Title: Dimensional metrology for high-aspect-ratio micro-nozzles

Abstract

Fuel injection nozzles, sonic micro-nozzles for gas flow measurements, cavitation micro-nozzles for liquid flow measurements and high frequency waveguides all require improved dimensional metrology (e.g. SI traceable measurements of the inside topography and dimensions (diameters 1 mm to 50 µm, lengths up to 10 mm). Methods for measuring position, orientation, diameter, form, surface waviness and roughness should also be improved. Self-sensing tactile microprobes based on piezoresistive silicon cantilevers should be used for roughness measurements inside high-aspect ratio nozzles and for force-modulated indentation in order to identify different contaminants and to determine surface mechanical properties. Double tip cantilevers should be developed for precise diameter determination. Traceable optical methods need to be established to measure the inner form and waviness of micro-nozzles with an uncertainty of 100 nm, and optical spectroscopy should be used to analyse different surface materials. Suitable reference standards for the calibration and quality control of the inner hole metrology systems and methods for traceable calibrations are also required.

Keywords

Micro-nozzle, high aspect ratio, microprobe, roughness, diameter, injection nozzle, sonic nozzle, cavitation nozzle, waveguide

Background to the Metrological Challenges

Fuel injection nozzles, sonic micro-nozzles for gas flow measurements, and cavitation micro-nozzles for liquid flow measurements are economically important. 1) Modern fuel injection nozzles have 6 injection holes, rather than 3, to improve the fuel-air mixture in the combustion chamber. This saves fuel and reduces emissions [1, 2]. The use of smaller hole diameters demands higher quality and measurement requirements. Also nozzle lifetime is more seriously limited by deposits growing on the inner surface of these smaller nozzles. Topography measurement is possible with piezoresistive silicon microprobes. The continuous stiffness method used in nanoindentation could be tested to differentiate between different deposition materials. 2) Sonic nozzles are used for gas flow measurements and the mass flow rate can be derived using ISO 9300 [3]. This standard needs to be extended to small and micro nozzles and all three measures (diameter, inner shape and inner surface) require a reliable measurement method. Currently only long piezoresistive silicon microprobes are able to measure internal roughness. 3) Cavitation micro-nozzles have the potential to realise and measure very small liquid flow rates e.g. in chemical, medical, pharmaceutical and mineral oil industries. First experiments indicate the possibility of using a similar approach to that used with sonic nozzles; but theoretical and practical verification are required.

The quality control of micro-nozzles with diameters below 1 mm is difficult as conventional CMM probes end at 300 µm diameter of the probing spheres. Micro-CMMs now offer smaller probing spheres with diameters down to 120 µm, or in the case of the fibre probes down to 20 µm. When measuring holes with high aspect ratios these act as an aperture for the imaging system of the fibre probe which leads to systematic errors. Furthermore traceable roughness measurements are not possible with these probes. Traceable measurements inside micro-nozzles, using piezoresistive silicon microprobes, could provide the information needed for quality improvement. Ten mm long nozzles will need to be measured; however, existing piezoresistive silicon microprobes can only measure nozzles up to 5 mm length. Developments are needed with respect to probe length, tip length, shape and position on the cantilever.

Other techniques that could be developed include optical form and waviness measurement, Computer Tomography, and vector network analysis. 1) Optical form and waviness measurements are much faster than tactile measurements, but they have worse lateral resolution and a stronger dependence on the

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cleanliness of the surfaces to be measured. However, they apply no force to the sample surface and very soft and brittle layers can be measured. Small diameter steel optical probing systems are >1.5 mm in diameter. By combining silicon and MEMS this could be reduced to 250 µm. Also the Raman effect could be used to identify most hydrocarbons. This would be a powerful tool to analyse deposits in fuel injection nozzles. 2) Computer Tomography (CT) is a powerful tool which can measure complete parts in 3D in a single shot. However, there are limitations to this technique including the limited power of the x-ray sources; and further development is required. 3) In vector network analysis, calibration and traceability is achieved by calculable standards, e.g. so called coaxial air lines. The quality of the result relies on the precision of the dimensional characterisation of the standards. While the dimensions of most standards can be obtained by CMMs with sufficient precision, for frequencies above 50 GHz surface roughness plays an increasing role. Measurements are often carried out at below, within, and above the 140 GHz - 1.1 THz range. Therefore surface roughness information is essential to establish traceability. Microprobes are required to measure surface roughness for circular apertures in nozzles (1 mm in diameter, <20 mm in length) and rectangular apertures (1.651 mm - 0.570 mm in width, 0.826 mm - 0.285 mm in height, <2.5 mm in length).

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the proposal.

The JRP shall focus on the development of dimensional metrology for high-aspect-ratio micro-nozzles by enabling the SI traceable measurements of the dimensions and inside topography of nozzles with diameters ranging from 1 mm down to 50 µm and lengths ranging from 10 mm to 0.5 mm.

The specific objectives are

1. To improve the measurements of position, orientation, diameter, form, surface waviness and roughness of micro-nozzles (nozzle diameter from 0.05 mm to 1 mm, nozzle length from 0.5 mm to 10 mm, measurement uncertainty below 100 nm).
2. To develop self-sensing tactile microprobes for inner roughness measurements and force-modulated indentation (to identify contamination and to measure the surface mechanical properties). The microprobe tip must be wear resistant with a reproducible conical shape and a height from 20 µm to 150 µm. The probe length should extend to 10 mm.
3. To develop optical methods to measure the inner form and waviness of micro-nozzles with an uncertainty of 100 nm. Optical spectroscopy must be applied to analyse the surface contamination. Both the width and height of the optical microprobes must be less than 500 µm; the length must extend to 10 mm.
4. To establish standards for the calibration and quality control of inner-nozzle metrology and to develop a traceable calibration of these standards.
5. To develop cost effective and easy-to-use technologies for dimensional measurements (diameter, inner shape and inner surface) in industrial environments.

Proposers shall give priority to work that meets documented industrial needs and include measures to support transfer into industry by cooperation and by standardisation. An active involvement of industrial stakeholders is expected in order to align the project with their needs – both through project steering boards and participation in the research activities.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs to be 1.5 M€, and has defined an upper limit of 1.8 M€ for any project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 30 % of the total EU Contribution to the project. Any deviation from this must be justified.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the “end user” community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Drive innovation in industrial production and facilitate new or significantly improved products through exploiting top-level metrological technology,
- Improve the competitiveness of EU industry,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Transfer knowledge to the automotive, aeronautic, gas and medical sectors.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects”

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.

Additional information

The references were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] Payri F, Bermúdez V, Payri R, Salvador FJ 2004 The influence of cavitation on the internal flow and the spray characteristics in diesel injection nozzles. Fuel, 83, 4-5, March, 419–431

[2] Jung D, Wang WL, Knafl A, Jacobs TJ, Hu SJ and Assanis DN 2008 “Experimental investigation of abrasive flow machining effects on injector nozzle geometries, engine performance, and emissions in a DI Diesel engine”, Intern. J. Automotive Technol., 9, 1, 9-15

[3] ISO 9300:2005 Measurement of gas flow by means of critical flow Venturi nozzles