Numerical processing of the eroding thermocouple signals related to heat transfer analysis in the reciprocating compressor

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Abstract

The purpose of this paper is to present applications of the NANMAC eroding-type thermocouples to record temperature histories of the surfaces, which take part in the heat exchange during the compression cycle. These thermocouples have a very small heat capacity and a short time constant. Additionally, similar measurements were taken using a thin film metal resistor.

The experimental stand is equipped with a single cycle reciprocating compressor – especially adopted for the purpose of this work. The thermal conditions of the compression process in the compressor are well defined. This enables to repeat exactly experiments and comparing measurement methods.

The paper presents measurement results of the surface temperature time histories of the cylinder head. The method of the numerical processing of these signals as well as the calculation of the related heat fluxes on the surface are also presented and discussed. Results obtained by measurements with eroding thermocouple are compared with those taken by thin film metal resistor.

All experimental data were processed numerically in order to exclude the noise of the measurement circuits.

1 Introduction

A heat transfer inside a cylinder of a reciprocating compressor is not known well yet. Theoretical and experimental investigations mostly
Concern combustion engines and only some of them deal with compressors. Similarities in a construction and working cycle of those machines lead to conclusion that some observations can be transferred from combustion engines to compressors. Especially that there were experiments conducted on heat transfer inside combustion chamber with an external drive of the engine, i.e. without a combustion process in the cylinder. But some authors showed that attempts to use equations obtained from the engines to the compressors did not give satisfactory results. That fact is caused probably from differences in a construction and action of valve systems. In case of reciprocating compressors a gas flow through the cylinder is completely different with regard to self-acting valves.

In the investigations of a heat transfer inside a reciprocating compressor cylinder described below a method of transient surface temperature measurement is used. After recording the temperature histories of chosen surface, calculations of local heat fluxes have been done. The calculating method is known since many years (Carslaw & Jaeger, Hall & Herzberg).

For this purposes a special type of ‘eroding’ thermocouple was used (Nanmac). The thermal junction is formed by abrasive action erosion. The junction is very thin, has low heat capacity and short response time of order of 10 microseconds.

Results obtained with the thermocouple have been compared with measurements using a thin film metal resistor. The metal sensor has also good dynamic properties and sensitivity (Wimmer & Pishinger).

2 Theoretical basis
The heat flux applied to the surface under investigation changes its temperature according to the well-known heat transfer rules. Local surface heat transfer rates can be calculated from the measured surface temperature histories by means of classical heat conduction theory. In the short periods of compressor cycle the depth of heat penetration into the wall is small so the wall of finite thickness can be treated as a half infinite material, and thus the local heat flow may be assumed one-dimensional.

If $T(t)$ is a time function of a wall surface temperature, the instantaneous surface heat transfer rate can be expressed by (Carslaw & Jaeger):
\[ q(t_n) = \sqrt{\frac{k \rho c}{\pi}} \int_{0}^{t_n} \frac{1}{\sqrt{t-\tau}} d\tau, \]  

where: \( k \) - heat conductivity,  
\( \rho \) - density,  
\( c \) - heat capacity.

The eqn. (1) can be solved if function \( T(t) \) is known. In experimental investigations the wall surface temperature is not given as a function but rather as a series of discrete values. Then the time derivative of temperature over the \( i^{th} \) interval can be approximated by \( \Delta T_i / \Delta \tau_i \). Thus, we can rewrite eqn. (1) as follows:

\[ q(t_n) = \sqrt{\frac{k \rho c}{\pi}} \sum_{i=1}^{n} \frac{\Delta T_i}{\Delta \tau_i} \int_{t_{i-1}}^{t_i} \frac{1}{\sqrt{t-\tau}} d\tau. \]  

Usually the measurements are taken in uniform time intervals \( \Delta \tau \) and time at step \( i \) is \( t_i = i \cdot \Delta \tau \). Solving the integral in eqn. (2) we can finally get:

\[ q(t_n) = 2 \sqrt{\frac{k \rho c}{\pi \Delta \tau}} \sum_{i=1}^{n} (T_i - T_{i-1}) (\sqrt{n-i+1} - \sqrt{n-i}). \]  

The time interval should be short to provide sufficiently accurate approximation. In our experiments data acquisition frequency was 5 kHz so the time interval was equal to 0.2 millisecond. This is very short comparing to the cycle time. Eqn. (3) gives a convenient formula for numerical calculation of a local heat transfer rate from time histories of a surface temperature.

### 3 Test stand

For investigations of a heat transfer it is very important to know exact conditions of experiments. The warm up time of running compressor is very long, and even after that time conditions change in respect to periodic processes inside the cylinder. To avoid these problems a special test stand has been built which allows to realise a single compression cycle.

For this purpose a complete drive system from a mechanical press has been used. It consists of a clutch that connects a flywheel with a
crankshaft at an angle corresponding to the piston dead point. After one revolution the clutch disconnects the flywheel and the break stops the crankshaft rotation. The drive system allows also change the crankshaft eccentricity so the piston stroke and compression rate can be adjusted.

Checking the measurement method requires a minimal number of variables changing during the process under consideration. For this reason the compressor cylinder was closed with a plate without valves. Moreover, one of piston rings (the nearest to the piston top) has been replaced with a rubber o-ring. The gas mass in the compression chamber remains constant.

For good match of thermal properties a stainless steel was used for the plate material. The temperature measurements have been taken on inner surface of the plate, near its central point. The thermocouple was of E-type (chromel-konstantan) with a high thermoelectric constant of 6.317 mV/100K.

The second steel plate was prepared for measurements with resistance sensor. The plate was covered with a thin layer (0.09 mm) of alumina (Al₂O₃) for a good electrical insulation. Next, the gold film sensor was formed by a vacuum deposition. The sensor occupies an area of 5x5 mm and has resistance about 160 ohms at ambient temperature. Its thickness is below 1 μm, so the temperature gradient across the metal film could be neglected.

The test stand has also been equipped with a piezo-electric transducer for pressure measurements in the compression chamber and a crank angle converter for the piston motion recording. All experimental data have been collected by an acquisition system and then transferred to the computer for further evaluation.

4 Experimental results

All experiments described below were conducted using the same compressing cycle. Fig. 1 shows the pressure change during the process.

Measurements taken with the eroding thermocouple shows that the maximum temperature increase on the inner surface of the plate closing the cylinder is of the order of 0.4 K (fig. 1). Despite a high thermoelectric force the signal amplitude is about 25 μV. Because of that a wide band preamplifier with gain of 10000 was used. The recorded signal is very noisy. It makes calculations very difficult because time derivatives determined from experimental data have big errors. Some signal filtration or smoothing was necessary.
Figure 1. Pressure change during the compression.

Figure 2. Change of the surface temperature recorded by the eroding thermocouple.
The frequency domain analysis of the temperature signal is presented on fig. 3. The fast Fourier transform (FFT) was applied to remove high frequency components starting from 15th harmonic. The smoothed signal is showed on fig. 4. The noise was filtered out and the original signal character remained unchanged.

![Figure 3. Fourier domain analysis of the thermocouple signal.](image)

The eqn. (3) was used to calculate the local heat transfer flux rate (fig. 5). Small disturbances are visible on the plot even during first stage of recording when the heat exchange process had not began. They can be explained by measurement and derivatives determination errors.

The same experiments were conducted with the thin film metal resistor. This sensor is more sensitive than the thermocouple. It made possible to decrement the amplifier gain by factor of 4 and resulted in significantly smaller noise amplitude (fig. 6). Placing the measuring resistor on the insulating layer results in an increment of temperature signal amplitude in the same compression cycle. The same smoothing procedure was applied to the signal.

In case of resistance sensor eqn. (3) can not be used. This equation is based on the assumption of half-infinitive body model with constant heat properties. Thin aluminium oxide layer with significantly lower heat conductivity causes that it takes a big part of total temperature rise.
Figure 4. The thermocouple signal after removing the noise.

Figure 5. Calculated heat flux rate from the thermocouple signal.
Figure 6. The surface temperature change measured by the film sensor.

Figure 7. Calculated heat flux rate from the film sensor.
Therefore local heat flux was calculated numerically on the basis of one dimension unsteady heat conduction in two-layer plate with the recorded surface temperature as a boundary condition (Jaluria & Torrance). Calculation results are presented on fig. 7. They are very similar to those obtained with the eroding thermocouple. The difference between maximum fluxes is only 7%. Higher differences are present at the final stage of experiments, after the stop of the piston. Heat exchange becomes less intensive and the influence of alumina layer is more visible. Determination of heat properties of used materials is also a source of errors.

5 Conclusions

Conducted experiments have proved that eroding thermocouple has a low time constant and is able to measure a transient surface temperature. It is easy to implement and has possibility of junction regeneration.

In our case obtained signals are very small. It is necessary to implement an amplifier with suitable gain and bandwidth witch causes a big noise in recorded signals. Before heat flux calculations the noise have to be filtered out. This can be easily done using FFT method.

Resistance sensor is more sensitive. Obtained signal is higher which results in less noise. In this case noise filtration is also necessary to avoid errors in determinations of time derivatives.

In both cases numerical procedures of local heat flux calculations are easy but demand the knowledge of thermal properties of materials the sensors are made of. It is especially important in eroding thermocouple that is made of several materials. Inside the stainless steel shell there are two metals forming a junction divided by insulation layer. Differences of thermal properties can make one-dimensional model of heat conduction too less accurate (inaccurate).

Film metal sensor needs insulation from metal substrate. Despite small thickness this layer has a thermal resistance. It causes that the sensor gives much higher surface temperature rise in the same heat exchange conditions. It has to be taken into account during the calculation procedure. Eqn. (3) for a half-infinitive uniform body can not be used. However the one-dimensional heat conduction model is valid and numerical calculations are not difficult.

In our case the insulation layer and resistance sensor were deposited directly on the plate closing the compressor cylinder and cannot be used in another place. Wimmer & Pishinger described removable construction of the sensor that can be mounted in any place.
but its dimensions were bigger than eroding thermocouple. The sensor is very sensitive to a damage without possibilities of regeneration.

Both sensors give similar results in investigations of a local heat transfer on the plate closing the compressor cylinder.

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References


