F2008-SC-037

EXPERIMENTAL RESEARCH ON THE HEAT TRANSFER INSIDE A HYDROGEN COMBUSTION ENGINE: EVALUATION AND CONSTRUCTION OF MEASUREMENT METHODS

Demuynck, Joachim*, Pauwels, Stijn, Verhelst, Sebastian, De Paepe, Michel, Sierens Roger
Ghent University, Belgium

KEYWORDS – hydrogen, combustion engine, heat transfer, measurement methods, convection coefficient

ABSTRACT - Hydrogen-fuelled internal combustion engines are attractive as they offer the potential of near-zero emissions, high efficiency, and zero greenhouse gas emissions. Computer simulation of the performance of such engines would enable a cheap and fast optimization of engine settings for operation on hydrogen. A model for the heat transfer between cylinder gases and combustion chamber walls is necessary for such a simulation and would improve the simulation program written by Verhelst [1]. A review of the literature shows that very few data is available on the heat transfer inside a hydrogen combustion engine. It can be expected that the heat transfer in hydrogen engines differs substantially from e.g. gasoline engines, because of the higher flame speeds and lower quenching distance. In this paper several measurement methods were investigated and compared to each other for mounting in a CFR engine. Two instantaneous heat flux sensors were chosen and installed on a calibration test rig. Initial results are discussed, determining the rise time of the sensors.

INTRODUCTION

An accurate estimate of the heat transfer between cylinder gases and cylinder wall of a combustion engine is necessary for a precise calculation of power, efficiency and emissions during engine development [2]. Several models exist for evaluating the heat transfer coefficient, of which the correlations of Woschni [3] and Annand [4] are the most widely used. But these correlations have been cited to be inadequate [5], even for gasoline and diesel engines. Wei et al. [6] evaluated heat transfer correlations in hydrogen fuelled engines and found Woschni's equation to under predict the heat transfer coefficient by 100%, Annand's equation by 20%. The shorter quenching distance of a hydrogen flame is put forward as the cause of this increased heat transfer, leading to a thinner thermal boundary layer. Furthermore, for near-stoichiometric combustion, flame speeds are high and cause intensified convection. Hydrogen also has a higher thermal conductivity compared to hydrocarbons. Therefore the heat transfer model should get a thorough revision to account for the specific properties of hydrogen. Shudo [7] proposed a new correlation for hydrogen combustion engines based on Woschni's correlation. He added the apparent heat release calculated from the indicator diagram to the term that represents gas velocity and concluded that the changed correlation successfully describes cooling losses for hydrogen. Shudo's conclusions haven't been confirmed since. A large review of the literature has been made to get a view on the existing measurement and calculation methods.

REVIEW OF LITERATURE

There are two possible ways for quantitative research on heat transfer in a combustion engine. The first option is to use a heat balance. The second option is to use a flux sensor which measures the surface temperature of the cylinder wall at two depths. The disadvantage of the heat balance is the fact that only a cycle average of the heat transfer can be measured. This method was only used by Woschni [3] and is not the best option for modern research which needs instant mean heat transfer data. With a heat flux sensor this instant heat transfer can be measured. New techniques make it even possible to determine heat flux from only a surface temperature measurement. Optical measurement techniques [8, 9, 10] are very promising, but will not be discussed as these are not an option on the available research engine.

Instant Heat Flux Sensor

The measurement of the cylinder wall surface temperature and the temperature at a certain depth are usually necessary for the measurement of the instant heat flux. The surface temperature varies very quickly due to the fast changes in the boundary conditions at the combustion chamber wall. The variation is smoothed quickly in the depth of the wall (≈1mm), so it is essential to measure the surface temperature to observe this variation.
Thermocouples and thermistors can be used to measure the temperatures. Due to the fast variation in temperature at the surface it is imperative to put strong demands on the construction of the surface thermocouple. It is necessary to keep the mass of the junction of the thermocouple or the thermistor small. Several types of thermocouples and thermistors are used in the literature. A review of the most important ones is given. Previous reviews were reported by Assanis and Badillo [11], Gatowski et al. [12] and Wimmer et al. [13], but new measurement methods have been developed since.

Coaxial Type

The two metals of the thermocouple are coaxially positioned and the junction is formed by a thin layer on top. This type of thermocouple was first used by Bendersky [14], to measure gun bore temperatures. Since his presentation many surface thermocouples of this type have been designed and refined to be used in engine heat-transfer research. Figure 1 shows a typical coaxial type surface thermocouple used by LeFeuvre et al. [15], Oguri and Aizawa [16], Sihling and Woschni [17], Overbye et al. [18] and Ebersole et al. [19] among others. As seen in figure 1, the centre wire (first thermocouple element) is coated with insulation and put into a tube (second thermocouple element). The end of the probe is plated with a vacuum deposited thin layer of metal (on the order of 1 μm thick).
Gilaber and Pinchon [20] among others used a ceramic insulation to ensure almost one dimensional heat flow in their flux sensor. Jackson [21] used an air-layer to improve the one dimensionality. Other heat flux sensor constructions were used by Choi et al. [22], Alizon et al. [23] and Rakopoulos and Mavropoulos [24, 25].
A special type of coaxial flux sensor, which is often cited in literature, is that from Yoshida [26]. It is not exactly coaxial, but has principally the same construction (see figure 2). The constantan cylinder has two bores, one through the cylinder and one blind hole (0.7 to 0.8mm from the surface). In these bores a copper wire with ceramic insulation is inserted. Around the constantan body there is also ceramic insulation to ensure one-dimensional heat flow. The fast response surface junction is created by deposition of a copper layer of 5 to 10 μm.

Pair-Wire Type

The two leads of a thermocouple wire are inserted into a metal tube (see figure 3). The leads are surrounded by a ceramic oxide layer to prevent contact between the two leads and the metal body. A fast response junction is created by vacuum deposition of a metal layer on top

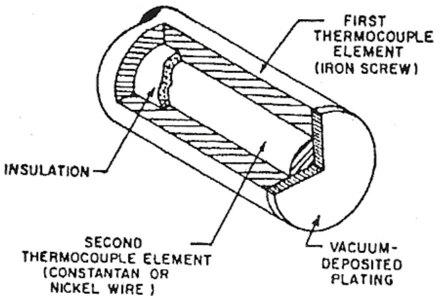
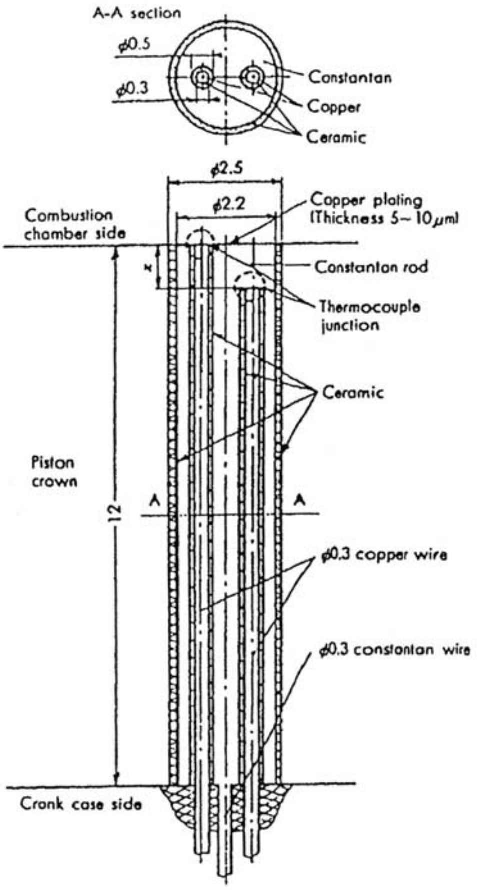


Figure 1: Coaxial type [15]



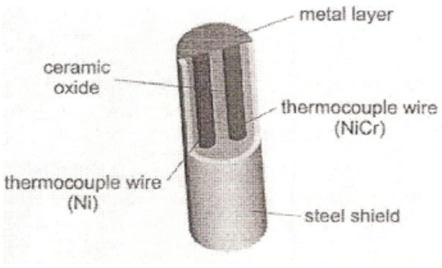


Figure 3: Pair wire type [13]

Figure 2: Yoshida's construction [26]

of the tube, which connects the two thermocouple wires. This type was used by Hohenberg [27] and Wimmer et al. [13].

A variation of the pair-wire type is the eroding ribbon type. The two metal components of the thermocouple are now thin sheets instead of wires (see figure 4). Thin mica sheets are inserted as electrical insulation. Small particles in the combustion gases will erode the surface and form a micro junction between the two metals. Alkidas [28] and Rakopoulos and Mavropoulos [24, 25] used the type for the surface temperature measurement. They started with a commercially available eroding ribbon thermocouple and they added a thermocouple at a certain depth to build a heat flux sensor. Buttsworth [29, 30] showed that such heat flux sensors don't have a great accuracy because of two dimensional influences, even if complicated models are used to calculate the flux.

Film Type

The thermocouple elements are thin layers which are deposited on each other. Thin film thermocouples (TFTC) respond very fast to temperature fluctuations because of their small mass. Annand [4] used a surface thermocouple which had three different layers of metal. The layers were deposited directly on the cylinder wall with vacuum deposition. Kreider [31] performed research on TFTC's to measure surface temperatures. A new type of sensor uses a thermopile [13, 32]. This consists out of several thermocouples next to each other. The voltage of all the thermocouples is summed to obtain a measurable signal because the signal from one thermocouple would be too small to measure the temperature in the thin layer.

Thermistor Type

A metal with a temperature dependent resistance is used. The direct-heat-flux gauge (DHFG) is a modern measurement technique developed by E. Piccini [33]. The heat flux is measured over an insulating layer of Upilex-s. There is a large temperature gradient over the layer which makes it possible to keep the distance between the two temperature measurements smaller without decreasing the accuracy of the heat flux measurement. The construction is shown in figure 5.

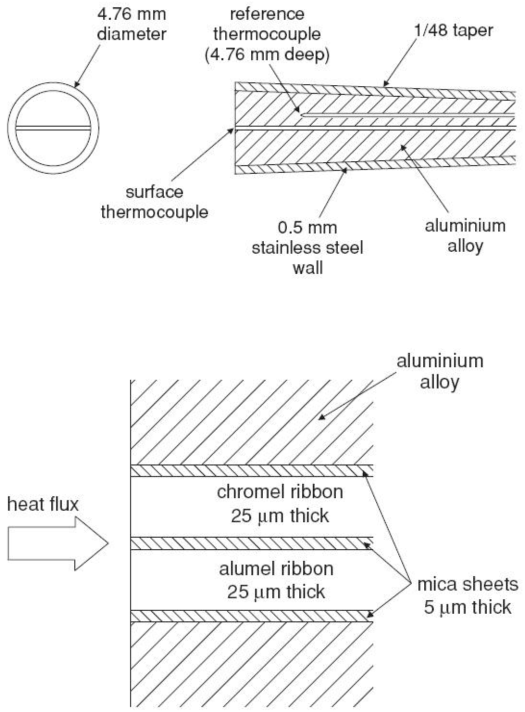


Figure 4: Eroding ribbon type [30]

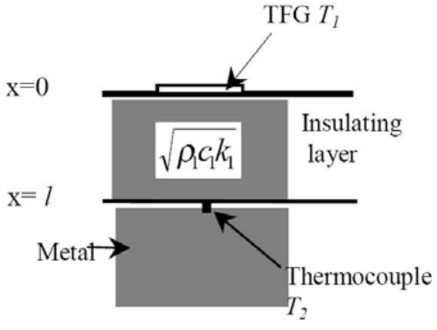


Figure 5: DHFG of Piccini [33]

A standard available thermocouple is placed on a metal surface and the insulating layer of Upilex with a thickness of 50 μm is taped on it. The layer of glue is 20 μm thick and is produced by 3M (3M VHB 9460). A layer of platinum is sputtered on top of the Upilex with a thickness smaller than 0.1 μm. The platinum acts as a thin film thermistor (TFG) . The response time of the sensor will increase when the dimensions of the platinum layer are smaller, but the sensor will become more fragile. A constant current is sent trough the platinum. The surface temperature is deducted from the variation of the resistance of the layer. The determination of the thermal properties of the insulating layer is very important for the accuracy of the sensor. Piccini describes how sqrt(pck) and l/k are determined for the total insulating layer. The DHFG is placed on a metal surface which is suddenly brought into contact with a known heat flux. The measured data has to be fitted to this step function. Piccini states that the thermal properties of the layer are determined with an accuracy of 4.2%. A response time of 10 μs is possible.

Calculation of Heat Flux

Method 1

A straightforward method is to use the following equation which describes the conduction through the sensor:

$$\dot{q} = \frac{Q}{A} = k \cdot \frac{T_1 - T_2}{x} \tag{1}$$

Where T1 is the surface temperature, T2 the temperature at a known depth x and k the heat conductivity of the sensor. This method gives good results in steady state problems, but is insufficient for transient problems.

Method 2

Another method starts from a Fourier analysis of the measured temperatures:

$$T_1 = B_1 + \sum_{n=1}^{\infty} K_n \cdot \cos(n\omega t) + G_n \cdot \sin(n\omega t) \tag{2}$$

$$T_2 = B_2 \tag{3}$$

Where ω is the thermal diffusivity, B_1; B_2; K_n and G_n are coefficients of the analysis (T_2 is considered constant) and ω is the natural frequency. These equations are used as the boundary conditions for the following differential equation of Fourier:

$$\frac{\partial T}{\partial t} = \alpha \cdot \frac{\partial^2 T}{\partial^2 x} \tag{4}$$

The analytical solution of equation 4 with boundary conditions 2 and 3 is:

$$\begin{gathered} T = B_1 - \frac{(B_1 - B_2) \cdot x}{X} + \sum_{n=1}^{\infty} e^{-F \cdot x} \cdot \\ [K_n \cdot \cos(n\omega t - F \cdot x) + G_n \cdot \sin(n\omega t - F \cdot x)] \end{gathered} \tag{5}$$

Where X is the distance between T1 and T2 and F is . The derivate in x = 0 of this function can be used in the following equation for the conduction through the sensor to calculate the heat flux:

$$\dot{q} = \frac{Q}{A} = -k \cdot \frac{dT}{dx} \tag{6}$$

According to Wimmer [13] this method can be used with only one surface temperature measurement. The unknown coefficient B_2 can then be determined with the help of a pressure measurement in the cylinder. Gas temperature calculated from this pressure measurement is used to find the moment where the wall temperature is equal to the gas temperature. At this moment the heat flux is zero and B_2 is the only unknown parameter in equation 6.

Method 3

Oldfield [34] developed a new method recently. His method uses the impulse response of the sensor which is a method that is commonly used in control theory:

$$q(t) = h(t) * T(t) = \int_{-\infty}^{\infty} h(\tau) \cdot T(t - \tau) \, \mathrm{d}\tau \tag{7a}$$

Where * is the convolution operator, q(t) the heat flux and T(t) the surface temperature. Equation 7a is transformed to the discrete time domain because the integral is very hard to calculate. The time dependent signals are sampled with a sampling period Ts:

$$\begin{aligned} q[n] = h[n] * T[n] &= \sum_{k=0}^{N-1} h[k] \cdot T[n-k] \\ &= \sum_{k=0}^{N-1} h[n-k] \cdot T[k] \\ for\ n &= 0, 1, 2, \ldots, N-1 \end{aligned} \tag{7b}$$

It is assumed that the signals are finite and equal to zero for n < 0. The impulse response of the sensor has to be determined once. The test functions $T_1(t)$ and $q_1(t)$ are chosen and filled in equation 7b which is transformed to the equivalent equation with Z-transforms of the signals:

$$Q_1(z) = H(z) \cdot T_1(z) \Leftrightarrow H(z) = \frac{Q_1(z)}{T_1(z)} \tag{8}$$

The heat flux can be calculated out of the measured temperature signal T(t) if the impulse response has been determined. The choice of the test functions is crucial. Oldfield describes several test functions for known heat flux sensors. This method makes it possible to calculate heat flux from only one temperature signal, but it can also be used for flux sensors with two temperature measurements.

TEST ENGINE

Research will be performed on a CFR-engine (CFR: Cooperative Fuel Research) . This is a single cylinder engine that has a constant rotation speed of 600 rpm. The engine was originally used to test anti-knock ratings of fuels and has the advantage that the compression ratio is variable. A disadvantage is the fact that the engine cylinder and head are one piece. That makes it hard to reach the interior of the cylinder. Several mounting options were investigated, but only one seemed practical. The selected measurement techniques will be mounted inside a bolt which is shown in figure 7. Such bolts can be screwed in several holes with an M18 thread that are available in the cylinder (see figure 8).

MEASUREMENT TECHNIQUE SELECTION

Only conventional flux sensors with two temperature measurements are discussed. All the temperature measurement techniques described in the literature review can be used for the new calculation methods where only one temperature measurement is necessary. Flux sensors that use the coaxial measurement technique are commonly used and the one Yoshida constructed was investigated in detail. The dimensions of the sensor are ideal for research in a combustion engine and the complexity of construction seemed the easiest comparing to several other coaxial types. Yoshida does not describe how the sensor has to be constructed so a personal process flow is discussed in the next section. The pair wire type was not examined because it is very similar to the coaxial type and its construction needs more production process steps. The eroding ribbon variant on the other hand seemed very interesting because it is the cheapest option and is produced industrially. It was not selected because Buttsworth [29, 30] advised other measurement techniques. This will be reconsidered if other selected measurement techniques do not turn out to be satisfactory. The film type was investigated as well. Vatell corporation constructs several heat flux sensors and they also have very fast and relatively small sensors, the HFM series. Wimmer [13] used them in his comparing research. The dimensions of the HFM (outer diameter 8.74mm) are the only disadvantage compared to the other described methods, but this is not a problem on our test engine. A custom made HFM-7

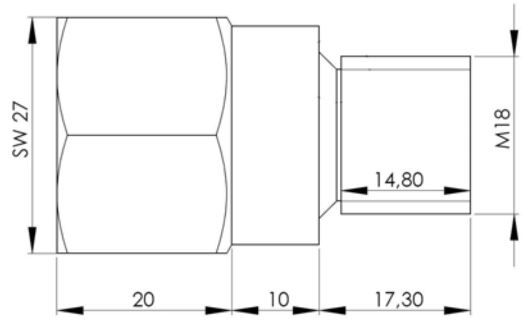


Figure 7: Bolt for sensor mounting (in mm)

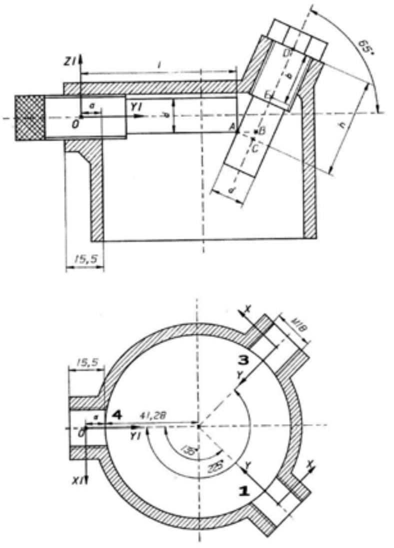


Figure 8: Side- and top-view of CFR-engine

E/L was bought. The sensor created by Piccini seemed indispensable for the research because a high accuracy is needed. A possible process flow was thought-out but the construction itself will be investigated in future research.

CONSTRUCTION OF COAXIAL TYPE

A personal process flow for the construction starts with a constantan rod with a diameter of 3.2mm and 200mm length, two copper wires and a constantan wire. The rod is hand sawed into little pieces of approximately 10mm and the wires are coated with a ceramic paste. Two holes, one through the cylinder, the other a blind hole with a diameter of 0.5mm are made in the constantan cylinder with EDM (Electrical Discharge Machining) hole drilling. The junction of the in depth thermocouple is formed by the process of percussion welding. The constantan wire is welded at the back of the rod. The surface junction is formed by sputtering a copper layer on the top of the constantan cylinder. The heat flux sensor is mounted in the bolt with ceramic cement around it to ensure one dimensional heat flux. So far no measurements have been carried out with this sensor.

HFM MEASUREMENT CIRCUIT

An amplifier with preinstalled software for the HFM sensor can be bought at Vatell, but it was decided to build a measurement circuit with available devices first to get some experience with the sensor. The sensor returns two signals. The first is the HFS-signal which is a voltage corresponding to the heat flux. The second signal is the RTS-signal which is the resistance of a platinum layer (thermistor) on top of the sensor. This resistance can be measured directly or it can be determined by sending a small current trough the layer and measuring the voltage drop over the layer (this option is used). The temperature of the surface corrects the HFS-signal which is temperature dependent. A Fluke power source sends a current of 101 µA trough the platinum layer. The HFS-signal and the voltage drop over the platinum layer are sent to an amplifier from Honeywell. The two amplified signals are sent to an oscilloscope and computer.

RISE TIME CALIBRATION TEST RIG

A rise time calibration test rig was build to determine the rise time of the sensors. The principle of such a test rig is shown in figure 9. The sensor is exposed to a pulsating heat flux. A chopper connected to an electric motor alternates the heat flux. The heat source is an electrical oven instead of the 5kW lamp in Jackson's test rig. The oven is mounted below the chopper so the heat flux rises towards the sensor which is mounted on top. The sensor can be mounted with the same bolts as described earlier.

INITIAL MEASUREMENTS

According to Vatell the rise time of the HFM sensor should be around 70 µs. The rise time of the measurement circuit was tested by using the test rig for several speeds of the chopper. The measured surface temperature and heat flux at a chopper speed of 700 rpm are shown in figure 10 and 12. The RTS-signal clearly has too much noise so the correct amplitude of the heat flux cannot be calculated correctly. The mean noise has a frequency of 50 Hz but noise with a frequency of 6 and 100 Hz are strongly present as well (see figure 11). The mean trace of the temperature is used to get an idea of the amplitude of the heat flux. The HFS-signal does not have that much noise so the shape of the heat flux trace is correct. The trace shown is an average trace of 10 cycles.

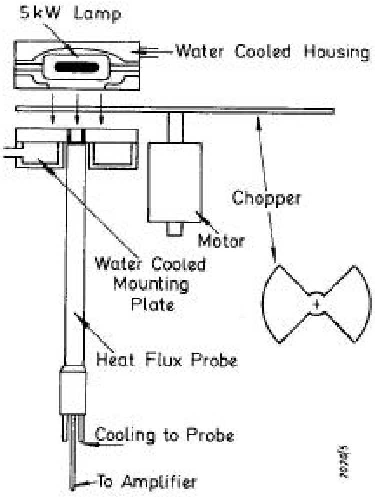


Figure 9: Test rig used by Jackson [21]

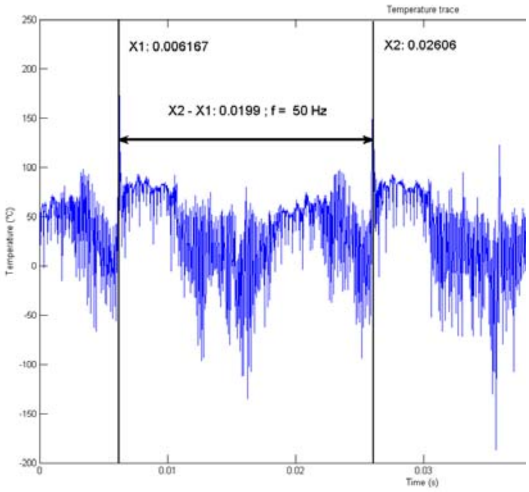


Figure 10: Temperature trace (700 rpm)

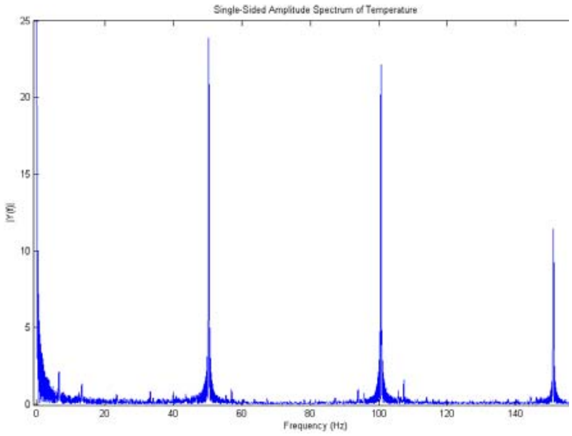


Figure 11: FFT-spectrum of RTS-signal (700 rpm)

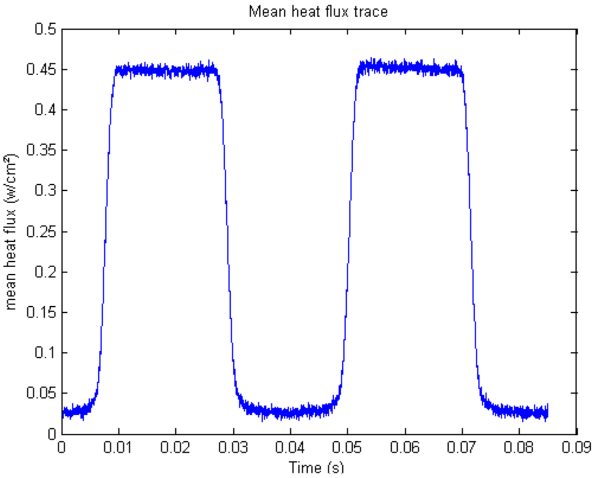


Figure 12: Mean heat flux trace (700 rpm)

The calculated rise time is 474 μs which is far from correct. The measurement circuit is not sufficient because the effects of the noise and slow rise time are not known. To little data (e.g. the gain bandwidth product of the amplifier which has an influence on the rise time) is available of the devices used and they have to be replaced by the amplifier from Vatell.

CONCLUSIONS

Based on a literature review three measurement methods have been chosen to measure heat flux in a hydrogen combustion engine. A HFM sensor from Vatell has been bought and a coaxial sensor has been constructed. Clearly the measurement circuit for the HFM sensor does not fulfil the requirements and the available amplifier from Vatell has to be bought. The construction of the coaxial sensor is completed but a measurement circuit has to be constructed before measurements can start. The DHFG will be constructed in future research so a detailed comparison can be made between three conventional flux sensors. The most important challenge will be the reduction of the noise for all the sensors.

Several calculation methods have been described. These will have to be compared to each other as well. The methods which only need one temperature measurement are very promising. These methods increase the number of available sensors. The eroding ribbon type will be in pole position because it is one of the cheapest and the hot junction cannot be destroyed by the combustion gases. After choosing the best sensor and best calculation method heat transfer measurements in several hydrogen combustion engines can be started in order to check Wei's and Shudo's conclusions. Finally an adjusted or new correlation can be put forward.

REFERENCES

[1] Verhelst, S.: A Study of the Combustion in Hydrogen-Fuelled Internal Combustion Engines. Ph. D. thesis, UGent, 2005. http://hdl.handle.net/1854/3378.

[2] Heywood, J.B.: Internal Combustion Engine Fundamentals. McGraw Hill, 1988.

[3] Woschni, G.: A universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine. SAE paper 670931, 1967.

[4] Annand, W.J.D.: Instantaneous heat transfer rates to the cylinder head surface of a small compressionignition engine. Proc Instn Mech Engrs, 185(72):976–987, 1971.

[5] Borman, G. and Nishiwaki, K.: Internal-combustion engine heat-transfer. Progress in Energy and Combustion Science, 13(1):1–46, 1987.

[6] Wei, S.: A study on transient heat transfer coefficient of in-cylinder gas in the hydrogen fueled engine. KHES and HESS, the 6th Korea-Japan Joint Symposium 2001 on Hydrogen Energy, 2001.

[7] Shudo, T. and Suzuki, H.: Applicability of heat transfer equations to hydrogen combustion. JSAE Review, 23(3):303–308, 2002.

[8] Wilson, T.S.: High bandwidth heat transfer and optical measurements in an instrumented spark ignition internal combustion engine. SAE paper 2002-01-0747, 2002.

[9] Lucht, R.P.: Heat transfer in engines: Comparison of CARS thermal boundary layer measurements and heat flux measurements. SAE paper 910722, 1991.

[10] Husberg, T.: Piston temperature measurement by use of thermographic phosphors and thermocouples in a heavy-duty diesel engine run under partly premixed conditions. SAE paper 2005-01-1646, 2005.

[11] Assanis, D.N. and Badillo, E.: Evaluation of alternative thermocouple designs for transient heat transfer measurements in metal and ceramic engines. SAE paper 890571, 1989.

[12] Gatowski, J.A. et al.: An experimental investigation of surface thermometry and heat-flux. Experimental Thermal and Fluid Science, 2(3):280–292, 1989.
[13] Wimmer, A. et al.: Heat transfer to the combustion chamber and port walls of IC engines - measurement and prediction. SAE paper 2000-01-0568, 2000.
[14] Bendersky, D.A.: A special thermocouple for measuring transient temperatures. Mechanical Engineering, 75:117–121, 1953.
[15] LeFeuvre, T. et al.: Experimental instantaneous heat fluxes in a diesel engine and their correlation. SAE paper 690464, 1969.
[16] Oguri, T. and Aizawa, T.: Radiant heat transfer in the cilinder of a diesel engine. JARI Tech. Memo., 10:357–369, 1972.
[17] Sihling, K. and Woschni, G.: Experimental investigation of the instantaneous heat transfer in the cylinder of a high speed diesel engine. SAE paper 790833, 1979.
[18] Overbye, V.D. et al.: Unsteady heat transfer in engines. SAE paper 610041, 1961.
[19] Ebersole, G.D. et al.: The radiant and convective components of diesel engine heat transfer. SAE paper 630148, 1963.
[20] Gilaber, P. and Pinchon, P.: Measurements and multidimensional modeling of gas-wall heat transfer in a s.i. engine. SAE paper 880516, 1988.
[21] Jackson, N.S.: Instantaneous heat transfer in a highly rated DI truck engine. SAE paper 900692, 1990. [22] Choi, G.H.: Analysis of combustion chamber temperature and heat flux in a DOHC engine. SAE paper 970895, 1997.
[23] Alizon, F.: Convective heat transfers in the combustion chamber of an internal combustion engine influence of in-cylinder aerodynamics. SAE paper 2005-01-2028, 2005.
[24] Rakopoulos, C.D. and Mavropoulos, G.C.: Experimental instantaneous heat fluxes in the cylinder head and exhaust manifold of an air-cooled diesel engine. Energy Conversion and Management, 41(12):1265–1281,2000.
[25] Rakopoulos, C.D. et al.: Experimental and theoretical study of the short term response temperature transients in the cylinder walls of a diesel engine at various operating conditions. Applied Thermal Engineering, 24(5-6):679–702, 2004.
[26] Yoshida, M. et al.: Variation of heat-flux through a combustion-chamber wall of prechamber type diesel engine (heat-flux through piston crown, cylinder head, suction valve, exhaust valve, pre-combustion chamber and exhaust port wall). Bulletin of the JSME-Japan Society of Mechanical Engineers, 25(201):426–437,1982.
[27] Hohenberg, G.F.: Advanced approaches for heat transfer calculations. SAE paper 790825, 1979.
[28] Alkidas, A.C.: Heat-transfer characteristics of a spark-ignition engine. Journal of Heat Transfer-Transactions of the ASME, 102(2):189–193, 1980.
[29] Buttsworth, D.R.: Transient response of an erodable heat flux gauge using finite element analysis. Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering, 216(D8):701–706, 2002.
[30] Buttsworth, D.R. et al.: Eroding ribbon thermocouples: Impulse response and transient heat flux analysis. Measurement Science and Technology, 16(7):1487–1494, 2005.
[31] Kreider, K.G.: Thin-film thermocouples for internal-combustion engines. Journal of Vacuum Science and Technology a-Vacuum Surfaces and Films, 4(6):2618–2623, 1986.
[32] Vatell: Heat flux microsensor, 2007. http://www.vatell.com/hfm.htm.
[33] Piccini, E. et al.: The development of a new direct-heat-flux gauge for heat-transfer facilities. Measurement Science and Technology, 11(4):342–349, 2000.
[34] Oldfield, M.L.G.: Impulse response processing of transient heat transfer gauge signals. Journal of Turbomachinery-Transactions of the ASME, 130(2), 2008.