Study on an injection quantity sensor. II: Evaluation of the sensing element

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Abstract—For further optimization of the combustion process, the information about the actually injected fuel quantity is desirable, especially in diesel engines equipped with direct injection technology. A miniaturized hot-film anemometer with a titanium/platinum metallization on a low-temperature co-fired ceramics substrate was developed and integrated into a Common Rail injection nozzle. The micro-flow sensor proved its high performance and its capability over the complete fuel quantity map of a high pressure hydraulic injection system where drive pulses for the operation of the injector range between 0.3 ms and 1.5 ms at injection pressures up to 135 MPa (1350 bar). In correspondence with measurements of an injection amount indicator integrated into the hydraulic test bench, the injected fuel quantity and the opening behaviour of the orifice were derived from the sensor signals as a function of injection parameters. Assuming a power law dependence on the fluid velocity for the flow-sensitive portion of the heat-transfer coefficient, a value of 0.5 for the exponent was determined experimentally, in excellent agreement with theoretical predictions.

Keywords: Common Rail injection system; LTCC ceramics; hot-film anemometer; thin-film technology; pressure oscillations; heat-transfer coefficient; on board diagnosis.

1. INTRODUCTION

The ‘on board’ diagnosis (OBD) of the fuel quantity injected into diesel engines equipped with Common Rail (CR) direct fuel injection technology is a challenging task due to extreme environmental conditions with working pressures ranging up to 135 MPa (1350 bar) and due to high requirements concerning the resolution of small fuel quantities ranging down to values substantially below 1 mm³. To our knowledge, up to now only two devices have been reported in the literature designed for measuring the injected fuel quantity during operation. Kanai et al. presented

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a miniaturized Prandtl tube with an integrated micromechanical silicon pressure
sensor [1] which can handle injection pressures of up to 15 MPa, typically occurring
in spark ignition engines with direct injection technology. In an earlier work by
Iwasaki et al., a micro turbine flow sensor with a rotor diameter of 1 mm fabricated
by electro-discharge machining in steel was presented [2]. A maximum working
pressure of 100 MPa was demonstrated, which is not sufficient for modern diesel
injection systems. In addition, the sensor was placed into the inlet connector of the
injector, leading to a distorted measurement of the desired fuel quantity, especially
in the lower working range due to the presence of governing fuel quantities needed
for the electro-hydraulic operation principle.

In this work, a novel miniaturized injection quantity sensor with a ceramic
substrate was developed. Its function is based on a thermal principle, thus avoiding
any moving components. Due to its small size it can be integrated directly into
the injection nozzle, minimizing the impact of governing or leakage fuel quantities,
which would otherwise require the application of complex compensation algorithms
as a function of temperature and injection pressure. The technology for integrating
this ceramic sensor chip into the nozzle body in a pressure-tight way and with
negligible influence on the hydraulic performance of the orifice is presented in the
accompanying paper [3].

It is the objective of this work to present and evaluate the experimental results
of this micromachine sensor element which is capable of covering the complete
range of drive pulses (between 0.3 ms and 1.5 ms) as well as pressures (between
25 MPa and 135 MPa) occurring in a Common Rail diesel injection system for
OBD purposes.

2. DEVICE PREPARATION AND EXPERIMENTAL PROCEDURE

A square-shaped low temperature co-fired ceramic (LTCC) sheet measuring 60 ×
60 mm$^2$ was used as substrate material, allowing the simultaneous fabrication
of about 100 sensor cells. Each individual sensor element features a metallized
heater structure at its centre and up to four electrical feed-throughs, as well as four
alignment marks. The latter are arranged symmetrically around the centre of the
sensor by punching holes in the uppermost ceramic layer in the ‘green state’ with a
nominal diameter of 100 µm, having a distance of 1.5 mm with respect to the centre.
The marks are necessary for aligning the ceramic sheet in the ultrasonic milling
process which is used for giving the final sensor elements a round design. According
to the specification of the manufacturer, the LTCC substrate has a maximum surface
roughness depth $R_{\text{max}}$ of $\approx 1700$ nm (roughness average $R_a \approx 350$ nm), which
is acceptable for substrate materials targeted for thick-film printing technology. In this
work, however, thin film technology was used for implementing the heater element,
thus reducing its thickness to about 100 nm. With this small height its influence on
the fuel flow field was minimized, even for flow velocities as high as 120 m s$^{-1}$ [4].
Therefore, the surface roughness characteristics of the fired LTCC tape had to be