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The influence of eccentric needle movement on internal flow and injection characteristics of a multi-hole diesel nozzle

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ABSTRACT

The internal flow characteristics and injection characteristics of each nozzle hole in a multi-hole diesel nozzle are significantly affected by transient needle movement which studies have shown to be unconventional (eccentric). This eccentric needle movement (unconventional movement of needle within nozzle) is considered as one of the main causes responsible for injection start delay and also variations in fuel injection quantities and spray patterns from symmetric multi-hole nozzles. Needle eccentricity movement creating conditions (causes) and the effect of the eccentric behavior on flow in a symmetric multi-hole diesel nozzle, were computationally studied by examining the in-nozzle geometrical flow area of each nozzle hole during the transient movement of the needle. Based on experimentally determined needle displacement, moving mesh technique was employed in modeling the eccentric needle movement in the computational domain during the simulation. After which the effects of eccentricity within nozzle on in-nozzle hole flow characteristics (cavitation distribution, fuel flow velocity distribution) and injection characteristics (fuel injection rate) were investigated. With a direct effect on flow distribution within nozzle holes, eccentric needle movement has a direct effect on injection and can therefore be considered as one of the main causes of non-homogeneity during fuel injection process. At low needle lift, cavitation distribution, fuel flow velocity and fuel injection rate of each nozzle hole vary considerably and are highly dependent on the needle position. The progressive variations in fuel injection rate non-uniformity from the nozzle are caused to some extent, by the rate of change in in-nozzle geometrical flow area for each nozzle during injection process. The nozzle hole close to the needle displacement shows high level of sensitivity with regards to eccentric needle movement. This nozzle hole therefore exhibits the most variations of injection characteristics under all the cases of eccentricities. Also, with varying degree of needle eccentricity, rate of non-uniform coefficient of cycle fuel injection quantity within the nozzle varies disproportionately.

1. Introduction

As one of the critical parts of IC engine fuel injection system, the injector disseminates the adequate amount of fuel required (to run the engine) into the combustion chamber. In-nozzle hole flow has therefore been extensively studied due to the established relationship with primary spray breakup, air-fuel mixtures and combustion processes [1–6]. As a result, lots of attentions have been generated in studying in-nozzle hole flow development and effect on spray.

For multi-hole-type injectors, it has been discovered that fuel flow characteristics inside the nozzle holes are strongly influenced by their internal geometry (size of sac chamber, rounding radius, hole inclination angle, etc.) [7–9]. In-nozzle hole cavitation developments are directly affected by fuel properties from the studies of [9–12] while from [13–17] in nozzle hole cavitation distributions are directly influenced to some extend by the injection condition and needle movement behavior.

Needle dynamics (such as vertical needle valve opening and closing) within nozzles are caused by pressure and force differences acting across the needle during injection process. For symmetric multi-hole nozzles, the influences of needle movement on in-nozzle hole flows are marginally non-uniform. This non-uniformity occurs as a result of the eccentricity caused by the misaligned movement (off-center motion) of the needle in the nozzle

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Nomenclature

A_{geo}	geometrical outlet section (m^2)
C_n	non-uniform coefficient (–)
d	nozzle hole diameter (mm)
e	maximum radial displacement (mm)
g	acceleration of gravity (m/s^2)
h	maximum needle lift height
h_o	maximum needle lift at Stage 1
k	turbulence kinetic energy (m^2/s^2)
M	interfacial momentum transfer (kg/s^2 m^2)
q_{max}	maximum cycle fuel injection quantity
q_{min}	minimum cycle fuel injection quantity
q_{mean}	average cycle fuel injection quantity
S	flow area
t	time (s)
v	flow velocity (m/s)
x	The gap between nozzle hole and needle tip

Greek symbols

∇	laplace operator
ΔP	effective differential pressure (Pa)
β	angle
δ	angle
θ	needle tip angle
ε	turbulence dissipation rate (m^2/s^3)
ρ	liquid density (kg/m^3)
Γ	mass exchange term (kg/m^3 s)

Subscripts

i	nozzle hole serial number
k, l	phase index

axis. From the experimental studies of Campanella [18], hydraulic characteristic differences (in spray pattern, fuel injection starting moment and fuel injection quantity) of each nozzle hole in a multi-hole VCO nozzle were studied. Whereas irregular spray pattern observed was attributed to micro-defects caused by drilling operations, the cause of non-uniform fuel injection starting point and fuel injection quantity were determine to be due to needle tip deformation and asymmetric feeding conditions. Ohnishi [19] studied the behavior of fuel spray in a multi-hole VCO nozzle experimentally by capturing each nozzle hole's injection phenomenon using a video camera and a micro-flash. They pointed out that fuel injection delays (non-uniform injection) from multi-hole nozzles occur due to nozzle hole blockage by displaced needle movement (eccentric) during injection process. Also in our previous research [20–22], momentum flux change rate of each nozzle hole in a multi-hole injector was measured experimentally. From the experimental results it was discovered that differences in momentum flux change rate exist at the initial stages of injection. In this regard, in-nozzle eccentric needle movement during injection process is considered to be one of the main causes of non-uniform fuel injection from symmetric multi-hole nozzle.

Therefore, in determining the degree of eccentric needle displacement, a high speed video camera was used by Ohnishi [19] to observe the needle movement trajectory during injection through a 0.06 mm window at the needle tip. They found that the maximum eccentric needle radial displacements are 0.06 mm inside a VCO nozzle and 0.024 mm inside a micro-SAC nozzle. With the same methodology, Shoji [23] also measured eccentric radial displacement to be 0.04 mm. With the development of X-ray technology, advanced imaging technique such as "high-speed X-ray phase enhancing imaging technique" is used in capturing in-nozzle needle movement just as in [24,25] nowadays. Time resolve measurements of needle movement in radial and axial directions are obtained using a synchrotron source as in the investigations of Kastengren [26], where the needle movements within four injectors were measured. The maximum and minimum eccentric radial displacement measured were 0.065 mm and 0.016 mm respectively.

To study the effect of eccentric needle movement on in-nozzle hole flow, Chiavola [27] investigated the instantaneous discrepancies in velocity flow field and cavitation behavior among nozzle holes by assigning a radial displacement of 0.04 mm to the needle tip at maximum needle lift in a SAC nozzle. Oda [28] also experimentally and numerically studied the internal cavitation flow and primary atomization within a large-scaled VCO nozzle under eccentric needle movement and observed the presence of complex flow regimes and atomization especially at low needle lift. Likewise, Salvador [29] determined the influence of needle position on flow characteristics by comparatively studying the effect of needle motions (one needle perfectly centered and the other with 0.07 mm displacement at full needle lift) on the internal flow of a real multi-hole micro-SAC nozzle. Xue [30] and Battistoni [31] in their investigations, imposed an X-ray measured off-axis needle motion boundary condition to determine the influence of needle movement on transient internal flow and near exit flow in a single and a multi-hole nozzle. They observed that off-axis needle movement (eccentric) influences the flow in the sac region, resulting in mass flow rate and near nozzle jet structural differences in symmetric multi-hole nozzle.

From the stated research works above, it is clear that the influence of needle unconventional motion on in-nozzle hole flow development of multi-hole nozzle has been extensively investigated from various perspectives. However, the quantification of the in-nozzle geometrical flow areas around each nozzle hole as a result of eccentric needle movement, especially hole to hole variations during the lifting stages of the needle are yet to be investigated. Therefore, in this study, the relationship between in-nozzle geometrical flow area accessible by each nozzle hole and needle valve lifts with regards to needle eccentricity will be computationally analyzed, and also the influence of eccentric needle motion on hole to hole fuel injection rate variations will be studied and quantified with regards to various degrees of needle eccentricity. Furthermore, for model validation of the nozzle, the fuel injection rate from each nozzle hole will be individually verified with experimental results instead of the total fuel injection rate (or mass flow rate) from the nozzle. These form the main motivation for this study.

As described in [26,30,31], the needle under high pressure undergoes elastic deformation and develops a cantilever effect when lifted, oscillating rhythmically in the injector. This effect results in eccentric movement and affects hole to hole flow distribution and injection propagation. Consequently in this study, the effect of the eccentric needle movement on hole to hole flow and injection differences will be computationally investigated in line with the experimental finding of Campanella [18] and Ohnishi [19]. As a result, contributing to the understanding of transient eccentric needle movement developments, using computation fluid dynamic software AVL Fire, 3D simulation investigations of