to obtain the surface temperature profiles.

If reversible TSP are to be used then a process similar to phosphor thermometry must be followed. The paints with known high thermal emissivity would be applied on the piston surface and using IR camera software the surface temperature are accurately evaluated.

During the course of this research study, contact with TSP suppliers were established and the complications involved with the technique were analysed.

In theory and on paper this technique, especially the irreversible TSP displays lot of positives. It is a non-contact method and requires no mechanical modifications. It is expected to be relatively inexpensive. Complete surface temperature profile in comparison to spot temperatures offered by thermocouple and templugs could be obtained. The process is expected to speedy.

The notable disadvantages are the inability to provide transient temperature values. Errors during interpretation of paint colours and sensitivity to harsh conditions.

Measurement Technique	Sensing Element	Speed	Transient Condition	Uncertainty	Run time/Service life	Modification Level	Financial Aspect
Fusible Plugs	Melting point	High [10]	No [00]	High, due to intervals in temperature between the melting points [04]	Short measurement time [05]	Low [08]	Medium [07]
Templugs	Hardness	High [10]	No [00]	Medium, Maximum temperature can be determined between 3% to 5% [07]	Typical measurement run is about 10 Hours [05]	Low [08]	Medium [07]
Mechanical Linkage	Thermocouple	Low [06]	Yes [10]	Low, as the possibility of signal noise or attenuation is low [08]	Typically measurement is limited to few hours due to stress [06]	High [01]	Comparatively High [06]
Inductive Telemetry	Thermocouple/ Thermistor	High [09]	Yes [08]	Low depending on how well the calibration process is done [08]	Good service life, until the thermocouples are working [09]	Medium [05]	High [05]
Microwave Telemetry	Thermocouple	High [10]	Yes [09]	Low Uncertainty [08]	Good service life, until the thermocouples are working [09]	Medium [06]	High [05]
Surface Thermography	Doped Phosphors	High [10]	Yes [10]	Depends on the calibration of lifetime curves. Comparatively Low [08]	Decent Service life, but soot deposition may cause hinder [06]	High [04]	Very High [02]

Infrared Measurement	Heat radiation	High [10]	Yes [10]	Low but depends on the line of sight and engine environment [06]	Decent service life [07]	High [05]	High [03]
Thermographic Paints (Irreversible)	Multi-colour Paints	High [10]	No [00]	Medium uncertainty levels depending on the paint colour interpretations [05]	One time usage [05]	Low [09]	Low [08]

Total	60
Fusible Plugs	34
Templugs	37
Mechanical Linkage	37
Inductive Telemetry	44
Microwave Telemetry	47
Surface Thermography	40
Infrared Measurement	41
Thermographic Paints (Irreversible)	37

- The selection of the measurement technique must be done depending on the requirements, availability of time and funds.
- Each method has its advantages and drawbacks. The above table and the weighted averages is to assist in easy comparison and selection of the techniques.
- [10] – is the maximum possible score and it always indicates to a positive outcome.
- Outdated Fusible plugs has the least score and the Microwave technique has the best score, indicating its balanced nature.

Table 2.22: Comparison of various Piston Temperature measurement techniques

Measurement Technique	Advantages	Disadvantages
Fusible Plugs	▪ Simple in operation, cost effective and easy to fit ▪ No external power requirement and no wires ▪ Low setup and measurement time	▪ Can measure only one operating condition per measurement ▪ Expected temperatures must be estimated in advance ▪ Low precision and accuracy
Templugs	▪ Can be used in large number of measurement location ▪ Inexpensive and simple in operation ▪ Comparatively high precision and accuracy ▪ Minimal alteration to pistons	▪ Needs to be removed from the engine to be tested ▪ Can measure only one operating condition per measurement ▪ Long measurement run time for better accuracy ▪ We only obtain a single maximum temperature value
Mechanical Linkage	▪ Can measure at both steady state and transient conditions ▪ High accuracy and reliable results ▪ Rapid temperature changes can be recorded	▪ High requirement of design modifications ▪ Maximum measuring speed is restricted due to fatigue and stress ▪ The measurement duration is limited due to cyclic bending of wires ▪ Usually applied to single cylinder engines
Inductive Telemetry	▪ Non-contact signal transfer ▪ High service life and can be used at high speed condition ▪ In comparison to linkage technique it requires less modification ▪ The extra weight of the electronics is low	▪ External power supply to the electronics is necessary ▪ The electronics have temperature limitations ▪ The setup of the thermocouples and electronics requires skill ▪ It is expensive in comparison to the previous techniques
Microwave Telemetry	▪ Non-contact signal transfer ▪ Good noise immunity and signal accuracy ▪ Communication is possible throughout the cycle ▪ The electronics can be reused	▪ Multiple antennas need to be set up for good signal reception ▪ It is a high cost method ▪ Appropriate modulation and demodulation software's are required ▪ Power supply is needed

Measurement Technique	Advantages	Disadvantages
Surface Thermography	▪ Highly responsive in nature ▪ No wiring or drilling required on the piston ▪ No speed limitation and temperature limitation ▪ Highly accurate surface temperature can be obtained	▪ Need for optical access to capture the spectral signals ▪ The formation of soot may cause problems ▪ Coating of phosphor material on the piston surface is tedious ▪ Low signal strength issues
Infrared Measurement	▪ Non-contact method ▪ Fast response time and ability to detect small variations ▪ No modifications required on the piston surface	▪ Optical access is needed ▪ Background interference due to the chamber environment is a major issue
Thermographic Paints (Irreversible)	▪ Non-contact method ▪ Complete surface temperature profile ▪ No mechanical modifications required ▪ Inexpensive and quick analysis time ▪ The piston can be cleaned and reused	▪ The environmental condition may be too harsh for the paints ▪ Issues of binding the paint to the piston surface ▪ Errors in interpretation of colors ▪ Measurement in single operating point

Table 2.23: Advantages and Disadvantages of various piston temperature measurements

3. Scania measurement systems

Scania designs and manufactures its own engines, this requires them to look into every aspect of the engine component. Piston design in an engine has a major impact on most of the engine parameters. The piston temperature plays a significant role in its design. This led to various measurement techniques and systems being used by Scania. Depending on the project requirement, various systems ranging from templugs to microwave telemetry have been used. Single cylinder research are also being conducted on phosphorescence methods. In this section, brief explanation about the systems that are currently in use at Scania are discussed.

3.1 Templugs

This technique of temperature measurement was used before the availability of modern RF and Inductive signal transfer systems.

The measurements were usually carried out in cooperation with a third party service organization. The design and drawings for the locations of the templugs were provided by Scania to the third party company, who would do the machining and installation. The test runs were then carried out by Scania once the modified pistons were received. The hardness measurement of the templugs and the appropriate temperature evaluation were again conducted by the third party organization and the final results were provided to Scania.

In recent past templugs have not been used intensively due to its inability to measure transient conditions and increased measurement time.

3.2 Telemetry Systems

Currently this technique is most widely accepted by most of the organizations, due to their quick setup time, reusability of electronics, high speed measurements and acceptable accuracy levels. Scania has microwave telemetry systems from three major suppliers

- Manner Sensortelemetrie
- Datatel Telemetry
- IR Telemetrics

Detailed explanation about the specifications of the system components and their construction will be discussed.

Manner Sensortelemetrie

Manner Sensortelemetrie had provided quotation for 2 systems, 4 channel and 8 channel respectively. Scania decided to purchase the 8 channel system in 2015.

This system measure the temperature signals using inductive data transfer. The thermocouples are affixed into the piston locations as per the designs provided by Scania.

Structure of the system

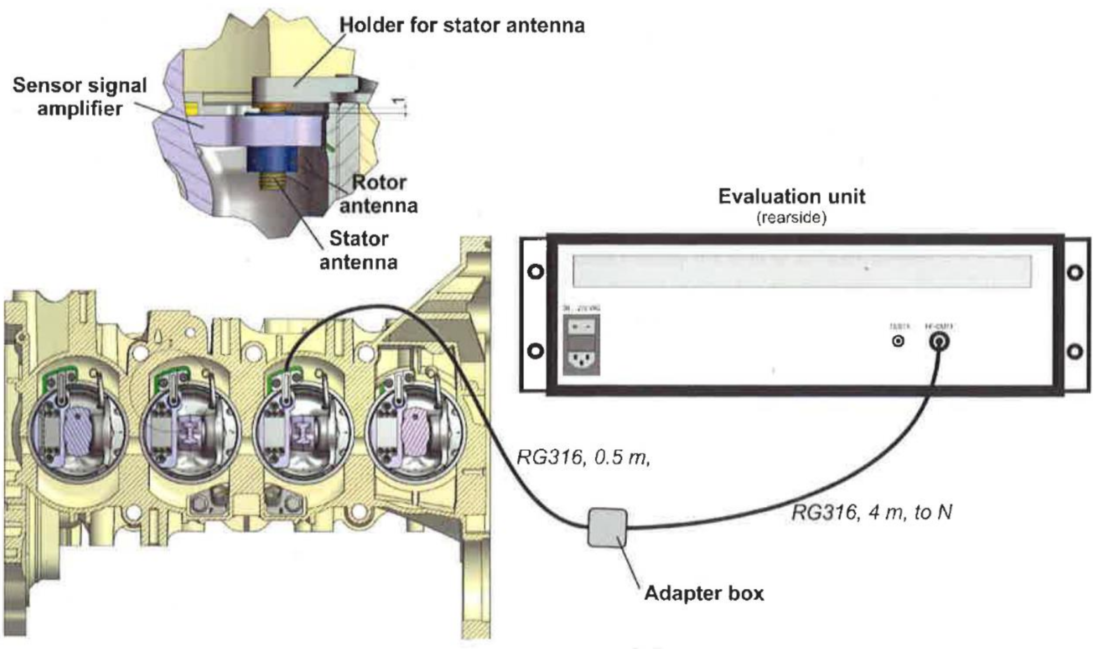


Figure 3.21(a): General layout of the Manner Sensortelemetrie system [29]

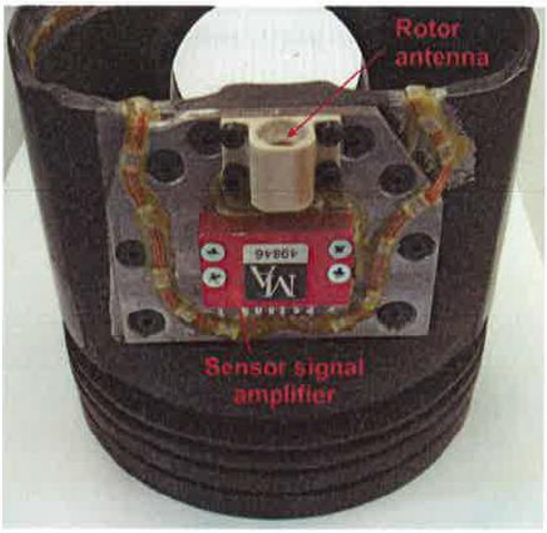


Figure 3.21(b):Modified Manner piston[29]

Technical Data about the components

Sensors and Signal amplifier

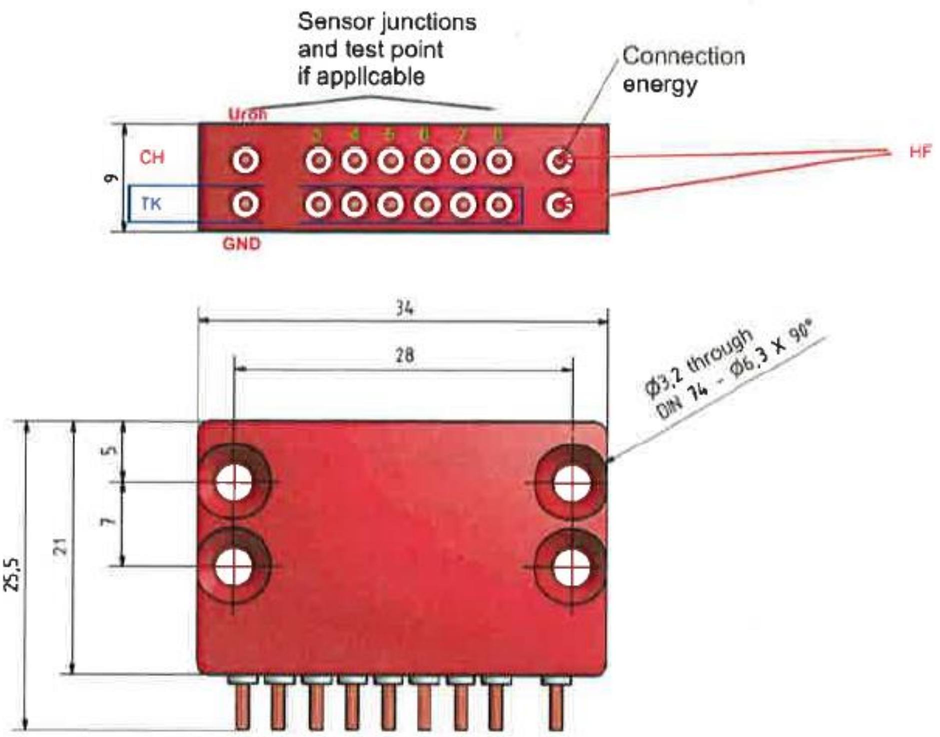


Figure 3.22: Manner signal amplifier [29]

K-type (NiCr-Ni) insulated thermocouple is used in this system. The minimum and maximum measurable temperatures are 0˚C and 650˚C respectively (with adjustment -40˚C to 650˚C).

Total of 8 channels are provided out of which 6 are usable for thermocouples and the remaining two are for the internal temperature and reference voltage. PCM type of modulation with a channel sample rate of 1200 (1/s) was provided. The amplifier can be exposed to a temperature range of -10°C to 180°C. It has a resolution of 12 bit and Zero point drift of 0.02%/°C. The dimensions and notations of the amplifier used is show in figure 3.22

Antennas

The rotor antenna is on the piston and the stator antenna is affixed on the cylinder block. The dimensions of the antennas are shown in the figure 3.23. They must be designed precisely to avoid mechanical interference during operation. The digital data transmission occurs through high frequency (13.56 MHz) inductive coupling and the power supply to the electronics is provided by the evaluation unit through the antennas. For transmitting the complete data package, minimum cross over time should be greater than 1.2 ms. Stator antenna is connected to the evaluation unit through a coaxial cable with an adapter box between them. The antenna are oil proof and work between -10°C to 180°C [29].

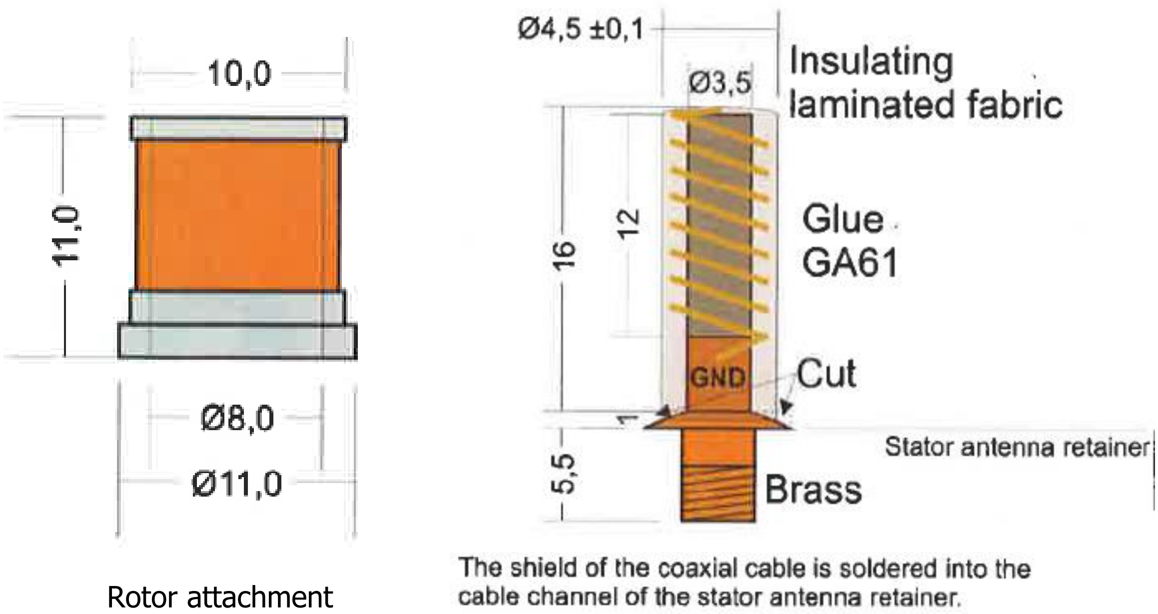


Figure 3.23(a) : Rotor and stator antenna structure and dimensions [29]

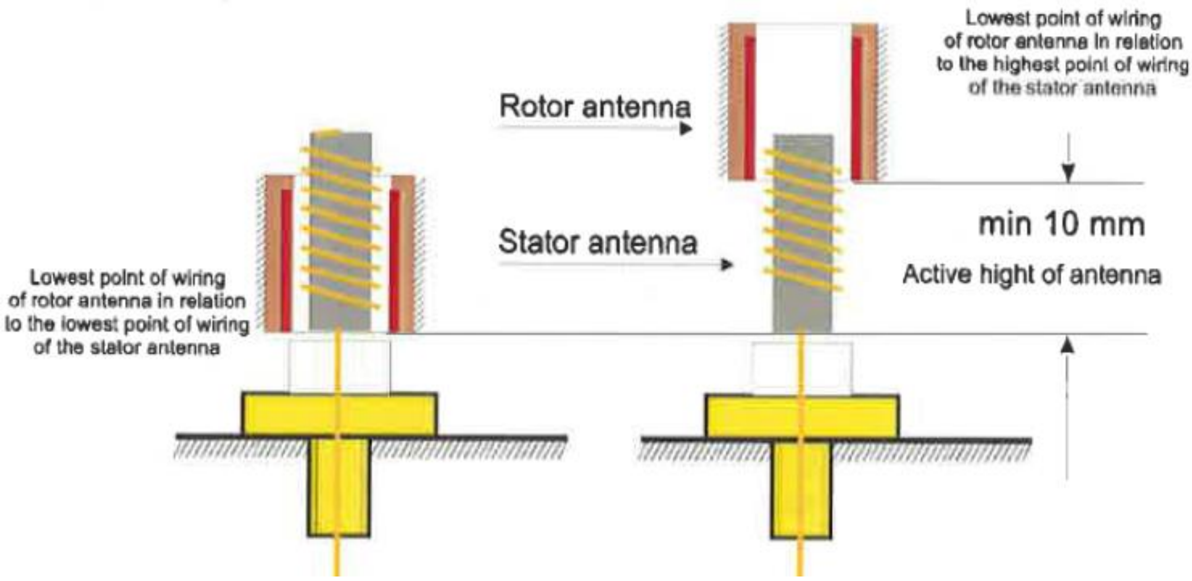
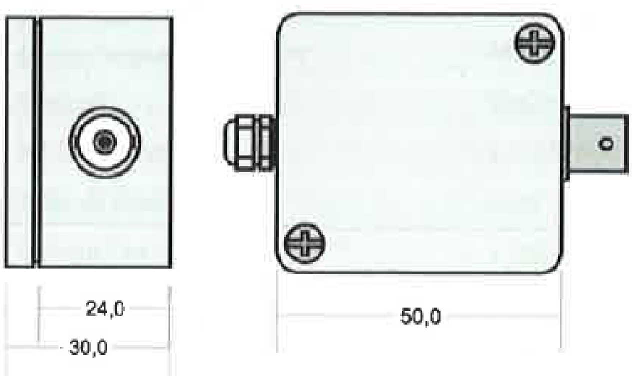


Figure 3.23(b): Rotor and stator antenna structure and dimensions [29]

Adapter box

This component is placed in between the stator antenna and the data processing unit. Its linked through a transmission cable. The figure 3.24 shows the adapter box structure and its interior components. The adapter box is an LC circuit used to adjust the transmission state[6]. It basically consists of an inductor (L) and a capacitor (C) connected together. It is used to generate signals at a particular frequency.



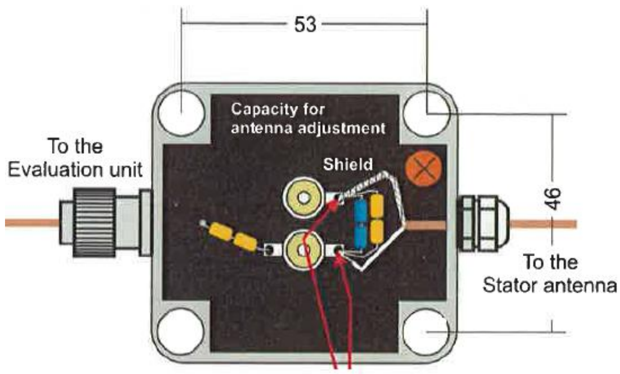


Figure 3.24: Adapter box specifications [29]

Evaluation unit

This unit basically receives all the measurement data from the setup and processes it to display on the monitor. It also acts as a power supply to all the electronics in the system. The front view and rear view of the Manner evaluation unit (8 channel) is shown in the figure 3.25. The required supply voltage is 90 to 270 V AC at 50/60 Hz. Output voltage of 0 to ±10 V can be obtained. The HF (High Frequency) power can be adjusted and varied from 2 to 10 W. The bandwidth of the unit is from 0 to 0.25 kHz. Operating temperature range of the equipment is -10°C to 70°C.

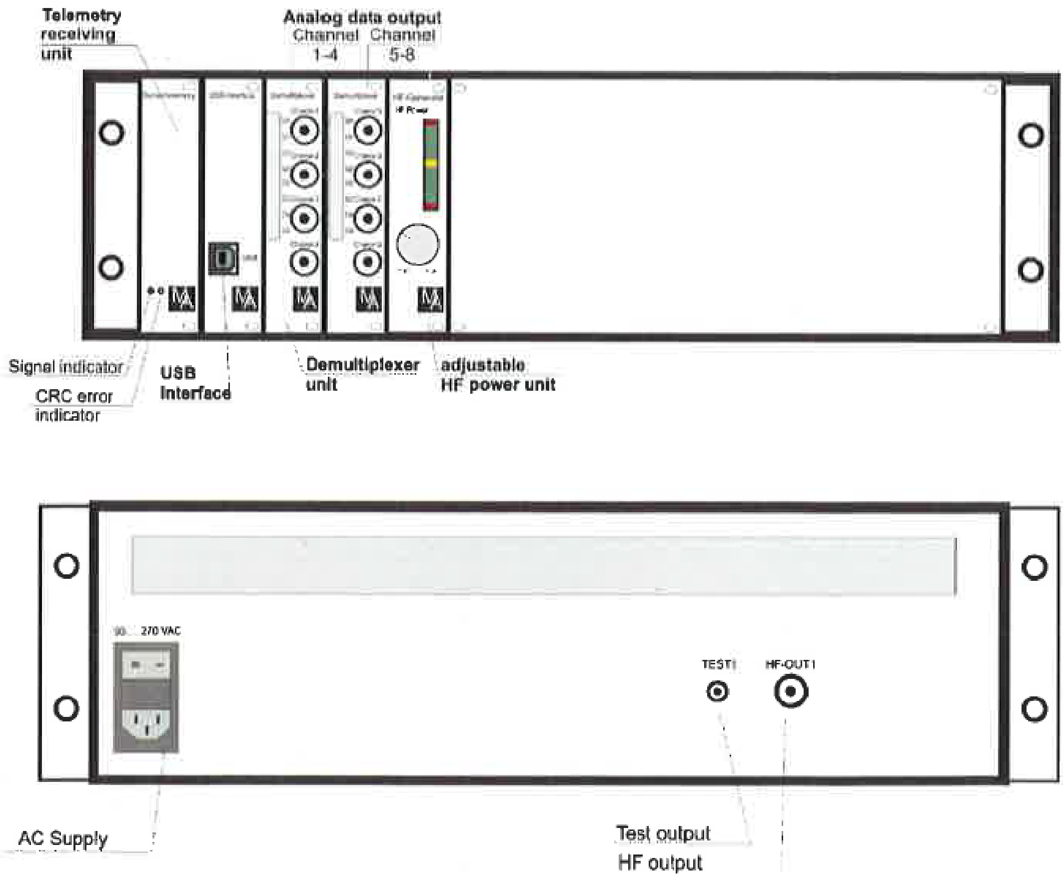


Figure 3.25: Manner evaluation Unit [29]

Single cylinder piston temperature measurements for this study was to be conducted with the help of this system. But due to mechanical interference of the pick-up coil with the crankshaft counterweights because of the difference in stroke of the piston, this system couldn't be used. The main advantages of this system is its low cost compared to other clients, signal accuracy of 0.5°C, less additional weight (5g), quick mounting, high noise immunity and operating temperatures of 180°C.

Datatel Telemetry

Scania bought this system in 2004, it has two different transmitter electronics purchased in April and November of 2004, the same receiver unit is used in both cases. This system is not in full scale use. The temperature measurements are obtained by microwave telemetry.

Structure of the system

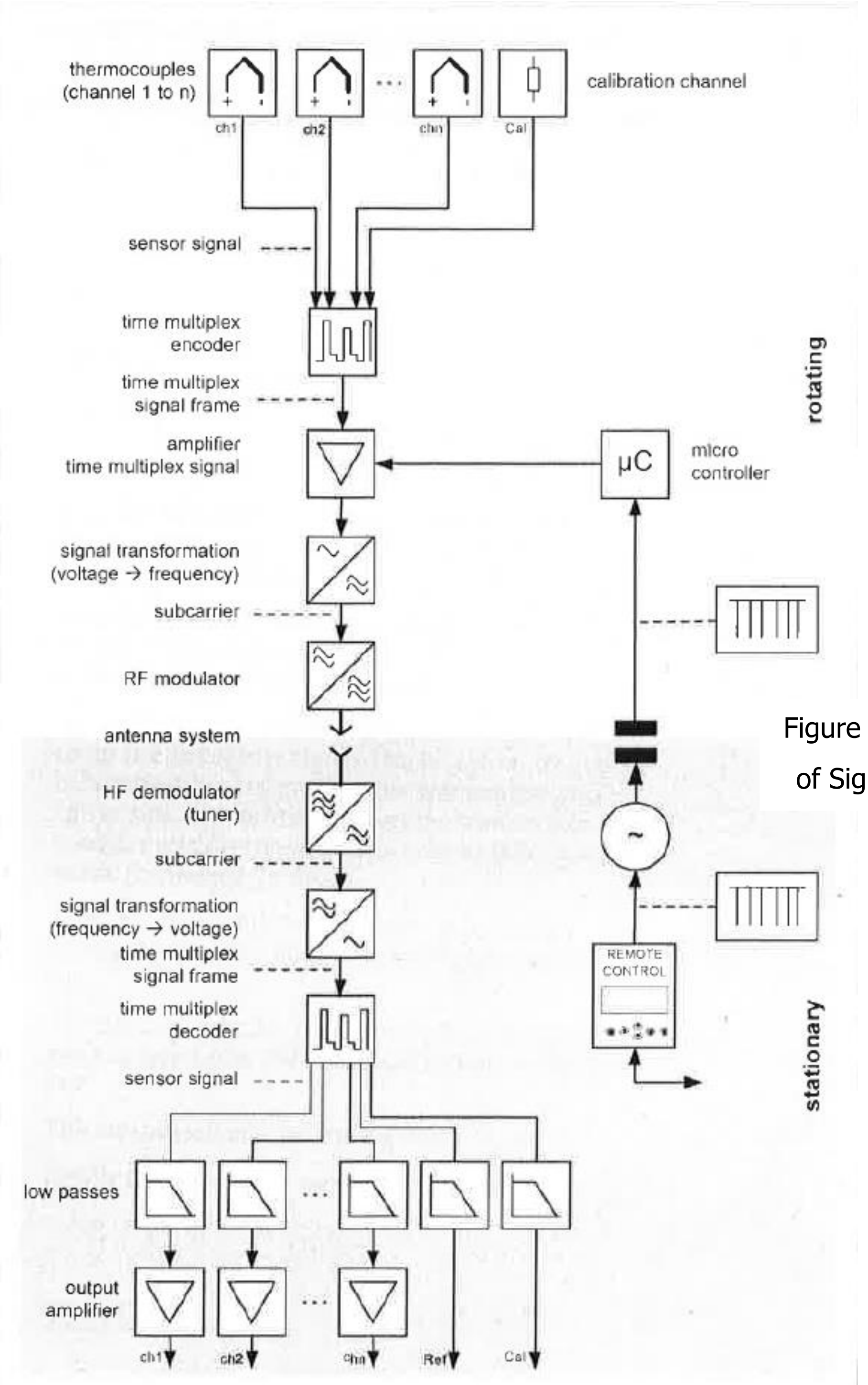


Figure 3.26: Block diagram of Signal processing [30]

The figure 3.26 shows the complete roadmap of the sensor signal from the thermocouples to the display unit. The thermocouple picks up the measurement values, which is then modulated and transmitted with the help of transmitter, which is received by the receiver unit and demodulated back to the original value to be displayed on the PC. The figure 3.27 shows a block diagram of the Datatel system and its major components.

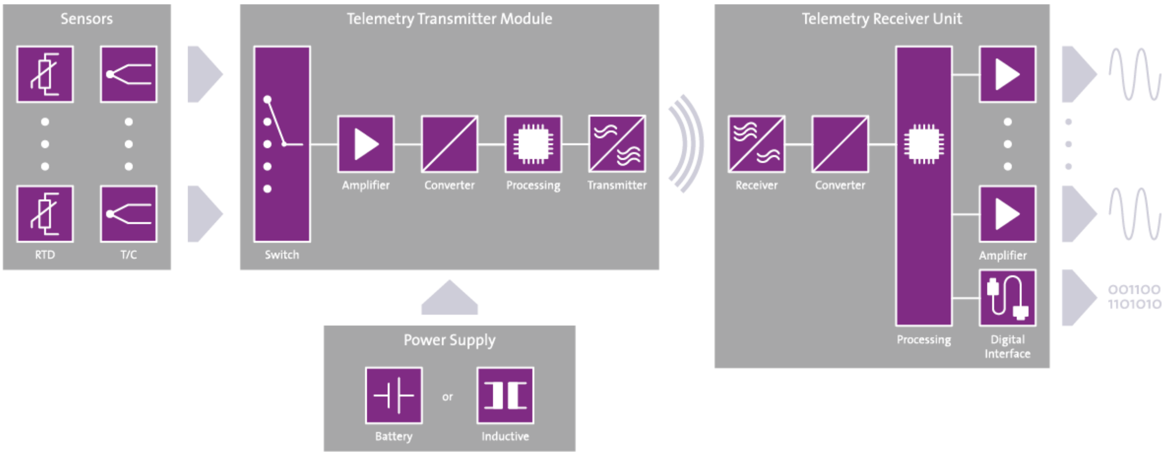


Figure 3.27: Block diagram of Datatel DT 300X Series [31]

Functional principle and technical information of the components

Sensors

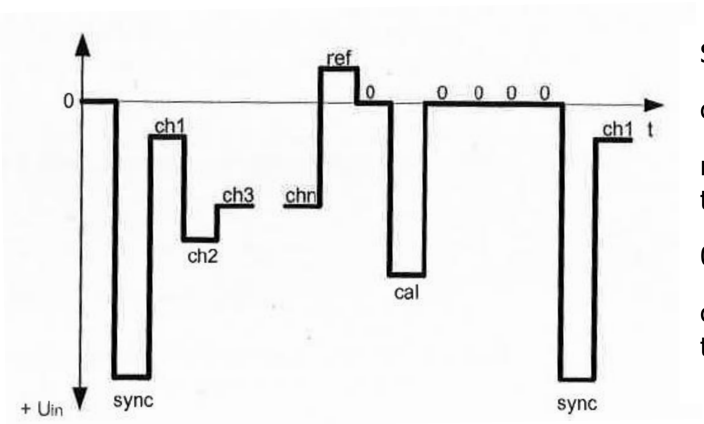
Type K thermocouples are used as temperature sensing element in this system. 8 measuring channels are available with a typical Datatel system. The locations of the thermocouples are decided by the design provided by the customer. Depending on the temperature at the measuring point and at the junction the thermocouple voltages vary. Calibrated reference tables for thermocouple voltage as a function of temperature are provided. The sensors cables are guided through the piston interior up to the transmitter.

Transmitters

The transmitter is the rotating component of the telemetry system. Scania has two transmitters dt3008T-T and dt3009T-TR respectively. Both of them are from the DT 300X series and are very similar in construction and specification except for few differences in supply conditions and measuring range (550˚C and 600˚C respectively).

Both the transmitters are 8 channel DC type with operating range of 0˚C to 125˚C. Both modules approximately weigh 19.3g and consumes about 30mA. The thermocouple leads are all connected to the transmitter channels. Calibration channel allows for signal evaluation for diagnostics purposes. Before the actual measurement process is started all the calibration (thermocouples, transmitter, receiver) are done and the values are tabulated. The transmitter module is composed of the following electronics subsystems.

Time multiplex encoder: This switches the channels consecutively to an amplifier and continuously transmits sensor signals to the amplifier in a particular order. The multiplexed signal can be tapped and displayed on an oscilloscope (Figure 3.28).



Sync: Synchronization Pulse

ch1…chn: Signals of measuring channels

ref: Reference signal for monitoring the transmitter temperature and CJC

0: Check signal "Zero"

cal: Calibration signal for monitoring the transmitter function

Figure 3.28: Time multiplex signal frame [30]

Amplifier: The time multiplex signal frame is conditioned by means of an amplifier. The gain is preset via the micro controller.

Signal transformation: The first modulation of voltage signal into frequency occurs here. A frequency that remains stable against the varying transmitter temperature is obtained. This frequency is called as subcarrier frequency. This frequency is about 165 kHz.

RF modulator: The second frequency modulation, where the subcarrier modulates the RF carrier frequency of the system occurs at this point.

Transmitting Antenna: The RF signal is transmitted out of the rotor system through this antenna.

Power supply:

To conduct all the modulation processes continuously the transmitter requires power. Depending on the application, the power supply is either battery or inductive. This particular system uses battery powering system.

In the stationary part of the system there is a power supply card dt450 which supplies the system with the required DC voltage. The power generator generates a sinusoidal current to supply the transmitter. The amplitude is modulated by the control signal from the remote at the receiver. A coil system is used to transmit the remote information contact free to the transmitter unit. Figure 3.29(a) shows a Datatel Power supply card.

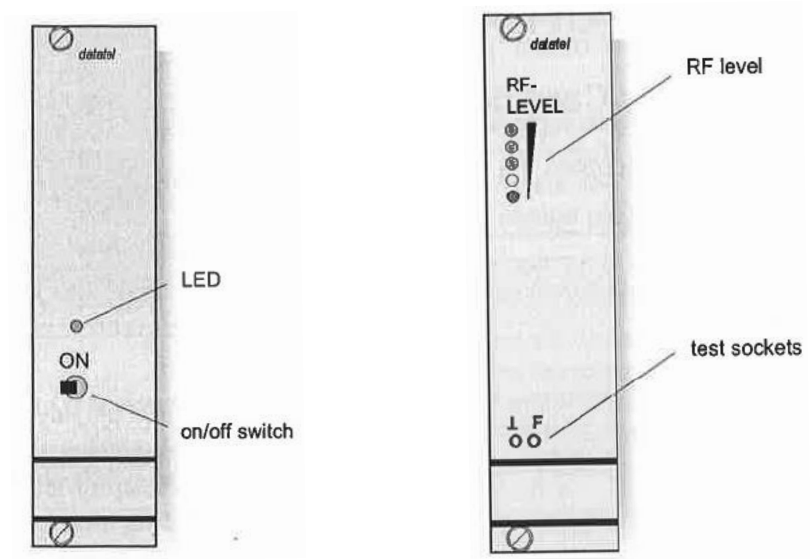


Figure 3.29: (a) Power supply card dt450 (b) Tuner card dt471 [30]

Receiver:

The receiver unit is the stationary component of the telemetry system. It receives and demodulates the signal and outputs analogue voltage signal. External data acquisition system can be directly connected. The detailed systems in the Datatel receiver unit are explained below.

Receiving Antenna: Receives the RF signal and leads it to the receiver unit. This forms the non-contact transmission of measurement data.

RF demodulator and signal transformation: A tuner card dt471 [Figure 3.29(b)] demodulates the RF signal from the receiving antenna and transmits the subcarrier signal to the demodulator card dt401. The demodulator card reproduces the time multiplex signal frame from the subcarrier signal, at this point the signal is converted back to voltage.

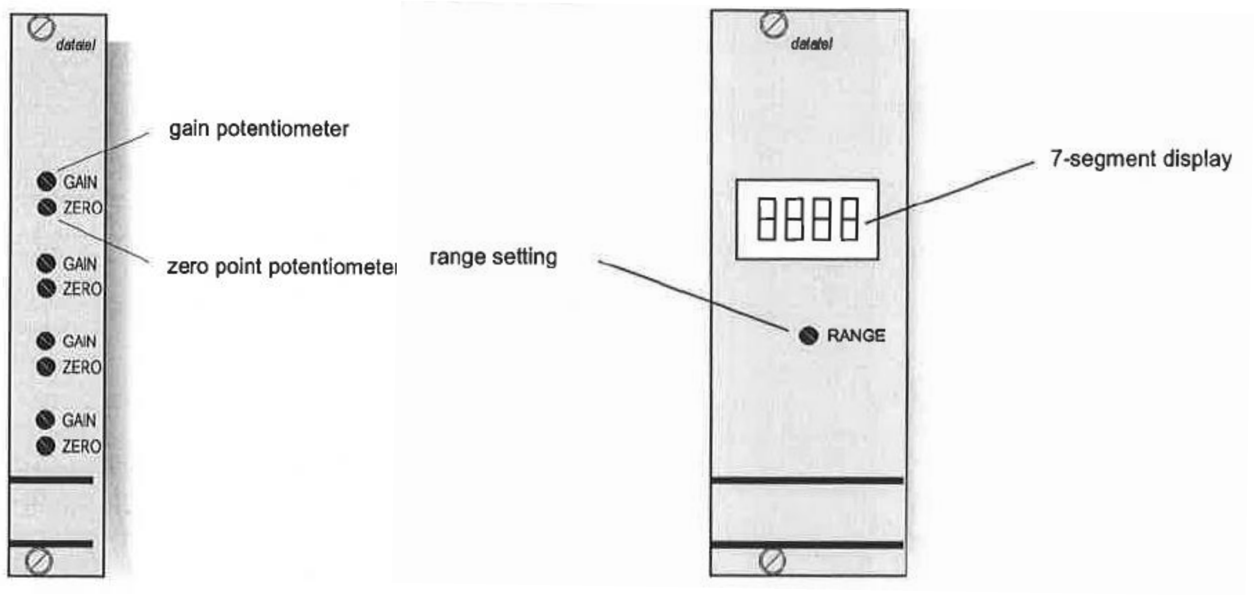


Figure 3.30: (a) Conditioning card dt441 (b) Digital display card dt415 [30]

Time multiplex decoder: Conditioning card dt441 [Figure 3.30(a)]conditions the signals of up to four measuring channels from the time multiplex signal frame and transmits the individual signal to low passes, where the signal is processed.

Output amplifier and Digital display: The signals are analogously amplified. A digital display card dt415 [Figure 3.30(b)] visualizes the output signal proportional to the sensor signal.

The Datatel telemetry system has a 390 μs sample rate per measuring channel and accuracy in the range of 0.3% to 0.5% F.S. The Zero drift and sensitivity drift in relation to the transmitter temperature are 0.005% and 0.02% F.S respectively. The accuracy of the Datatel system is good and it can be run for long duration of testing with the inductive power supply system. In comparison to the Manner system, Datatel can transmit continuous signal over the entire crank cycle with help of multiple antennas. But the piston mounting add up more weight and considering the financial aspect the service provided Datatel system is on the higher side. Also the operating range of Datatel system is only up to 125˚C.

IR Telemetrics

Infrared Telemetrics, Inc. is a USA based worldwide supplier of wireless data transfer from reciprocating and rotating components. Scania CV AB since recently (2018) have been in cooperation with IR Telemetrics. A microwave RF Telemetry unit had been rented for initial testing phase. Modified pistons with sensors at required positions have been received for both temperature and pressure measurements. As expected the organisation has completed a full purchase deal of this telemetry unit in May 2018.

Structure, Signal processing and Principle of Operation

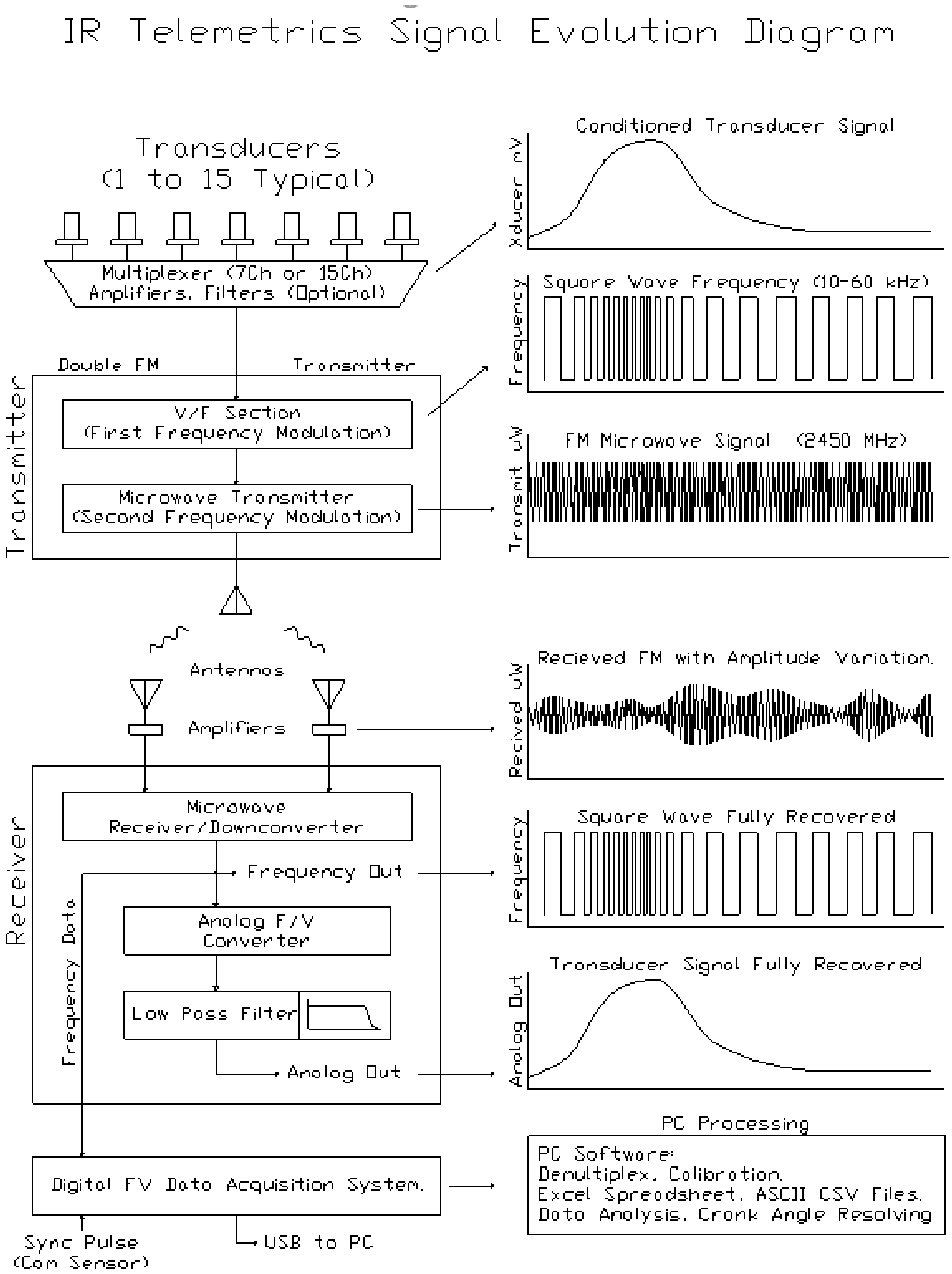


Figure 3.31: Block diagram of signal processing [32]

The signal processing path is similar to the Datatel system with the sensor signal amplified, modulated and transmitted by the transmitter and picked up and demodulated by the receiver to be displayed on the PC. In accordance with the microwave telemetry, the transmitter is mounted on the piston underside with thermocouple leads guided to its channels. The electronics is inductively powered with the pickup coil in IR Telemetrics systems. Multiple receiver antennas are placed in the cylinder block and crank case, therefore there is continuous reception of signal over the entire crank cycle. The data acquisition software records and displays all the measured data and provides for control of supply power and measuring range. Figure 3.31 shows the block diagram for the signal processing in IR Telemetrics.

Systems and specifications

The telemetry system currently at Scania is a multichannel sequentially multiplexed data transfer unit.

Sensors:

Type K thermocouples are used as temperature measuring transducer. 7 or 15 thermocouples can be drilled into pre-decided piston locations, at Scania only pistons with 7 thermocouples are existing. Even pressure sensors can be located into piston locations if pressure data is to be acquired. The thermocouples were placed at a depth of 1mm from the piston surface, with precision drilling [Figure 3.32]. Insulation was done around the thermocouples to protect it from destructive conditions, but it was taken care that it did not vary or deviate the heat transfer coefficient.

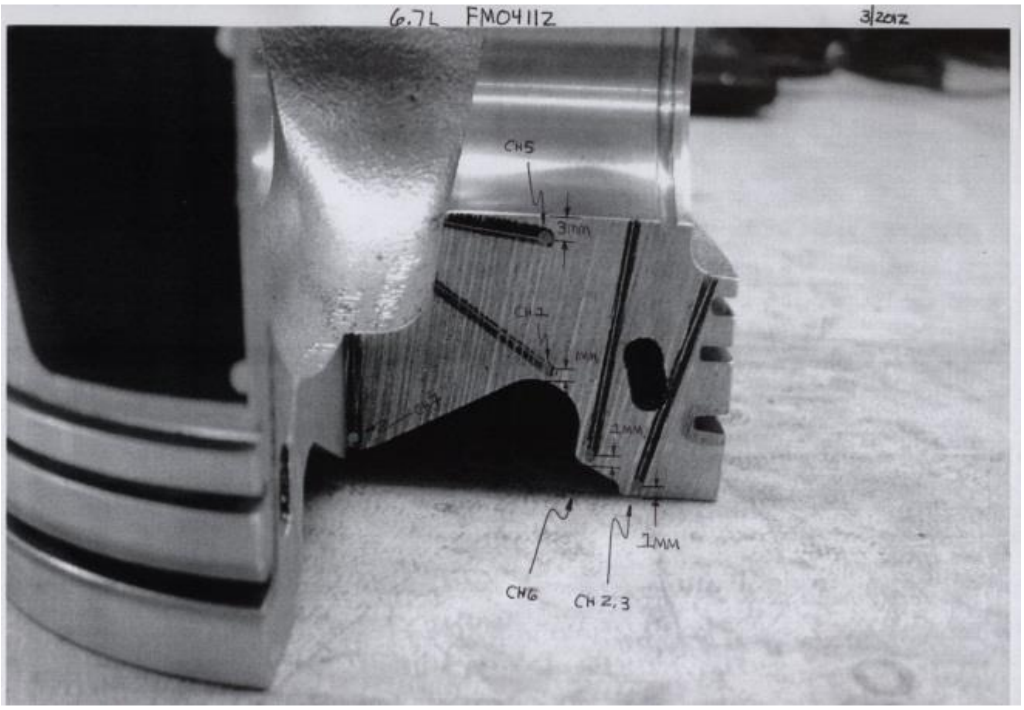


Figure 3.32 : Example of Drill path for thermocouples [32]

Appropriate correction factor for the heat flux and temperature difference is evaluated for the 1mm gap. The thermocouple leads are guided through drilled paths, appropriate adhesives/epoxy are used to keep them in place during high speed and high temperature operations with minimum influence to signal attenuation.

Transmitter Unit:

The guided thermocouple leads are brought to the transmitter location. Figure 3.33 (a) displays the transmitter and the wires leading to it in a test piston. The cables are secured tightly and accurately. The transmitter is custom built according to the requirements. In general they are compact in dimensions. Figure 3.33 (b) exhibits a comparison of transmitter size with a coin.

This unit is installed on the piston as seen in Figure 3.33 (a). It modulates and amplifies the analogue signal received from all the thermocouples and transmits it in a non-contact manner to the outside of the engine. Maximum of 15 data channels are available, but as per requirement of the project and financial difference only 7 channels were used in the current system.

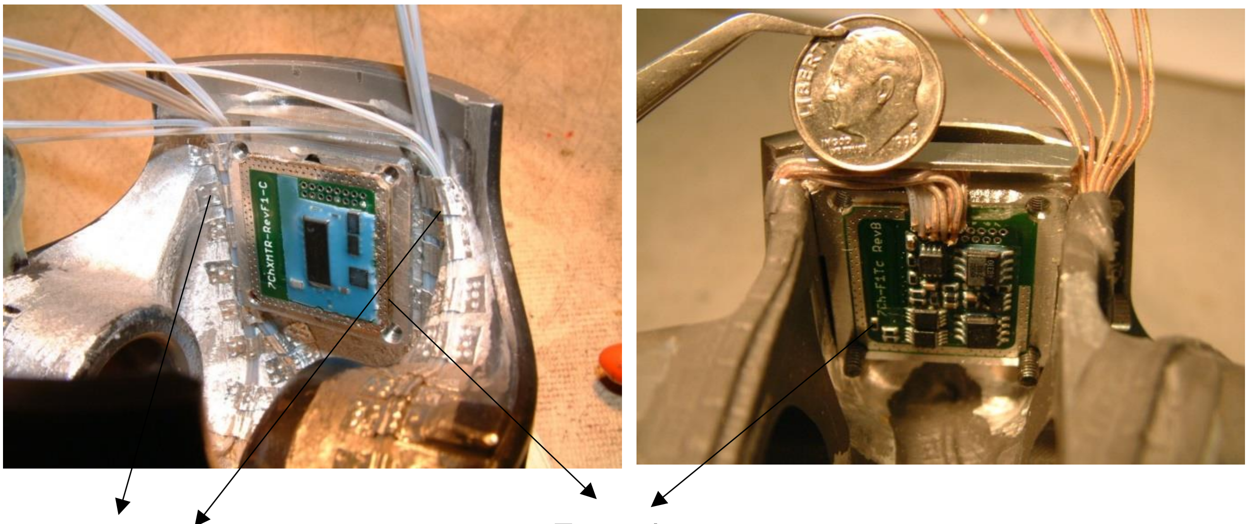


Figure 3.33: (a) Transmitter installation and thermocouple leads ; (b) Display of transmitter compactness [32]

Power supply:

IR Telemetrics offers powering to wireless transmitter unit by either battery power or inductive power supply. Our system was equipped with inductive supply as it was more suitable to the conditions and requirements. Figure 3.34 (a) and (b) show the inductive power supply unit. When the piston reaches towards the BDC the exciter coil mounted on the liner and the pickup coil mounted on the piston interfere and contactless information transfer (transmitter control) and power generation occurs. The power supplied to transmitter electronics is controlled by the frequency supplied to the exciter coil.

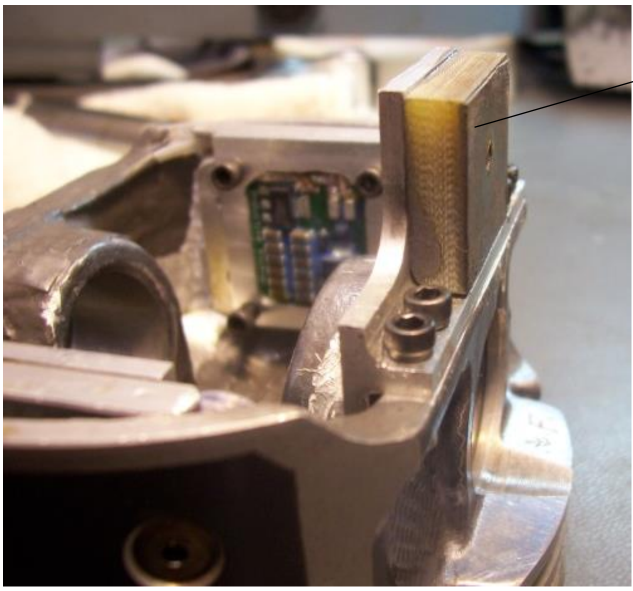


Figure 3.34(a): Piston mounted pick up coil [32]

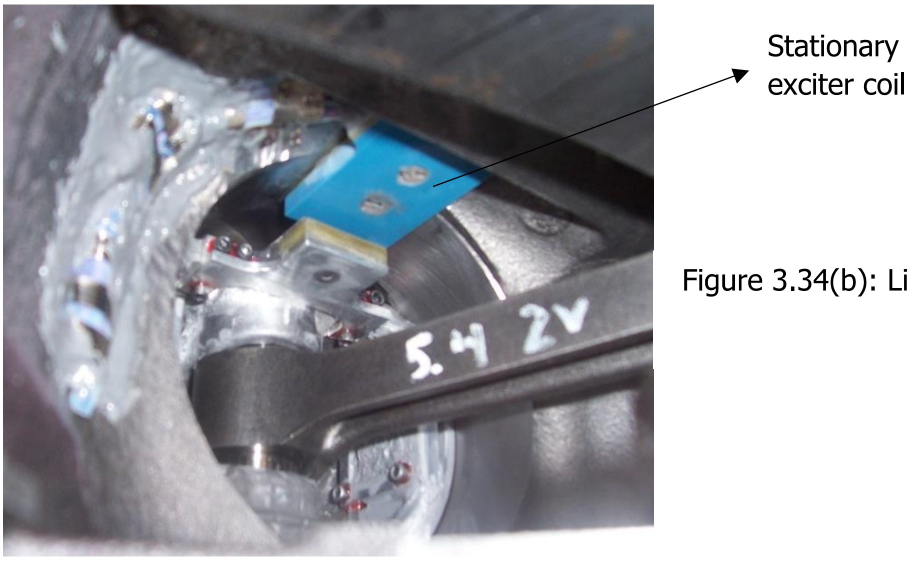


Figure 3.34(b): Liner mounted exciter coil [32]

The below figure 3.35 shows a telemetry piston with all its mountings. Most of the components are custom designed on demand from the customers.

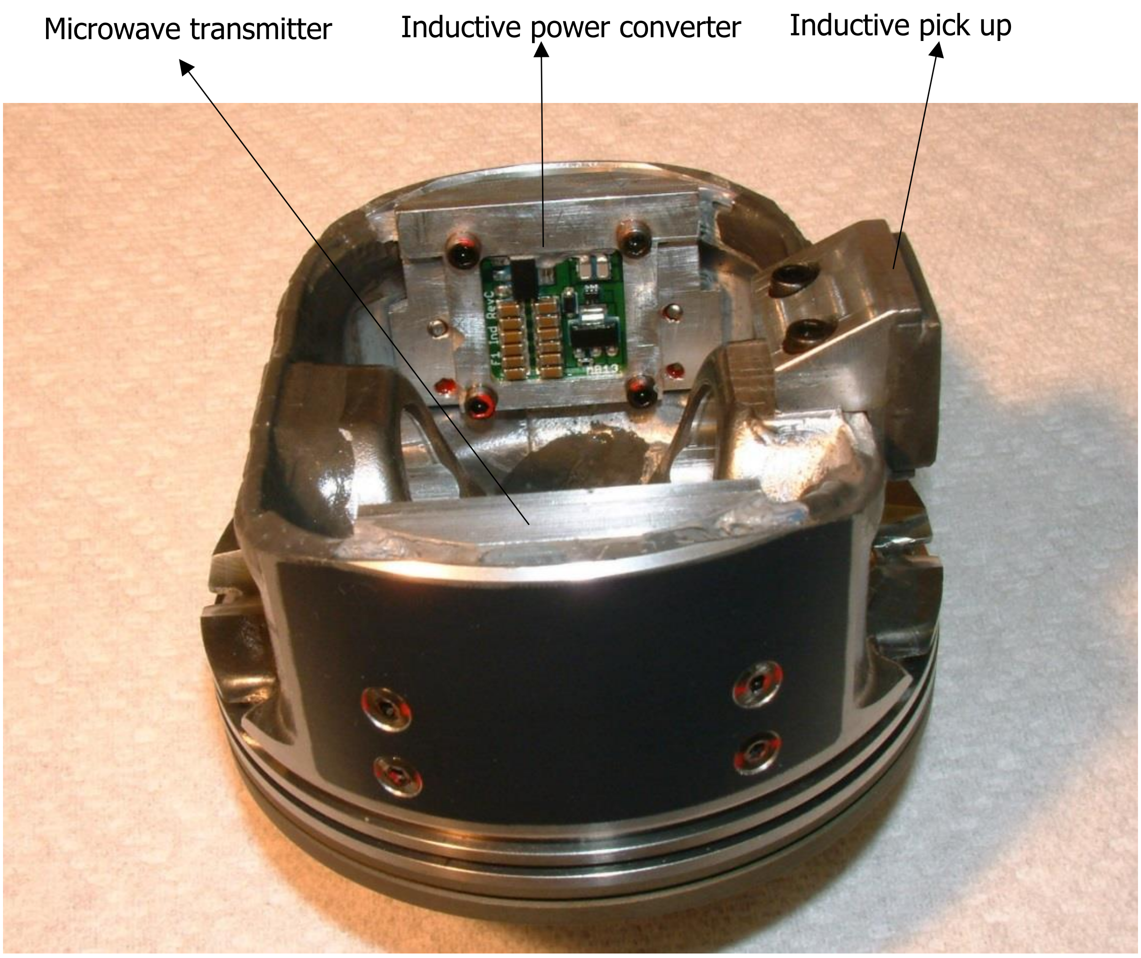


Figure 3.35: Microwave telemetry piston with all reciprocating components mounted [32]

Receiver and Data acquisition unit:

The transmitted signals are received by multiple antennas that are installed in the cylinder block. Figure 3.36 shows an example of receiver antennas installed in an experimental setup. These signals are sent to the receiver unit through high quality cables with low signal losses. The frequency signal is demodulated and converted back to the original analogue measurement values at the receiver. The DAQ software displays the temperature values and required data on the PC monitor. IR telemetrics DAQ system is simple and user friendly. Figure 3.37 shows a complete picture of the bench equipment and the software windows of the DAQ system.

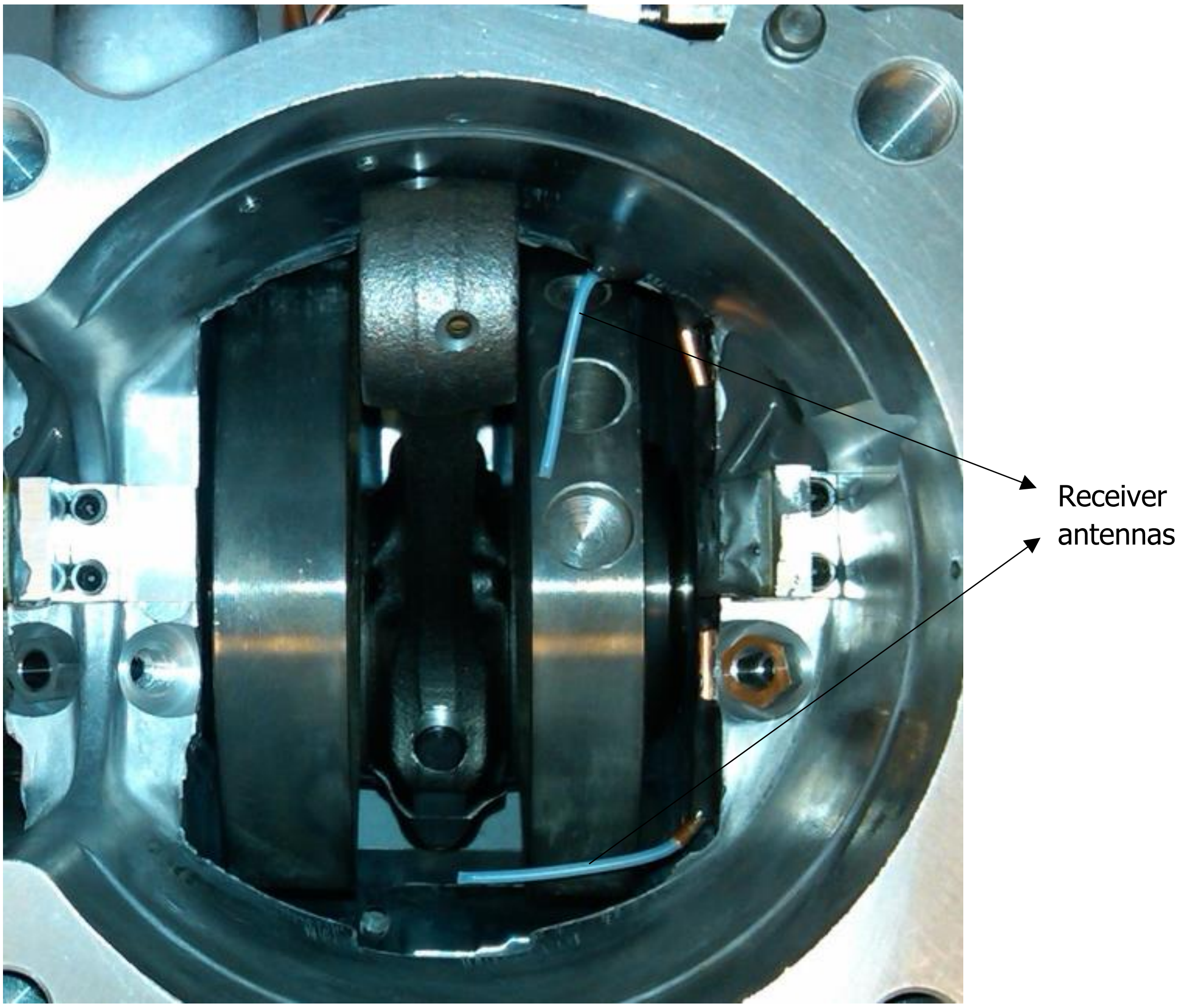


Figure 3.36: Multiple receiver antennas installed at the cylinder block [32]

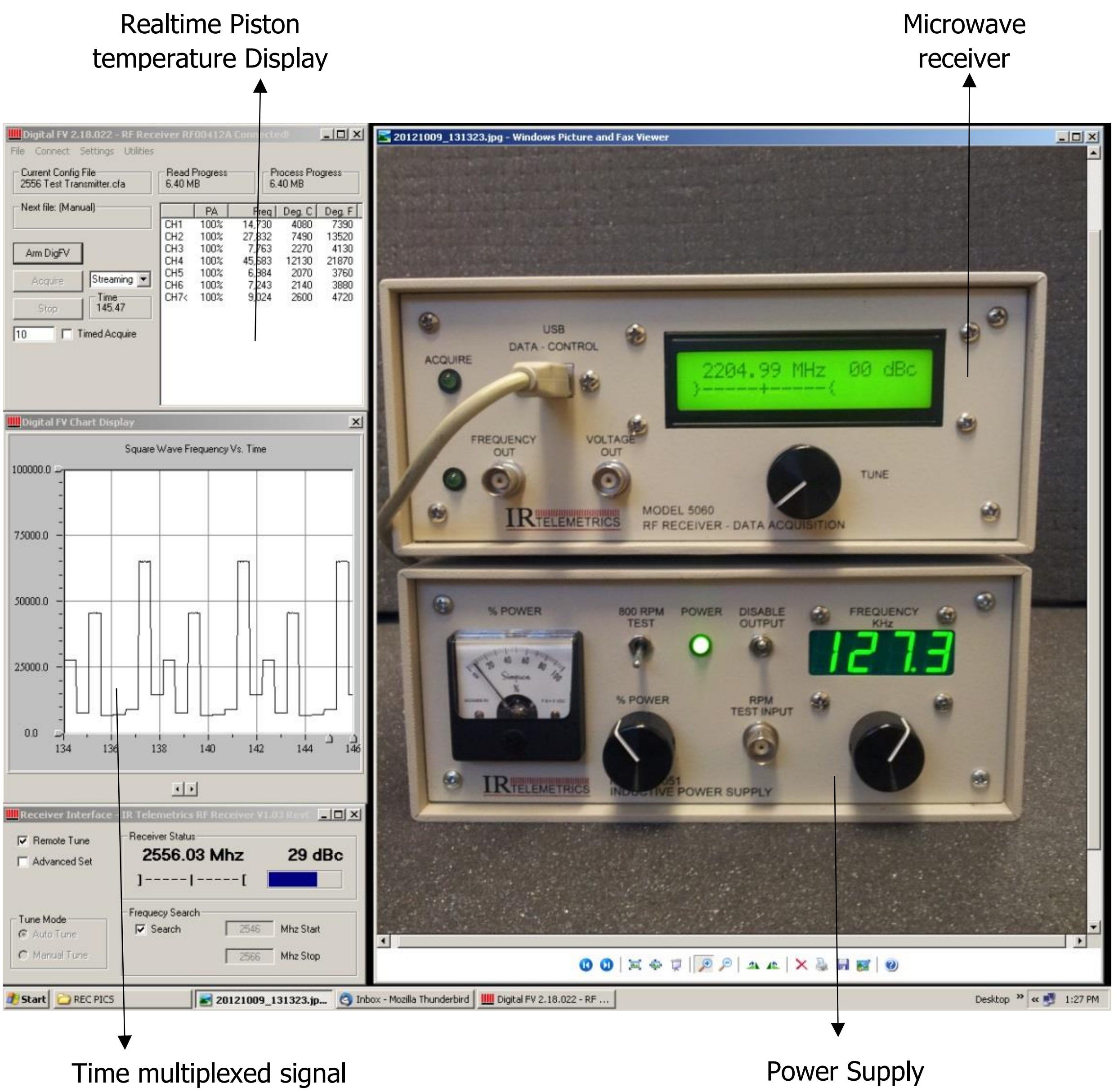


Figure 3.37: IR Telemetrics DAQ software and bench equipment [32]

The measurement conducted with IR telemetrics system were done for a specific SCANIA CV AB project with already pre-defined measurement points. Only single point maximum temperature at various condition were sufficient. Since this was a new system, it was not synced with the AVL PUMA unit.

The measurement done were highly satisfactory. This system offer an accuracy of ± 2% FS with thermocouples as sensors. It has a maximum bandwidth of 10 kHz and electronics operating temperatures of 185°C. There is no speed limitations and system is not constrained by line of sight transmission.

Uncertainty of measurement:

It is a known fact that it is not possible to measure the true valve of a quantity, to compensate this the term uncertainty was introduced. The doubt created due to various factors are quantified.

This section tries to list most of the factors that leads to uncertainty in temperature measurement for above systems and how they can be quantified. Uncertainty is universally divided to two major types

(I). Type A – Quantified using Statistical methods [Measurement data]

(II). Type B – Quantified using calibration and other supplier information

The factors that create uncertainty in piston temperature measurement in telemetry technique are

- The depth at which the thermocouple is placed and the type of bonding used
- Uncertainty generated by the thermocouple
- Uncertainty due to the reference channel
- Amplifier generated uncertainty
- Measurement signal noise uncertainty

To obtain valid surface temperatures the sensors must be as close to the surface as possible, but due to risk of damage to the sensors they are kept at particular depth from the surface and this generates uncertainty. The compensation factor for this is provided by the supplier. This factor depends on various properties such as the material of piston, the method and material of epoxy or bonding used.

Next, uncertainty is generated by the thermocouple (both active and reference). Every system must be calibrated time to time to have acceptable readings. The calibration for the Scania systems are always done by the suppliers and the corrected data charts are provided. Uncertainty in thermocouples are generated due to the resistance in the lead wires and because of zero drift with extended usage.

Input impedance of the amplifier slightly attenuates the sensor signal and this is corrected during the calibration process using the thermocouple resistance and transmitter input impedance values.

Measurement uncertainty can be estimated once the temperature data is available by applying suitable statistical formulas.

It should be noted that numerous repeated sample temperature data must be obtained. Average (mean) of these sample are calculated. It is then subtracted and squared from each individual data point. Sum of these values are calculated and divided over a constant (one less than the number of samples) over a square root, this gives the Standard deviation of the sample space. Uncertainty can easily be calculated by dividing the standard deviation value over the square root of number of samples. The equations below depicts the process of uncertainty calculation.

Number of temperature data points (N)

Individual temperature values (X)

Mean temperature ($\bar{X}$)

Calculate $\Sigma(X - \bar{X})^2$

Standard deviation (σ) = $\sqrt{\frac{\Sigma(X - \bar{X})^2}{N-1}}$

Uncertainty due to measurement noise (U) = $\frac{\sigma}{\sqrt{N}}$

The overall uncertainty of the system is estimated by summing up all these factors. Before summing them up, they are all expressed in similar terms using appropriate statistical formulas.

System / Parameters	Manner	Datatel	IR Telemetrics
Method of working	Inductive signal transfer [7]	Microwave signal transfer [9]	Microwave signal transfer [9]
Power supply	Inductive [10]	Battery [5]	Inductive [10]
Sample Rate	1200 Hz [6]	2500 Hz [8]	50000 Hz [Maximum available] [10]
CA Resolution	Maximum up to 2 CA, but would require supporting systems [7]	Up to 1 CA resolution is possible [8]	With appropriate transmitters 0.1 CA should be possible [10]
Modification	Moderate [5]	Moderate [7]	Moderate [9]
Accuracy	Signal Accuracy – Up to ±0.5 C Overall Accuracy up to ±1.5 C [8]	S/N ratio in the range of 60dB Accuracy up to ±0.3% to 0.5% FS [8]	Thermistors - ±1% Thermocouples - ±2% [8]
Electronics operating temperature	180 C [8]	125 C [5]	185 C [9]

System / Parameters	Manner	Datatel	IR Telemetrics
Financial Aspect	[8]	[6]	[7]
Total Points	59	56	72

Table 3.10: Comparison and ranking of Scania telemetry measurement systems

The ranking points are given in comparison to each other and the maximum point of [10] is given for a positive effect on the respective parameter. Few of the parameters are compared based on the new systems specifications available from the supplier for fair sharing of points.

From the total points it is clear that the IR telemetrics system is more suited for crank angle resolved measurements out of the other systems available. Datatel has the lowest rating but has the ability to better its ranking with upgraded systems from the supplier. Manner system could also improve its rating with upgrades.

3.3 Thermographic Paints

The prospects of thermographic paints for quick surface temperature measurements looks positive and interesting, due to which it was decided that contact with suppliers had to be established, to understand more about the products and its possible usage. In this section discussion about the supplier contacts established and its outcomes along with details about TSP (Temperature Sensitive Paints) are done.

The core requirements for Scania were to have an irreversible, multi-change TSP which would provide an overall temperature profile with minimum piston modifications. Multiple credible suppliers were contacted and details about the discussion are described below.

LabIR:

This company specializes with non-contact temperature measurement with the help of thermographic paints. It is located in Plzeň, Czech Republic and they collaborate with the University of West Bohemia [35]. Contact was established stating the requirements.

This type of paints were not in the range of products offered by LabIR. Their thermographic paints are used to support temperature measurement by IR camera. This would be a process similar to phosphor thermometry and would require optical access resulting to complex modifications. Therefore, the discussion died out.

Olikorm:

OliKrom Smart Pigments is situated in Bordeaux, France. They assist industries throughout the entire technological process, from the conception to the production and integration of the smart pigments [38]. OliKrom does not have any out of the shelf product which could satisfy the current requirements but they are willing to customize it, as that is how they always work. They would research on creating a suitable pigment (matrix) and deposit it on an already available high temperature paint on the market. If the R & D agree on the possibility of such a product, initial conception and production would be initiated. OliKrom have previously cooperated with few aerospace organizations with regards to high temperature sensitive paints.

But naturally all this comes with a price. The initial conception and first prototype delivery would cost somewhere between 15000-25000 euros depending on the time required for production.

Thermal paint services:

USA based Thermal Paint Services (TPS) specializes in single and multi-colour change thermal paints. The organization provide on-site consulting, setup of paint laboratory and technology transfer along with quality thermal paints.

According to the general information provided, TPS have 8 single change and 8 multi-change paints. The paints colour isotherms can be accurate up to ±10°C and interpolation can give accurate assessment of temperature fields [34]. These paints can also survive high temperatures ranging from 176°C to 1380°C and can be applied on variety of surfaces. The 8 multi-change paints and their temperature range are shown in Table 3.20

Paint Name	Temperature Range °C
KN 3A	430-1225
KN 5	140-1250
KN6	158-1380
KN 7A	333-1280
KN 8	350-1050
KN 11	120-300
KN 12	155-290
KN 13	510-1290

Table 3.20: Multi-change Paints (TPS)

Detailed information and quotation for KN 5 and KN 8 paints were requested, as they would be suitable for Scania engines/pistons.

The minimum quantity for ordering is 1 litre but for experimentation by new users 0.25 litre can be ordered. They have had past experience of using paints for other components of engines and turbines. They also mention that in practice there may be limited number of colours (6 to 7) which can be recognized after testing.

The cost of 0.25 litre of both KN5 and KN 8 would be $750.80 each excluding the shipping and consultation charges. The lead time for the delivery of paints would be 2-4 weeks. The figure 3.38 shows the calibration chart for KN 5 paint colour vs temperature.

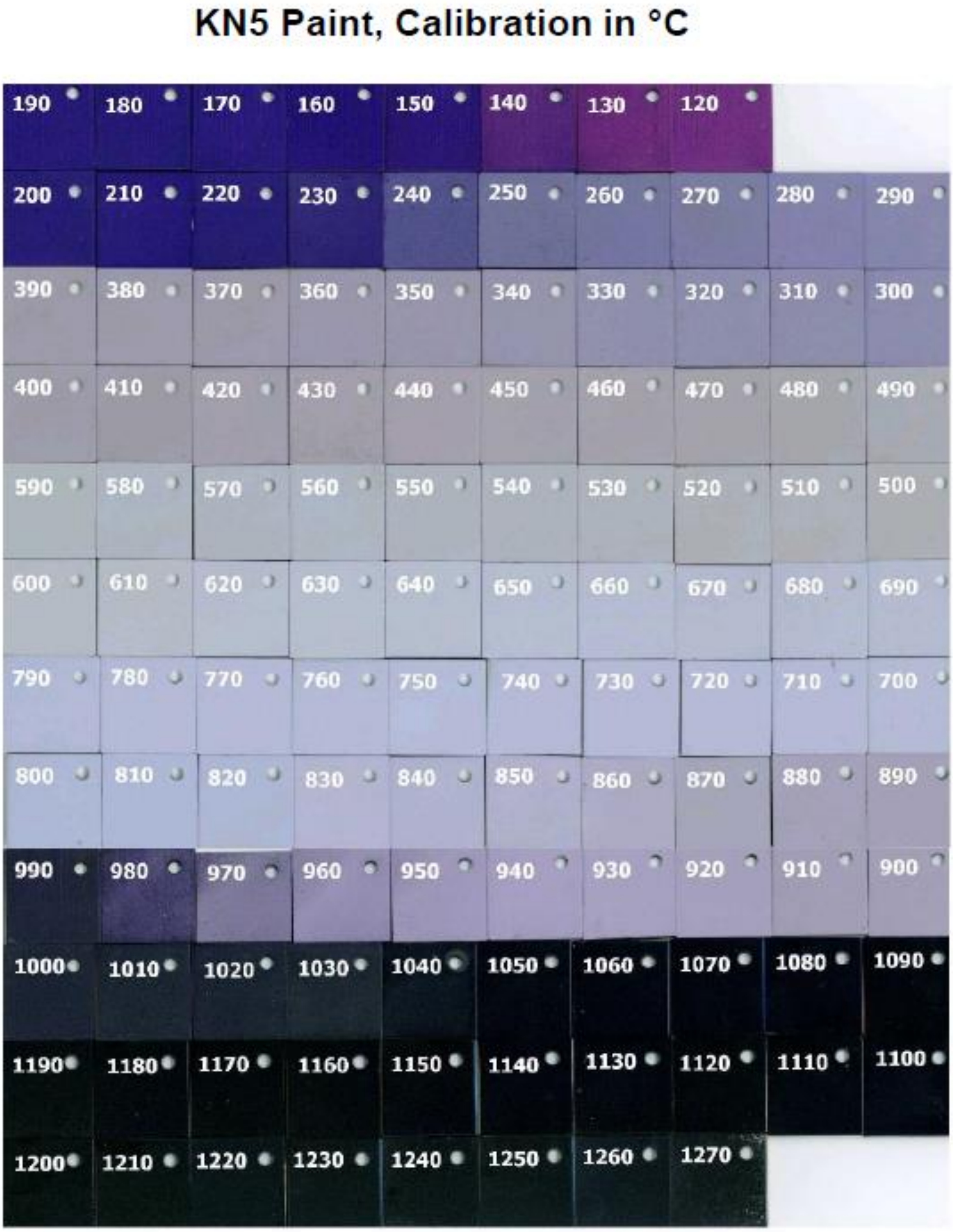


Figure 3.38: KN 5 Paint calibration chart

LA-CO Industries:

After going through the website [37] decision was made to request information regarding their product and if it could fit our needs. They had many high temperature sustainable paints (Tempilaqs) but they were all of single colour change in nature. They suggested the use of different Tempilaqs with varying colour changing nature depending on our predicted temperature values. But this would result in discontinuous in temperature profiling and might lead to increased uncertainty, so it was discarded.

ISSI – Innovative Scientific Solutions, Inc:

ISSI is a R & D company providing innovative measurement and instrumentation solution [36]. They have a detailed explanation of TSP and examples of previous projects. We hoped they had detailed information regarding TSP that could be suitable for piston surface. But their standard TSP's were not capable of combustion temperatures and conditions. But again they had "research high temperature paints" similar to phosphor thermometry. So it was a no go again.

4. Measurement

The measurement run for this research study was conducted on one of the Scania single cylinder research engine (Flex_2). The technical details of the test bench are listed down in the Table 4.10. The piston whose temperature is measured, is a Mahle MonoWeld type. A general Mahle MonoWeld piston is as shown in the figure 4.10. The temperature measurement was conducted with the help of IR Telemetrics system.

Engine Specifications	
Bore (mm)	130
Stroke (mm)	160
Displacement (cc)	2123.72
Compression Ratio	26:1
Number of Valves	4
Injector type	Scania XPI
Number of holes in the injector	9
Injector hole diameter (mm)	0.18
Cup flow (pph)	275
Swirl Number	1.5

Table 4.10: Engine Specifications

Figure 4.10: General Mahle MonoWeld Piston [2]

4.1 Test cell and Piston Preparation

During the initial stages of research, it was decided that the piston temperature measurements would be done with Manner's inductive telemetry system. The thermocouple, inductive electronics installed marine application piston and cylinder liner were already in storage and the missing parts such as the pickup coil and the adapter box were obtained. But during the simulation of the piston motion in Catia, it was observed that the crankshaft counterweights were colliding with the pickup. It was not sensible to do a lot of adjustments, as the piston was scheduled to be run on other projects later this year. This is when it was decided that using IR Telemetrics system would be a better option.

From the above situation, it is easy to see the advantage of Microwave telemetry system, where the receiver antenna can just be setup at a remote location in the crankcase. Also, it was evident from the sample rate numbers that both the systems were unable to obtain the temperature values crank angel resolved. The electronics setup on the IR telemetrics piston was of lower specification due to the fact that the previous projects only required cycle averaged maximum temperatures.

The piston was installed with 7, K-type thermocouple elements which were about 1mm from the surface. The installation of thermocouples and the temperature measurement electronics were done by IR Telemetrics. The locations of the thermocouples were decided by Scania and their details are explained in figure 4.11. The cylinder liner is installed with the inductive supply unit. It is located carefully taking into account the stroke of the engine, to get good interference time for power supply.

The piston and the liner were installed into the single cylinder engine using appropriate conrod and crankshaft. Two ports were required on the engine to lead the wires for power supply and receiver antenna. Figure 4.12 displays how the wires were led out of the crankcase. Only one receiver antenna was setup as it was sufficient for signal reception. Also, voltage converter had to be installed, as the IR Telemetrics systems are rated at 110 Volts.

Single cylinder control and data acquisition were done with the help of a AVL PUMA system. To measure the engine emissions, a Horiba MEXA 7100DEGR was connected to the test engine. This measured the NO_x, HC, CO emissions. The soot emissions were evaluated using an AVL 415S Smoke meter.

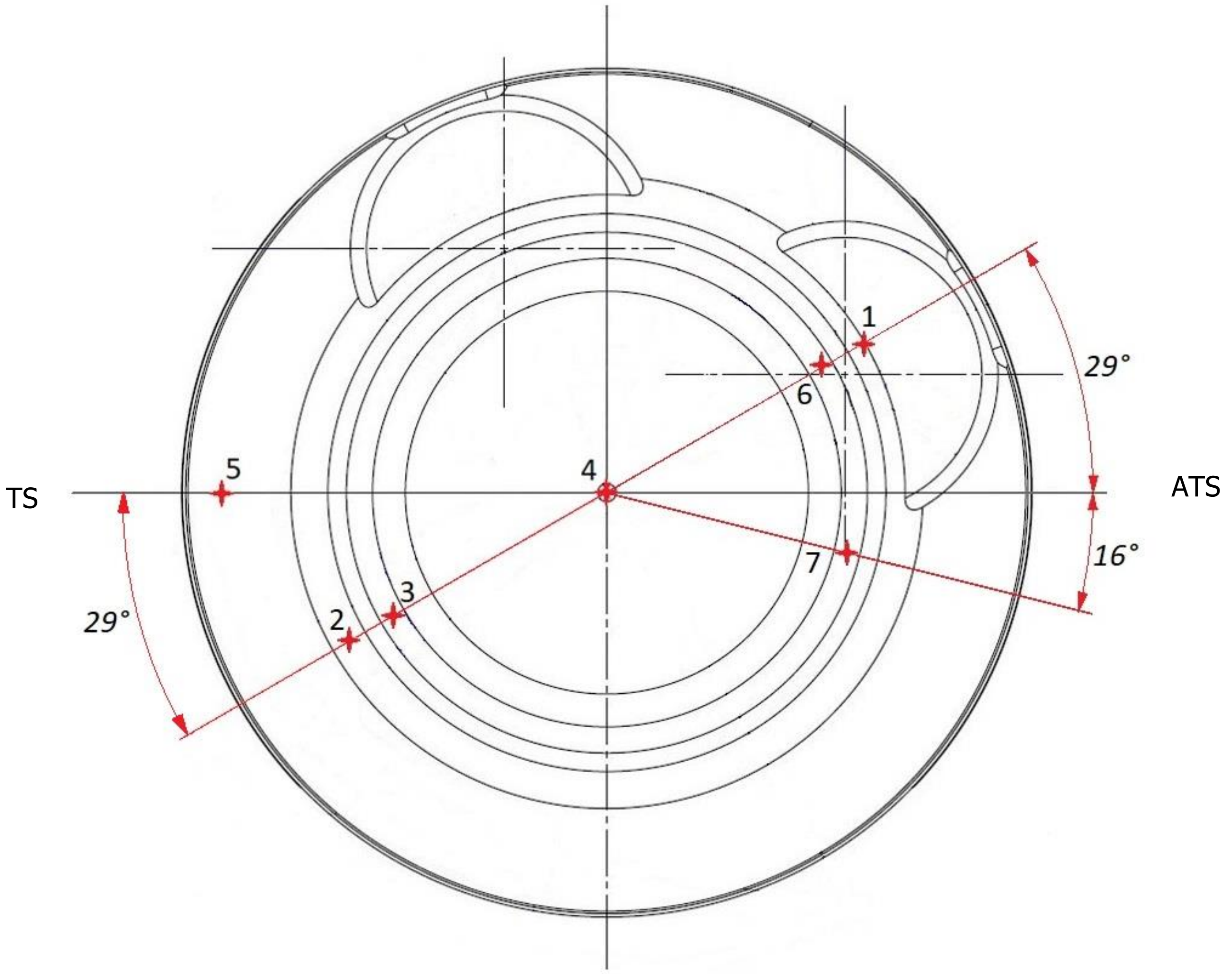


Figure 4.11: Thermocouple locations on the Mahle MonoWeld piston

Thermocouple number	Position
1	Upper bowl rim on valve pocket (29° from antithrust)
2	Upper bowl rim opposite valve pocket (29° from thrust)
3	Lower bowl rim opposite valve pocket (29° from thrust)
4	Centre of piston crown
5	Upper compression ring groove, on thrust
6	Lower bowl rim on valve pocket (29° from antithrust)
7	Lower bowl rim 16° from antithrust

Table 4.11: Thermocouple Location description

This piston has a bowl volume of 60.18 ccm and Compression ratio of 26:1. The inlet valves were at the position where the valve pockets are placed and exhaust valves being opposite to them. The oil inlet to the gallery was close to the inlet valves on the thrust side (TS) and its outlet under the exhaust valves on the antithrust side (ATS). The 9 hole injector was inserted randomly, so the spray cone may or may not be hitting the thermocouples. The fuel used during this measurement run was Diesel. This piston previously had been run for Ethanol fuel based Scania engines. Figure 4.13 shows the single cylinder test cell used for this research study.

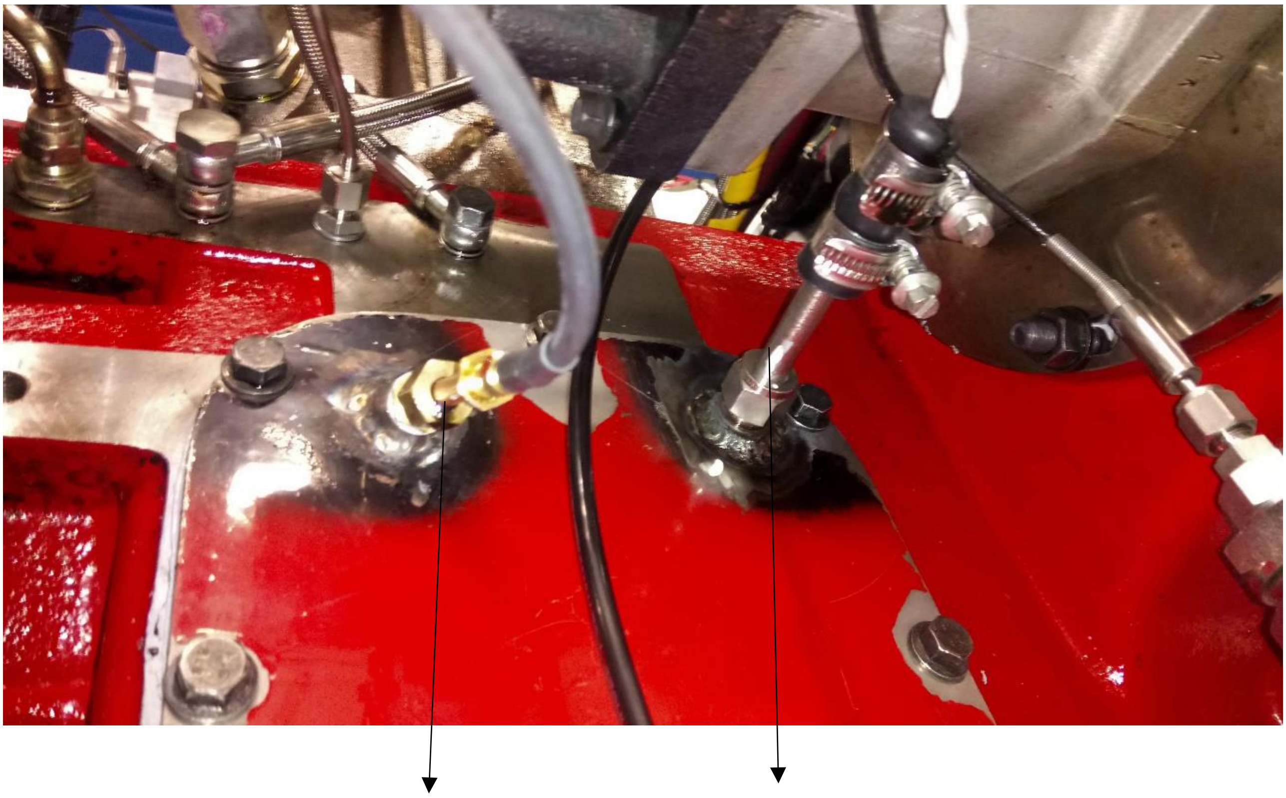


Figure 4.12: Ports for telemetry wires

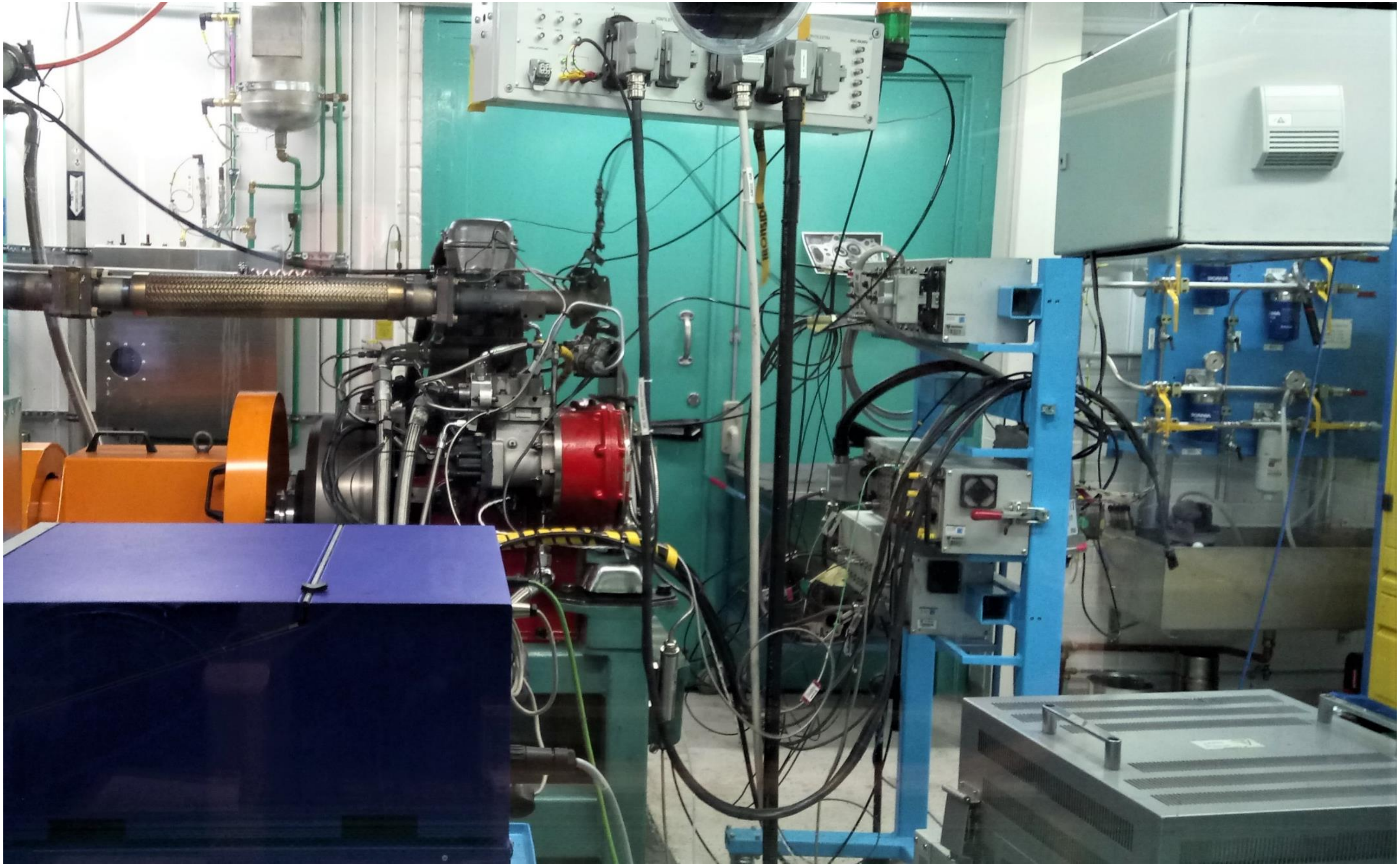


Figure 4.13 - Test Cell overview

4.2 Measurement Plan

After going through all the research papers and literature, a measurement plan was created to understand the influence of piston temperature on various parameters. The table 4.20 lists down the various sweeps that were planned to run during this measurement period.

Test Number	Parameter evaluated	Load in %	Water/Oil temperature in °C	Speed in RPM
1	Motoring	Motoring	80,80	1200 Constant
2	Speed Sweep	25	80,80	800 – 1800
3	Speed Sweep	50	80,80	800 – 1800
4	Effect of Oil temperature	75	80,60	800 – 1800
5	Effect of Oil temperature	75	80,80	800 – 1800
6	Effect of Oil temperature	75	80,100	800 – 1800
7	SOI	75	80,80	1200 Constant
8	SOI	50	80,80	1200 Constant
9	SOI	25	80,80	1200 Constant
10	Lambda Sweep	50	80,80	1200 Constant
11	Rail Pressure sweep	50	80,80	1200 Constant

- Data successfully obtained (green)
- Failed to obtain data (yellow)

Table 4.20: Overview of test points

The speed sweeps were planned to be conducted between 800 RPM and 1800 RPM with 200 RPM intervals. The load would be varied by changing the amount of fuel quantity injected. 25% load is about 60 mg/injection. 50% and 75% are 120 and 180 mg/injection respectively. The SOI sweep were hoped to be conducted by retarding the injection from -8 °CA to 2 °CA by varying 2 °CA in each step. Lambda sweep were planned to be done from 1.6 to 2.8 at 0.4 step by keeping SOI constant at -4 °CA. Rail pressure sweep were planned to be done from 700 bar up to 1700 bar with 200 bar steps, Lambda kept constant at 2.4.

With successful completion of all the measurement points, discussions regarding results and trends followed by the Scania designed piston bowls could be made. In addition to that, verification of the results and statements mentioned in the literature review section can be done.

4.3 Measurement preparations

The IR Telemetrics system was fairly new and the system software interface had not yet been fully understood. This is why the temperature information obtained by the IR Telemetrics could not be synced into the AVL system. The temperature data obtained by the receiver was stored locally in a different PC for this study. System engineers were working on linking the two systems for easier and faster processing in the future.

It was decided to run an automatic test of all the points using the XLS test feature on the PUMA software. For this, all the test points had to be encoded in detail on an excel sheet. Doing the automatic measurement meant that some sort of link between the IR Telemetrics and the PUMA system was required, so that it was possible to trigger the IR system to initiate measurement and stop measurement. This link was obtained through a basic COM (Communication) port. This also meant that the protocol names of both the PUMA data and the IR Telemetrics were synced, to make the data analysis easier.

Before writing the excel code it is necessary to check manually, few of the points which might create issues with peak pressures and emission limits (as the piston was designed for ethanol fuel). Also, recalibration of the values of inlet charge pressures and exhaust back pressures are done to simulate the effect of turbocharger. Once these values are obtained, the detailed excel code for the measurement run is written. The main parameters that need to be defined are Engine speed, load, rail pressures, injection timing, inlet charge pressure, exhaust back pressure and oil temperature. Definition of time for change of operating conditions and appropriate time for stabilization of all the parameters must be written. The time for measurement of all the data also set, which was 60 sec for all points. The time for the engine to change the operating parameters was also 60 sec. The stabilization time was varied depending on how drastic the change was, it varied from 480 sec to 180 sec.

The engine is preheated for some time before the start of measurement. Then the .csv file is read and the automatic measurement is initiated. Close watch on the IR Telemetrics system is a must, as in the event of engine shut down, it needs to be turned off immediately. The reason for this is, in case the piston stops at BDC then there will be constant supply of power to the transmitter electronics which might result in complete destruction of the module.

4.4 Data Acquisition

At all the measurement points, once the engine parameters have stabilized, the data were acquired for 60 sec. The engine data were all recorded by the AVL and Horiba system and stored into the server. The piston temperature were acquired by the IR Telemetrics and stored in the .prh file format locally.

During the acquisition, the IR telemetrics system has to be set in particular power and frequency range to obtain the best signal. The power supply was set to 40% power and the supply frequency was held as stable as possible at 187 kHz. The receiver was set to scan frequency between the range 2390 MHz to 2400 MHz. The figure 4.40 show the IR Telemetrics system during the acquisition process.

Figure 4.40: IR Telemetrics setup during data acquisition

The only way to read the acquired temperature data in .prh file is to convert it to .csv format. This can be done only using the IR Telemetrics software as the data in .prh is not in pure ASCII format. The IR software reprocesses the .prh into .csv which can be opened in excel and sorted accordingly.

On observation of the .csv file it was clear that the transmitter sends an average of 15 setpoints of data for each channels in about 60 sec. From this, an estimation that the transmitter switches between channels on an average of 0.5 sec/channel can be made. Also, it should be noted that the obtained temperature is cycle averaged for the instant of measured time. IR Telemetrics system converts the received frequency value to temperature using a simple formula as seen below.

$$T = 19.7243208E\text{-}3 \bullet F - 272.8951174$$

Where, F = Transmitter output frequency in Hertz

T = Thermocouple temperature in degree Celsius

4.5 Data Analysis and Discussions

After setting up the test cell, understanding all the procedures and completing all the prerequisites, the engine is run for decided test points. 50% of the planned test data were successfully obtained. Test point number 1-6 as seen in table 4.20 were completed. Unfortunately due to fatigue issues the coupling between the flywheel of the single cylinder engine and the dyno failed, and due to time constraints between the submission of the thesis report and the process of obtaining the spare part, the remaining points were not completed.

This section of the report will deal with the discussions about the successfully obtained data and our conclusions. All the temperature values are normalized considering a suitable coefficient factor due to confidentiality reasons.

Motoring

The engine was run at a constant speed of 1200 RPM and stabilized. 3 sub measurements were taken by varying the intake charge pressures or boost pressure. The engine is allowed to stabilize in-between each points. Both the coolant and Oil temperature were held steady at 80 °C. The figure 4.50 shows the trend of piston temperature with boost pressure for various thermocouple location.

It is clearly visible that the piston temperature increases almost linearly at all TC locations with increase in boost pressure. Increasing the boost pressure results in increase of the air mass flow into the cylinder. This means that more compression work needs to be done by the piston. Also, increase in boost pressure results in increase in turbulence and density inside the cylinder. Both these parameter influence the heat transfer coefficient positively, hence increasing the overall piston temperature.

We observe a maximum of 23.68% rise in piston temperature at the upper bowl rim region (TC1), similar value is observed at TC2. Both these points are the closest to the inlet/exhaust valves and are topmost point among all the TC locations. Minimum temperature rise of 17% is noted at TC6.

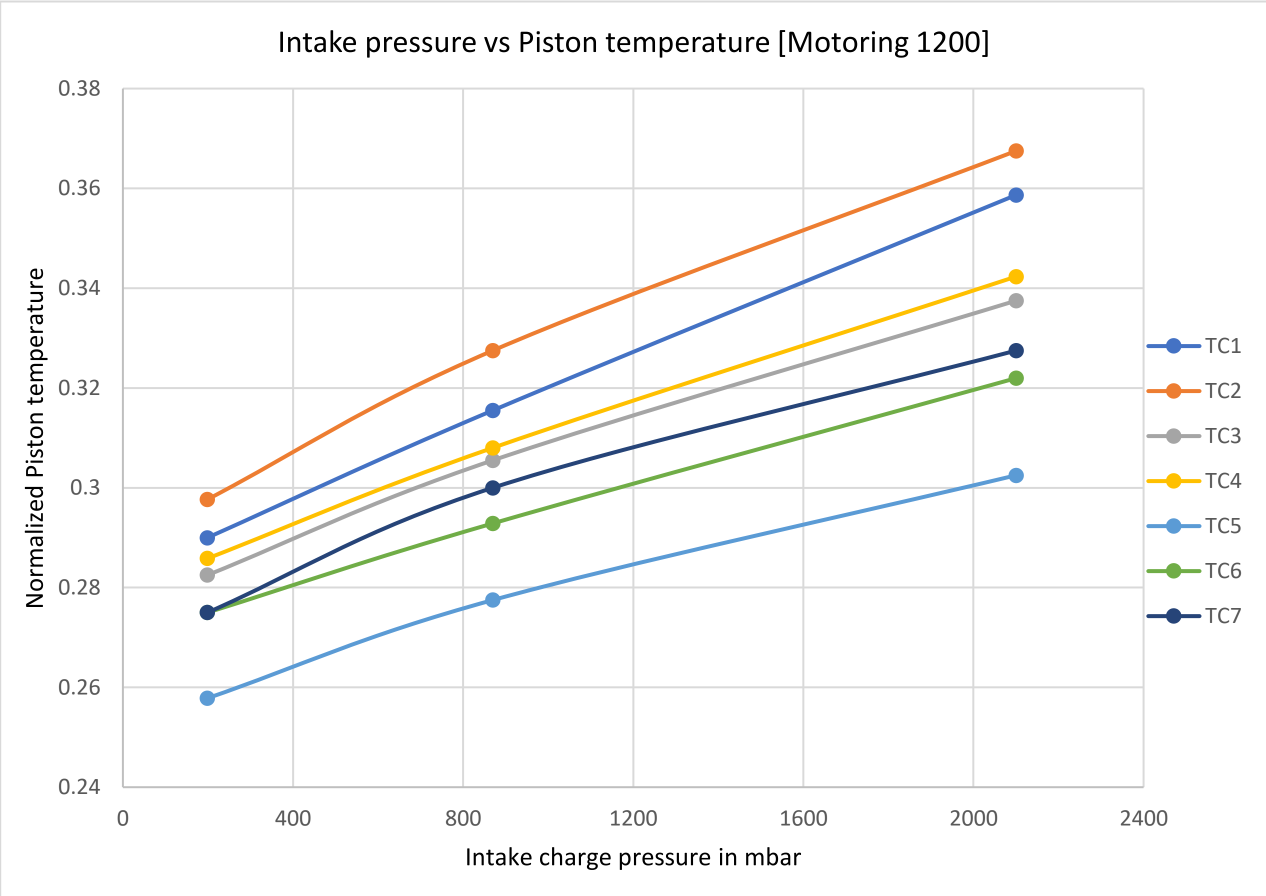


Figure 4.50: Normalized Piston temperature vs Intake pressure [Motoring]

According to me, we would see similar trends of increasing piston temperatures with increasing in charge pressures even during the combustion phases. This increasing piston temperatures might influence the volumetric efficiency negatively. It should also be noted that the inlet temperature was also maintained at 30 ˚C for all measurements in this report.

Speed sweep at 25% Load

The engine is run at a constant load of 25% by supplying/injecting a constant fuel amount of 60 mg/injection. The oil and coolant are both held steady at 80 °C. The RPM is varied from 800 to 1800 at steps of 200 RPM. The figure 4.51 shows the trend of piston temperature with the increase of RPM for different thermocouple locations.

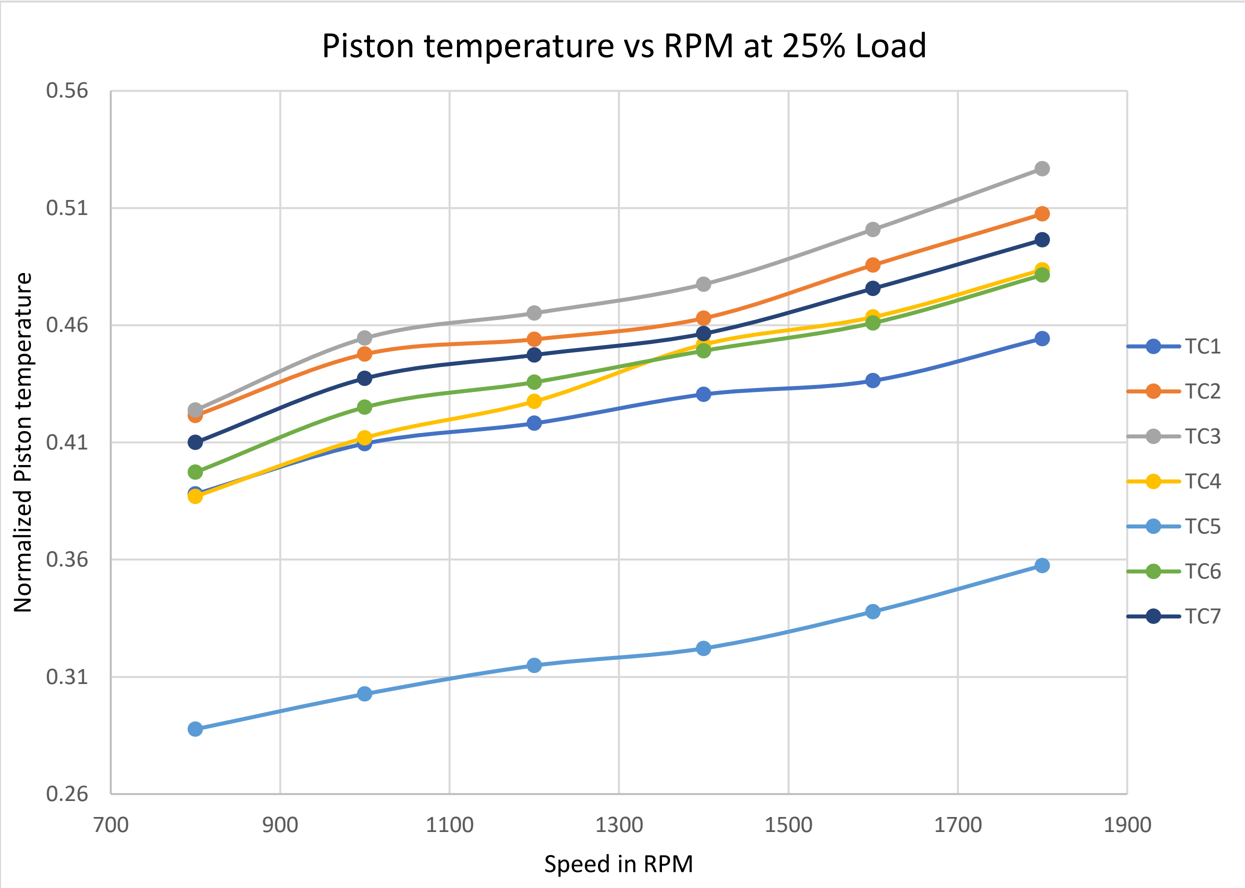


Figure 4.51: Normalized Piston temperature vs RPM [25% Load]

Looking at the graph, an obvious trend of increase in piston temperature with increase in engine speed. This may be because of increased friction, increased turbulence, increased number of combustion/sec. We observe a temperature rise of 25% at thermocouple location 4 (center of piston crown), but we have comparable rise in all the TC locations. The maximum temperature is reached by the TC3 which is at the exhaust side, so it make sense for it to be the most heated point. In comparison TC6, which is radially at similar location but at the inlet side is on an average 8% lower than TC3.

Speed sweep at 50% Load

The engine load was kept constant at 50% by suppling 120mg of Diesel per injection. Speed was varied from 800 to 1800 RPM with most of the parameters similar to the previous run at 25% load. Figure 4.52 depicts a trend of piston temperature with engine speed.

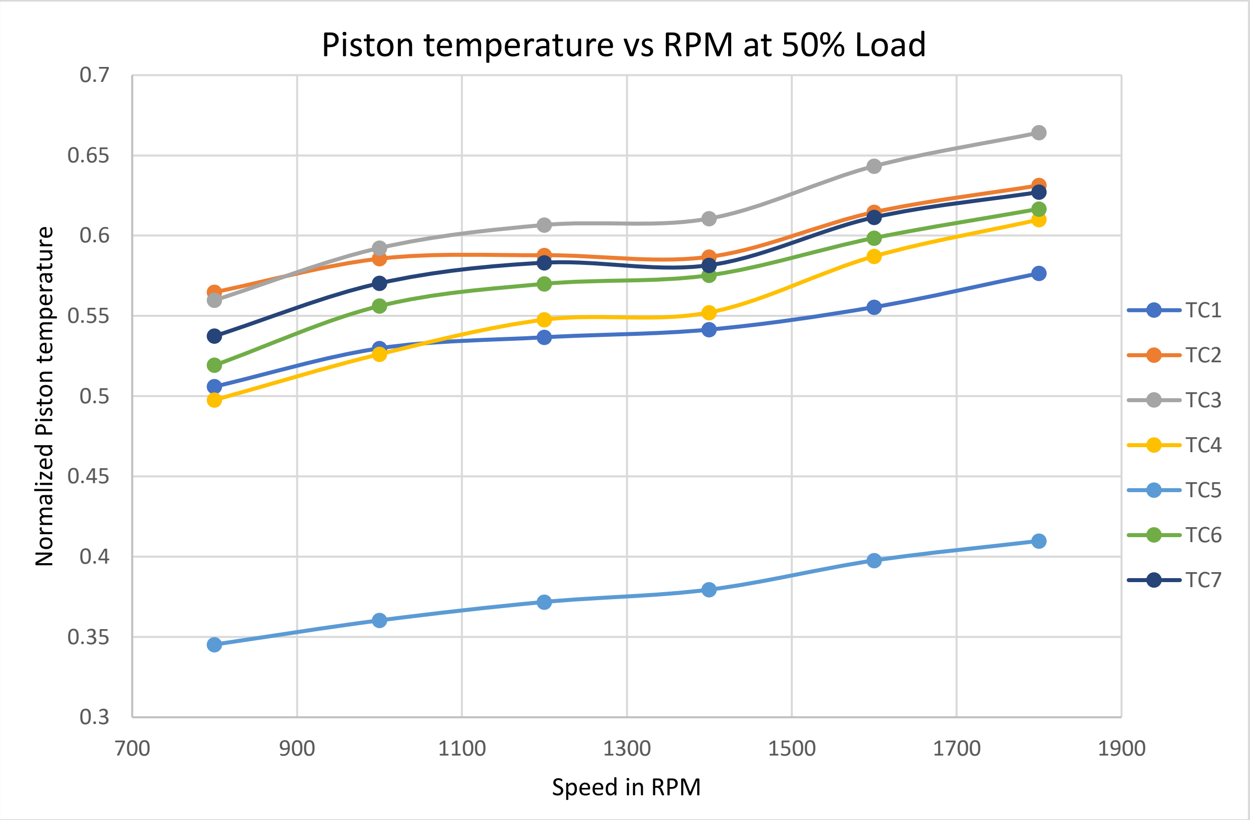


Figure 4.52: Normalized Piston temperature vs RPM [50% Load]

Similar to figure 4.51, a trend of increasing piston temperature with increase in RPM. But with increase in load an overall average increase of temperatures by 29% is observed. Again TC3 is the hottest and TC5 (ring groove) has lowest average temperature values. TC4 again has the maximum temperature rise when swept from 800 RPM to 1800 RPM.

It is also notable that there is some kind of stagnation in temperature between 1200 RPM and 1400 RPM. This is probably due to the difference is calibration values of single cylinder engine or maybe due to the varying back pressure conditions in each steps. The results of Zhang *et al.*, (2011) [13] show similar curve structures, but they were also unable to explain the reason for this phenomenon.

Speed sweep at 75% Load

All the engine parameters except for the fuel injection quantity were held similar to the previous test point. 180 mg/injection was supplied for 75% load. This was the maximum load applied during this testing phase. Higher loads were not tried due to physical limitations. Figure 4.53 portrays the piston temperature with the engine speed.

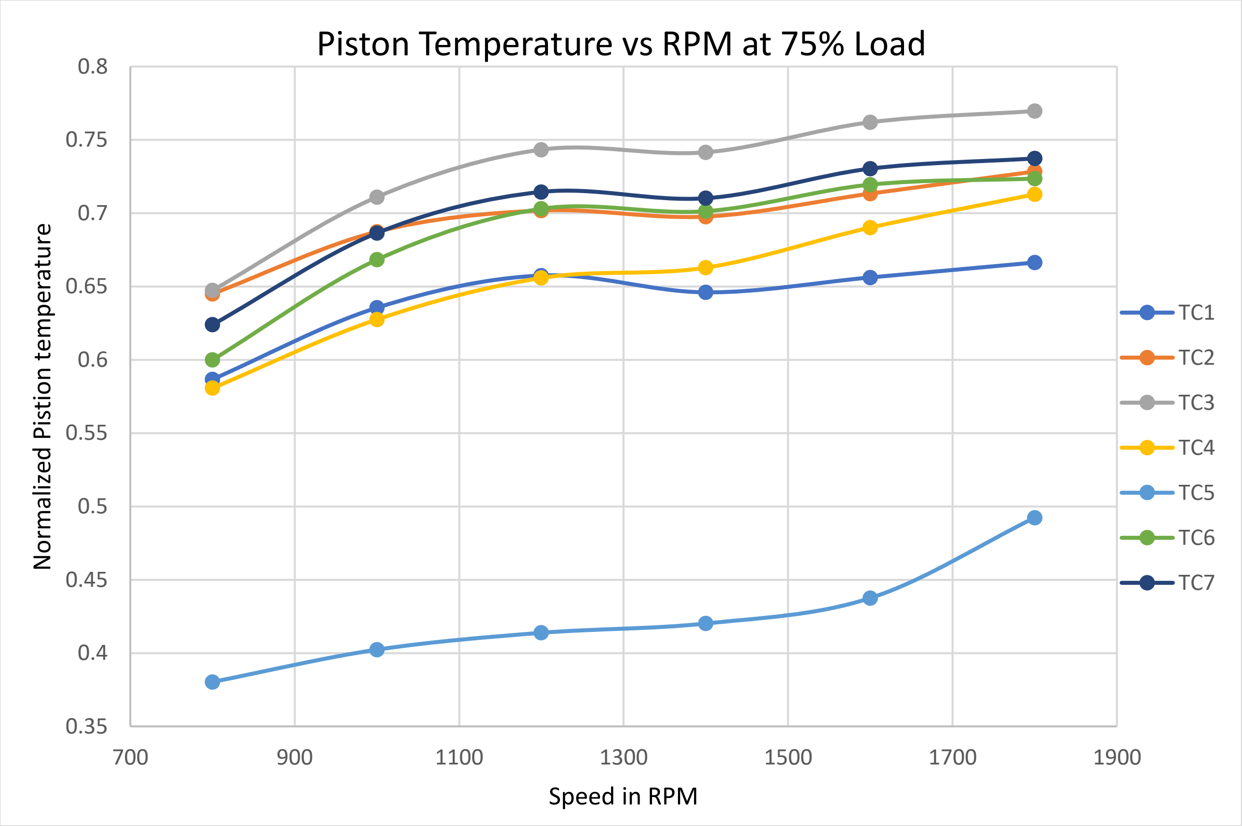


Figure 4.53: Normalized Piston temperature vs RPM [75% Load]

The overall trend of the piston temperature remains the same as lower loads. But the overall average temperatures increased by 19%, 53% in comparison to 50% and 25% load respectively (excluding TC5).

The TC5 has a sudden increase in temperature at higher speeds, this is probably due to increase in friction or decrease in cooling effect offered by the oil gallery to this location.

It is interesting to see how TC2 and TC3 located close to each other and starting off at similar temperatures, deviate about 6% at the end of the sweep. Perhaps it's due to the spray profile. Looking at the trends followed by TC3, TC6, TC7, the diesel spray is probably focused more to the lower bow rim area. TC1 and TC2 on an average are always 9% apart from each other in temperature. The fact that they are in the same radial distances clearly explains the temperature drift in piston surface at inlet and exhaust regions. The figure 4.54 shows piston temperature variation of TC3 with speed at different load %.

Effect of engine load on piston temperature

According to theoretical knowledge and explanations we expect the piston temperature to increase with increase in load on the engine. Similar effect is observed. In figure 4.54 the effect of increasing load and increasing engine speed on piston temperature at TC3 location is seen. It is clearly visible that the percentage increase in piston temperature is more with increasing load than engine speed. An average increase of 54% in temperature values are seen when load is increase from 25% to 75%. This is majorly due to the increase in combustion temperatures due to increase in amount of fuel burning.

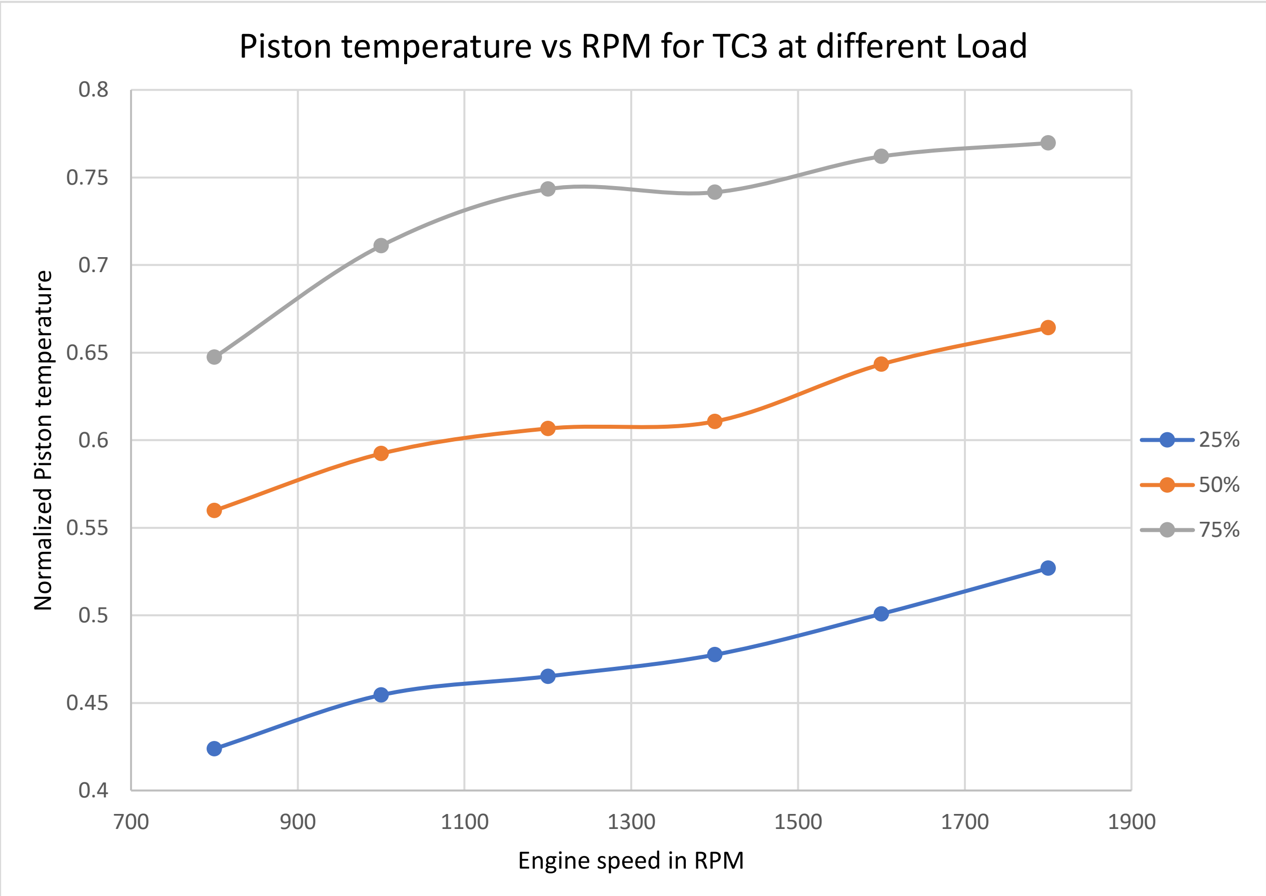


Figure 4.54: Normalized Piston temperature of TC3 vs RPM

The figures 4.55(a)(b) displays the trend of piston temperature with varying load at constant engine RPM. The data is obtained from the above test points by isolating the values for a particular point.

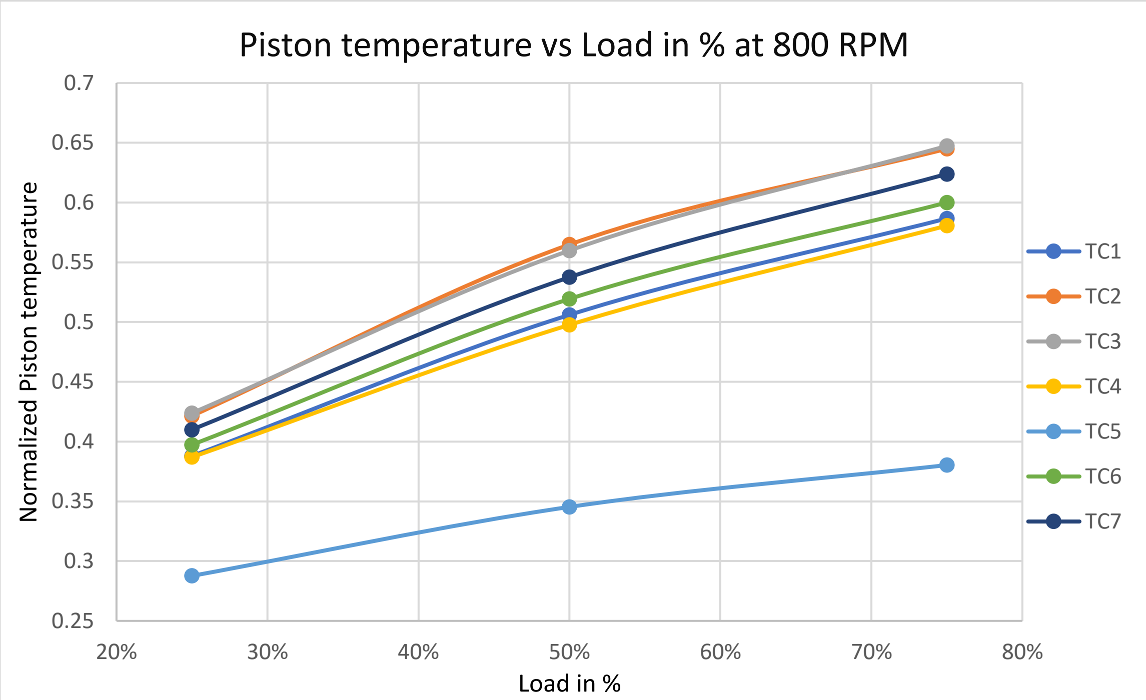


Figure 4.55(a): Normalized piston temperature vs Load at 800 RPM

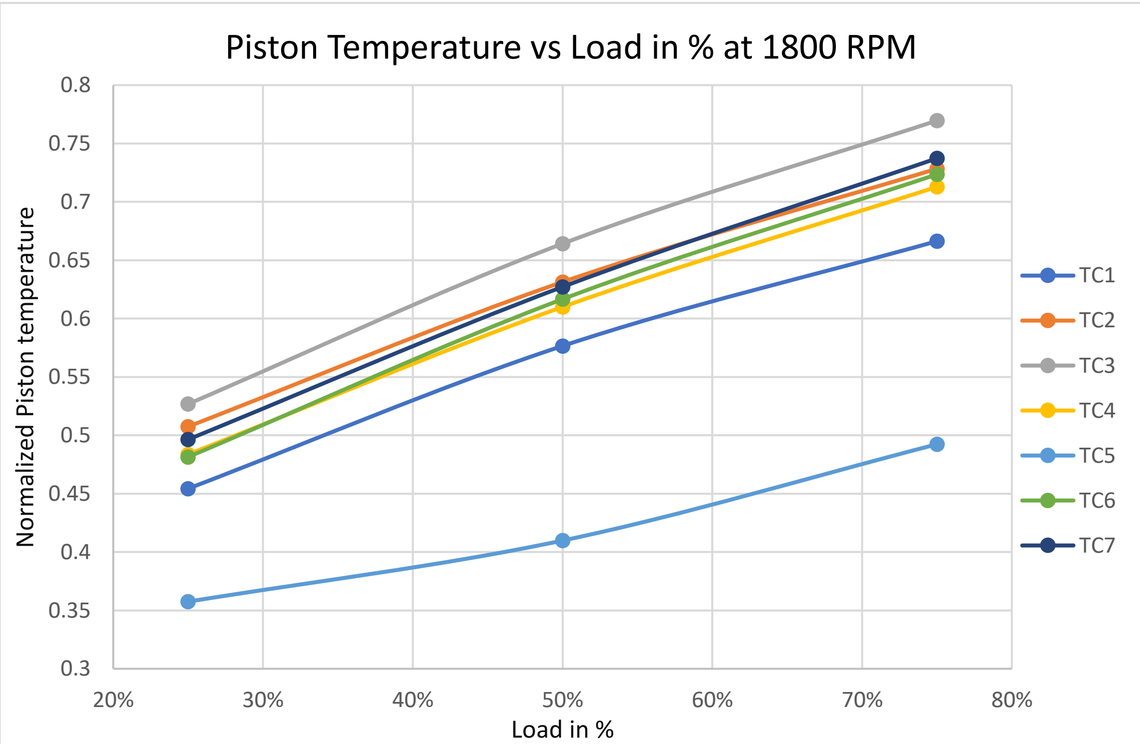


Figure 4.55(b): Normalized piston temperature vs Load at 1800 RPM

The linear increase of piston temperature with load is visible as expected. This holds true at all engine speeds. From the above two graphs one notable observations is how TC3 and TC1 deviate away from the other thermocouples in the bowl regions. It can be said that the load has an overall increase of temperature effect, but when it comes to local temperatures the engine speed creates the variations. Figure 4.56 displays the temperature of TC1 at three different loads and three different speeds at each load.

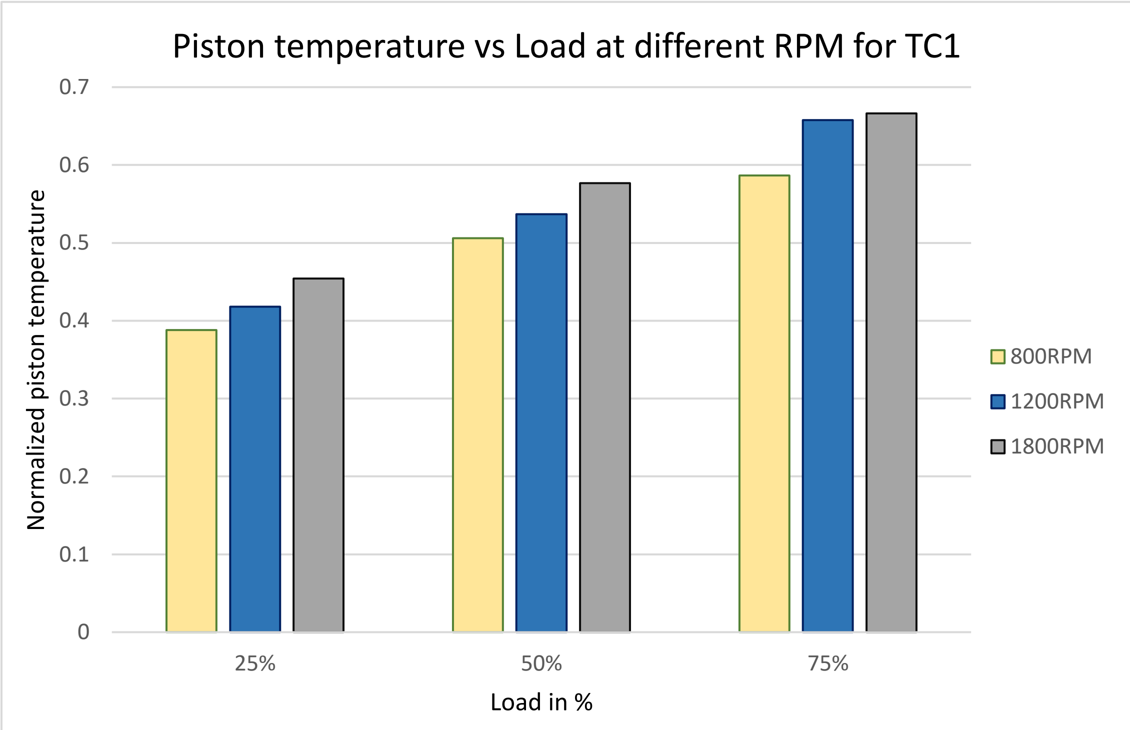


Figure 4.56: Normalized piston temperature of TC1 vs load at different RPM

Effect of Oil temperature on piston temperature

In the next set of test points the load is kept constant at 75% and the oil temperature is changed to 60°C, 80°C, 100°C with speed sweeps at each state. The coolant temperature i.e., water temperature is held steady at 80°C. Only measurements up to 1400 RPM for oil temperature 100°C were obtained, after which the test cell broke down. The figure 4.53 shows the trends at oil temperature 80°C, similar trends with decreasing and increasing piston temperature are obtained at 60°C and 100°C Oil temperatures respectively.

The below figures 4.57(a)(b) exhibits the relation between the piston temperature and the oil temperatures at a constant engine speeds.

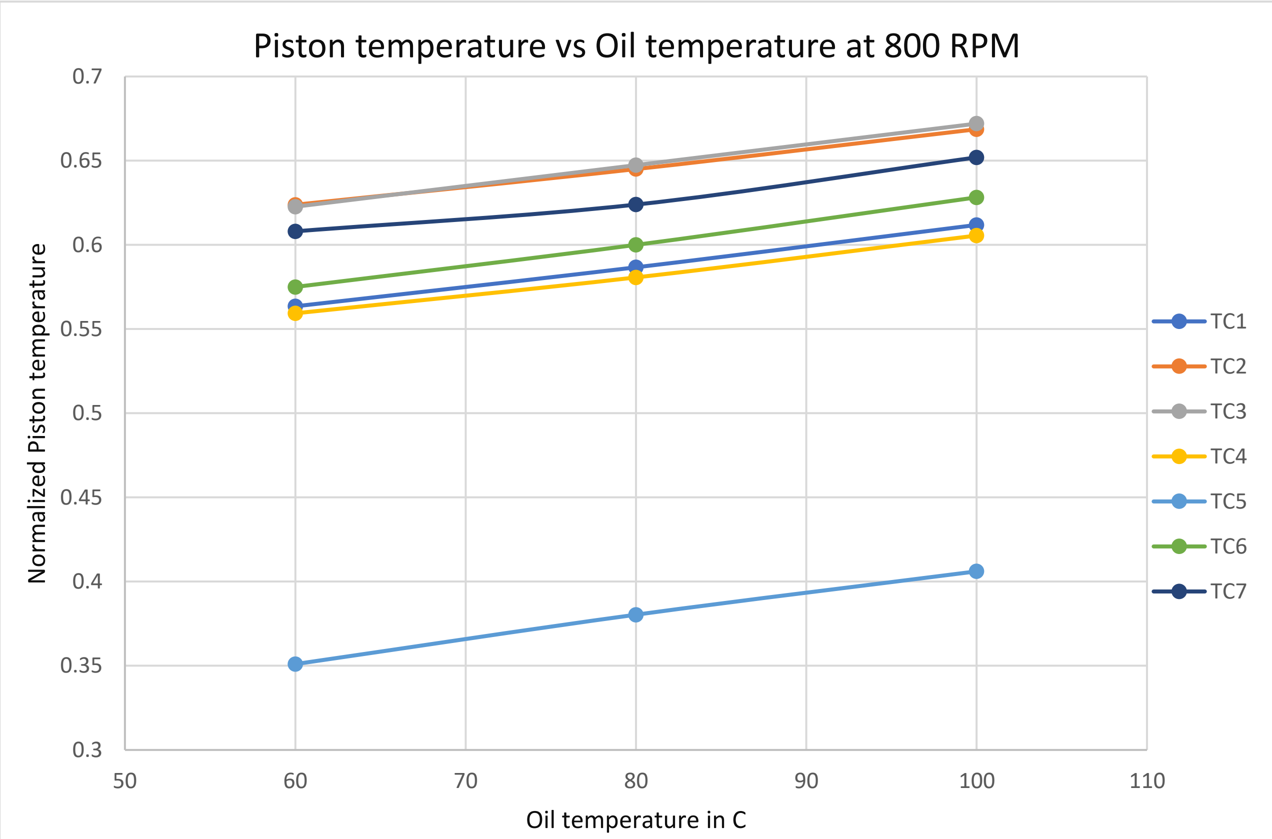


Figure 4.57(a): Normalized piston temperature vs Oil temperature at 800 RPM

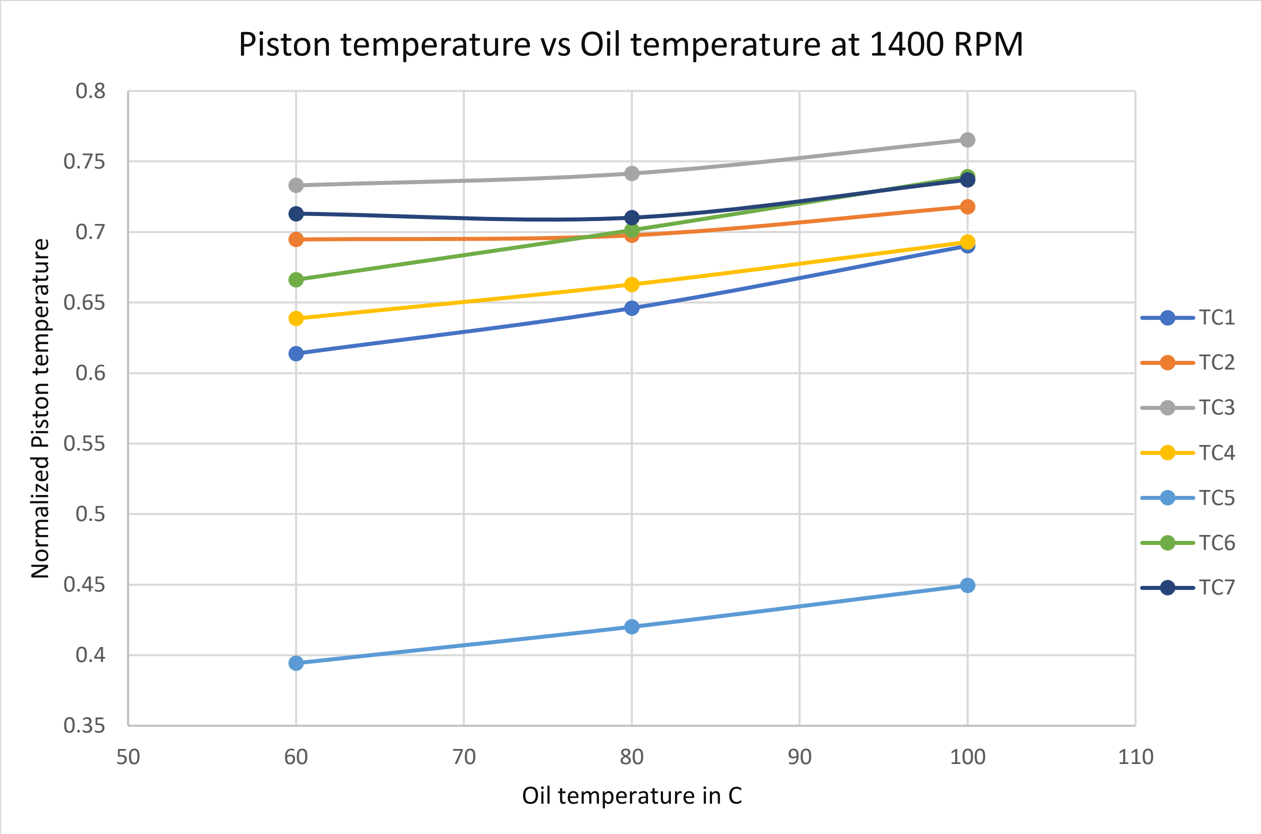


Figure 4.57(b): Normalized piston temperature vs Oil temperature at 1400 RPM

As the oil temperature increases the average piston temperature for all thermocouple location increase in near linear manner, especially at lower RPM. At 1400 RPM, we rather see almost constant temperatures at some TC locations (TC2 and TC7). The trend could have been explained better if the higher RPM data had been obtained. But, an increasing trend in most of the other thermocouple location is observed.

The increase in oil temperature decreases the ΔT term in the heat transfer equation 4.1 resulting in decreased cooling effect and heat flux. This keeps the piston at higher temperatures. It can be said that a direct correlation between the oil and piston temperature exists.

Equation 4.1 - $\mathbf{\dot{Q}=UA(T_{pist} - T_{Oil})}$ where,

$\mathbf{\dot{Q}}$=Heat transfer rate, **U**=Heat transfer coefficient, $\mathbf{T_{pist}}$**=** Piston temperature and $\mathbf{T_{oil}}$**=** Oil Temperature, **A**=Surface area.

Piston temperature variation at different locations

It is fascinating to see how the surface temperatures vary at different thermocouple locations at almost similar instant of time and condition. 75% load at 1200 RPM and the oil temperatures were at 100˚C was chosen. The figure 4.58 displays the bar graph of various locations and their temperature. Also, the percentage variation from the maximum temperature is denoted.

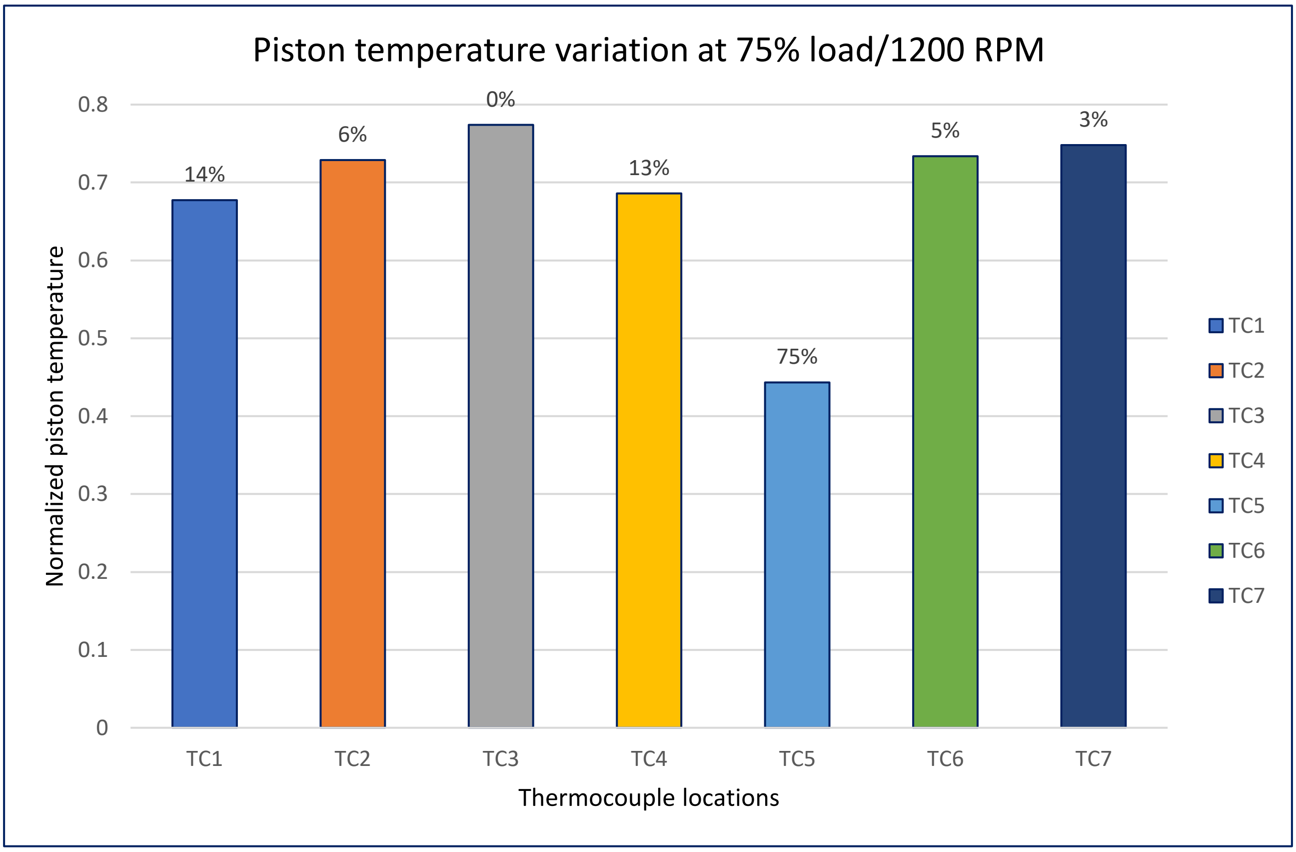


Figure 4.58: Normalized piston temperature vs different thermocouple location

TC3 is at highest temperature, this is true even in most other engine conditions. It's probably due to its location being closer to exhaust valves and spray profile hitting the lower bowl rim region. TC6 in similar radial distance but at inlet side is at 5% lower temperature. It's also interesting to see the TC1 and TC2 having 8% difference in temperature. TC5 being out of the combustion bowl is always much lower than other thermocouples. From this diagram you can see how the piston faces varying thermal loads at just one condition. It's always good to do a temperature measurement whenever there is prominent local issues. There may be a chance that temperature might be the reason.

During the data analysis, no strong trends of piston temperature with emission elements were noted. Emissions are majorly a combustion related phenomenon and its relation with piston temperature may vary depending on the type of engine used.

Data acquisition and signal strength

The figure 4.59 tries to explain how the average temperature values were acquired. Considering the measurement point at 75% load, 100˚C oil temperature and 1200 RPM for TC3. The measurement data was acquired for almost 60 seconds, during which 15 sets of temperature data of TC3 were recorded. The plot shows how the temperature varies during each point of time and their average value. The third line (brown) represents the signal strength when the data was acquired. During the complete measurement process at all points the signal strength was between 99% and 100%, which is highly satisfactory.

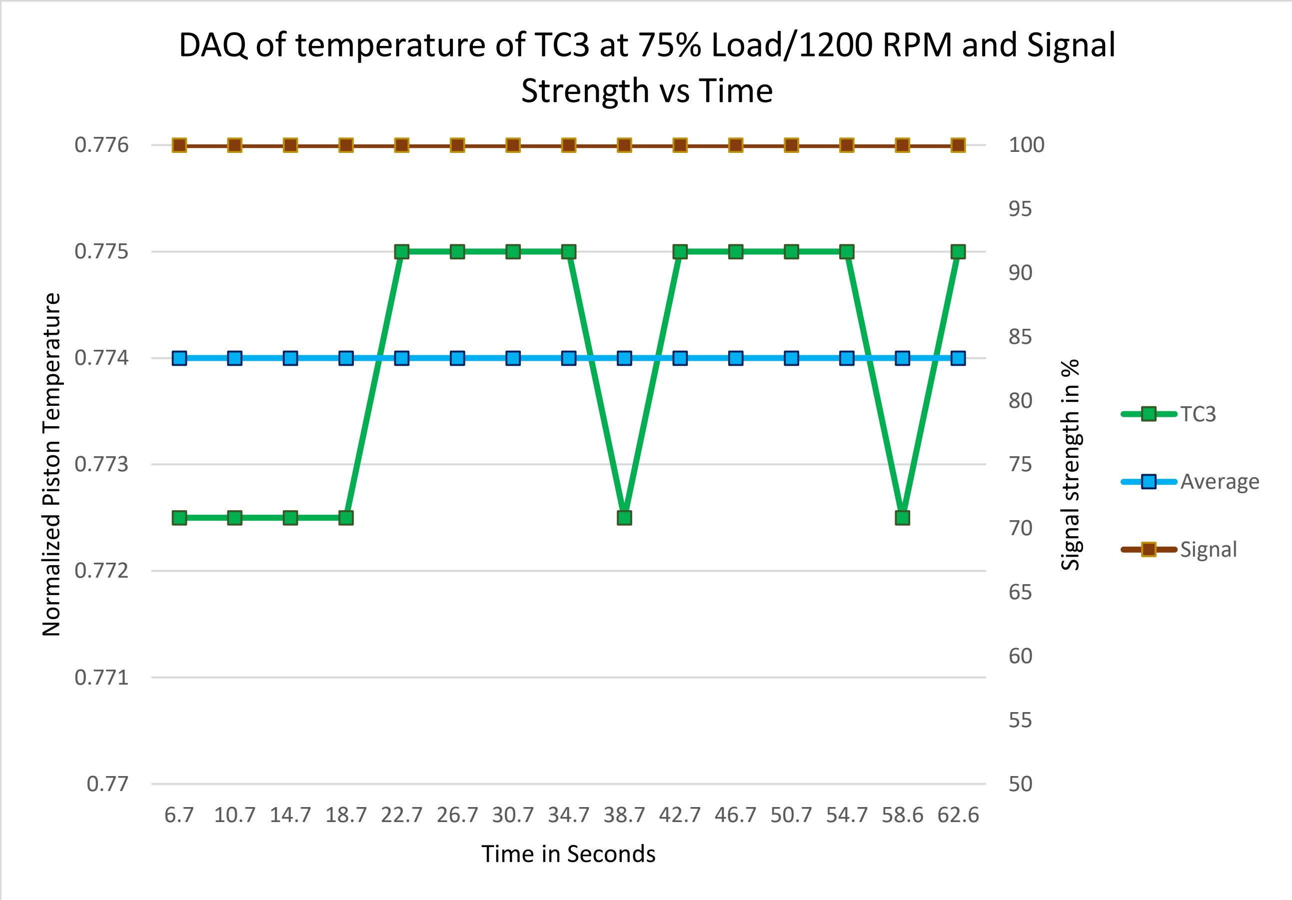


Figure 4.59: Normalized piston temperature and Signal strength vs Time

Measurement data deviation and uncertainty:

The standard deviation and uncertainty for the above set of data can be calculated. It is comparable with the whole range of data during this study.

Number of data points (N) = 15

Normalized mean temperature ($\bar{X}$) = 0.774

Actual $\Sigma(X - \bar{X})^2 = 3.6$

Standard deviation (σ) = $\sqrt{\frac{\Sigma(X-\bar{X})^2}{N-1}} = \sqrt{3.6/14} = \pm 0.507\ ^{\circ}C$

Uncertainty due to measurement noise (U) = (σ/√N) = $\frac{\pm 0.5\ ^{\circ}C}{\sqrt{15}} = \pm 0.130\ ^{\circ}C$

Overall it can be assumed that an uncertainty of about ±0.1 °C can be generated during the signal transfer if the obtained data are averaged and used. Similar calculation can be used for the data obtained from other systems.

The signal strength also plays a strong role in the uncertainty levels, with lower percentage of signal strength the uncertainty increases. If the obtained temperature data is crank angle resolved, it doesn't need averaging and this will decrease the uncertainty levels from measurement.

4.6 Future work and suggestions

Much of the future work towards obtaining the valid crank angle resolved piston temperature must be towards placement of the temperature sensors at the surface. In the current market, there are systems which have the capacity to transmit the signals well within a crank angle at good accuracy, It's just about getting the sensors as close to the surface as possible to obtain the true surface temperatures.

Detailed, complex measurement plans would provide more insight about piston temperature correlation with various parameters. Doing a full cycle measurement run with piston temperature data would be interesting.

It would be fascinating to obtain the piston temperature data using the temperature sensitive paints and to compare their accuracy and viability.

Conclusions

The main objective of the thesis was to understand about the various piston temperature measurement techniques and how they have been put to use to evaluate the effect of piston temperature on various engine parameters. Focus was also required to be given on the comparison on various techniques and their suitability in obtaining crank angle resolved temperature data.

During the course of this study, brief explanation of all the measurement techniques their advantages and drawbacks are highlighted. Ranking of various techniques based on important parameters such as accuracy, uncertainty, required modifications, durability, financial feasibility etc., are completed. Microwave telemetry technique has a good balance between complexity, feasibility and has the ability to obtain crank angle resolved piston temperature with acceptable accuracy.

The latter part of the study is focused regarding the Scania measurement systems and practical measurement of piston temperature. Ranking of the available system at Scania is done based on similar parameters as mentioned above. All the three systems have good specification and accuracy but, IR Telemetrics system stands out. A Short research on temperature sensitive paints and their possible future usage was completed with positive outcomes.

The piston temperature measurement campaign was carried out satisfactorily using a microwave telemetry system from IR telemetrics. Increasing temperatures with increasing engine speeds and loads were obtained as expected. Interesting trends of fluctuating temperatures at various thermocouple locations are noted and explained. Piston temperature trends with intake pressures are explained during the motoring stages.

No strong correlation of piston temperature and emission were observed. Part of the measurement campaign was unfinished due to test cell related issues.

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