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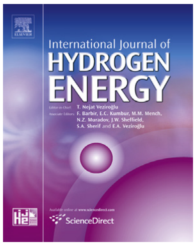

Performance of piezoelectric actuators in a hydrogen environment: Experimental study and finite element modelling

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ABSTRACT

Significant improvements in fuel efficiency and emissions can be achieved in internal combustion engines (ICE) by electronically controlling the fuel injector opening valves with piezoelectric actuators. Hydrogen is considered an attractive alternative fuel with near-zero emissions at the point of use; however, the current understanding of the performance of piezoelectric actuators in a hydrogen environment is very limited. Variation in the performance of piezoelectric actuators due to their continuous and cyclic exposure to hydrogen at 100 °C and 10 MPa is experimentally investigated in the present work. The actuator's stroke-voltage relationship is evaluated under quasi-static as well as dynamic electric loading conditions within the ambient temperature range of 5–80 °C. A 3-D finite element model is also developed to simulate the behaviour of a single stack of an actuator exposed to hydrogen by using experimentally determined piezoelectric coefficients. The importance of coating technology to protect the actuator material from hydrogen is confirmed by the experimental study and numerical modelling.

Introduction

Smart materials are a special class of engineering materials which exhibit coupling between multiple physical domains. Piezoelectric materials are a class of smart materials exhibiting coupling between mechanical and electrical fields. They have been utilized to develop sensors and actuators. Direct injection of fuel into the combustion chamber of an internal combustion engine (ICE) is one such application where a piezoelectric actuator is used to control opening and closing of an injector needle. Typically, *stack-type* piezo actuators consisting of hundreds of thin piezoelectric disks sandwiched between electrodes, as illustrated in Fig. 1, are used. Application of an electric potential difference across the electrodes produces expansion or contraction in each disk within the stack which translates into the overall stroke of the actuator. The fuel injector's function is to control the supply of fuel into the engine's combustion chamber. This control is achieved by utilizing the stroke of the *stack actuator* to actuate the injector's needle, as shown in Fig. 2. Compared to the conventional electromagnetic solenoid technology, injectors based on piezoelectric actuator technology provide specific advantages such as: a) rapid response; b) precise positioning; c) improved

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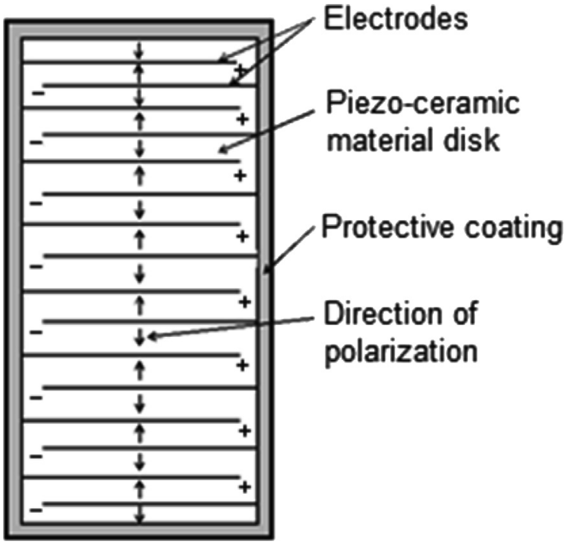

Fig. 1 – Cross-section of a *stack type* piezoelectric actuator.

fuel metering; d) variable stroke length; and e) increased injection pressure capacity. Enhanced control of combustion is, therefore, possible through multi-pulse, closely spaced injections or rate shaping [1]. Position self-sensing techniques for piezoelectric actuators have been developed which can further optimize the control process [2]. These advantages can collectively contribute towards reduction of vehicular emissions and fuel consumption by up to 15% in ICEs [3].

Hydrogen is considered a "green" fuel that can be used to reduce greenhouse gas emissions and develop sustainable transportation systems. If hydrogen is used to power ICEs, the availability of existing manufacturing infrastructure for petroleum-based ICEs can be leveraged to support the hydrogen economy while fuel cells reach a mature commercial stage [4]. Therefore, the use of hydrogen as a fuel for transportation and power sectors is being considered by the world's major engine developers [5–9], including Vancouver-based *Westport Innovations Inc*. Hydrogen can be produced locally from diverse sources thereby increasing energy security [10]. However, hydrogen is highly reactive chemically and diffuses into almost every material which is a major concern in the development of hydrogen technology. Additional issues related to hydrogen-based transportation technology are safe on-board storage, refuelling infrastructure and diagnostic systems.

The development of hydrogen injectors is a topic that is relevant to both ICEs and fuel cell technology. In this regard, research is in progress to assess the viability of piezoelectric actuator technology for hydrogen injectors. Past studies on bulk material samples have indicated that exposure to hydrogen can produce changes in the properties and microstructure of lead zirconate titanate (PZT), the most widely used piezoelectric ceramic material for actuators. Experiments conducted by Wu et al. [11] have shown that the piezoelectric constant d_{33} and the remnant polarization P_r of bulk PZT are strongly influenced by the hydrogen content. Peng et al. [12] observed hydrogen-induced initiation and growth of micro-cracks along the grain boundaries of PZT. Wang et al. [13] observed reductions in the values of strength and fracture toughness with increased hydrogen content. Ma [14] developed a sophisticated phase field model to simulate evolution of hydrides in PZT under stress. Following similar concepts, Guo et al. [15] developed a phase field model to simulate hydrogen-induced cracking of PZT ceramics and predicted one to two orders of magnitude decrease in their fracture toughness due to hydrogen ingress. Under hydrogen exposure conditions (13.8 MPa, 100 °C) comparable to a typical fuel injector, Alvine et al. [16] observed hydrogen-induced blistering on the PZT surface and found that the rate of hydrogen absorption into the PZT thin film samples increased due to the presence of Pd electrodes on them. Recent studies conducted by Shafiei et al. [17–19] indicate changes in the microstructure and electrical properties (capacitance, resistance, dissipation factor) of hydrogen treated PZT.

Performance of piezoelectric stack actuators under quasi-static electric loading [20], dynamic electric loading [21] and cyclic fatigue loading [22] has been investigated in the past under conditions that are similar to the operating and ambient conditions of a fuel injector. Senousy et al. [23] investigated self-heat generation in the actuators and its resulting effects on performance. Narita et al. [24] conducted a combined experimental and numerical study to explain the variations in the electromechanical response of multilayer piezoelectric actuators from room to high temperature. These

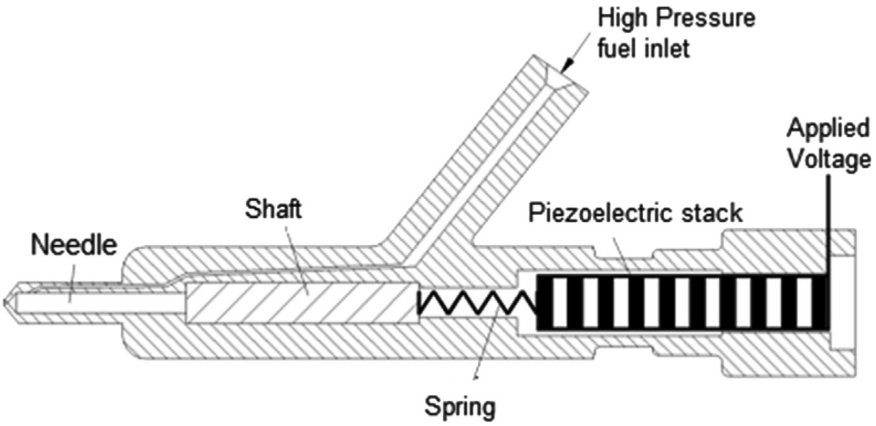

Fig. 2 – Cross-section of a *piezoelectric stack actuator* based fuel injector.