

Development of a Fast-Acting, Time-Resolved Gas Sampling System for Combustion and Fuels Analysis

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ABSTRACT

Development of new fuels and engine combustion strategies for future ultra-low emission engines requires a greater level of insight into the process of emissions formation than is afforded by the approach of engine exhaust measurement. The paper describes the development of an in-cylinder gas sampling system consisting of a fast-acting, percussion-based, poppet-type sampling valve, and a heated dilution tunnel; and the deployment of the system in a single cylinder engine. A control system was also developed for the sampling valve to allow gas samples to be extracted from the engine cylinder during combustion, at any desired crank angle in the engine cycle, while the valve motion was continuously monitored using a proximity sensor.

The gas sampling system was utilised on a direct injection diesel engine co-combusting a range of hydrogen-diesel fuel and methane-diesel fuel mixtures. In-cylinder gas sample composition was investigated at two sampling locations; within the diesel fuel spray and between adjacent spray cones. Concentrations of NO_x were found to be higher between the two diesel sprays relative to within the spray cone for both hydrogen and methane addition. In the case of hydrogen-diesel fuel co-combustion, the particulate levels were observed to be higher in the diesel fuel spray relative to between two sprays; however, in the case of methane-diesel fuel co-combustion, higher particulate levels were measured in the region between the two sprays. This was attributed to methane contributing significant quantities of particulates to the total particulate concentration produced from the methane-diesel fuel mixture in between two sprays.

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INTRODUCTION

Rising concerns about pollutants from fossil fuels have heightened the need to obtain a comprehensive understanding of the combustion characteristics of future fuels in order to develop novel strategies for improved efficiency and reduced pollutant emissions. New insights about the diesel combustion process with modern combustion systems require knowledge of how combustion progresses within the engine cylinder. High pressure and temperature studies inside engine combustion chambers are particularly challenging due to extremely short reaction rates, with unsteady environment conditions posing further complications. Attempts to follow the course of engine incylinder combustion and evolution of intermediate species have been carried out by a number of investigators by means of both optical and physical sampling techniques. The application of optical diagnostic methods, despite possessing the advantages of higher spatial and temporal resolution, and being of a non-intrusive nature [1], are particularly difficult to apply in diesel engines, as robust optical access to the combustion chamber is required. Considerable density and composition gradients of species concentrations can occur across the cylinder and the wide-ranging spectrum of blackbody radiation from carbon soot particles can eclipse spectral radiations emitted by other in-cylinder species [2]. Furthermore, optically accessible engines often run at lower compression ratios

than commercial engines and are not sufficiently suited for running continuous, long duration tests, not only because of possible thermal fatigue but also because the optical windows can get covered with combustion deposits and require cleaning at frequent intervals [3]. Physical sampling techniques, where samples are extracted after combustion, have been applied to shock tubes and rapid compression machines which replicate some of the characteristics of combustion in an engine [4]-[9]. Similarly, many research and commercial engines readily allow analysis of the composition of the engine exhaust. Since only the end products of the combustion process can be sampled and analysed, these methods do not provide significant insight as to the composition histories of the combustion and pollutant intermediates. Total cylinder dumping has been used as a method of extracting time-resolved in-cylinder gas samples and involves the rapid emptying of the entire contents of the cylinder during combustion, at a selected crank angle, into a sample collection bag or vessel [10]-[14]. Since the entire contents of the combustion chamber are extracted, this technique is not able to provide spatially resolved in-cylinder information [3].

Timed, fast in-cylinder sampling is an attractive approach that can provide spatially and time-resolved quantification of stable species formed in the course of combustion. With this approach, sampling

can be timed so that the extraction of the gas sample from the cylinder occurs at a specific narrow crank angle window. In-cylinder gas sampling valves have been employed in internal combustion engines to improve understanding of various physical and chemical processes associated with combustion; such as the phenomena of knock in spark-ignition (SI) engines [15] and diesel fuel-air mixture distribution in compression-ignition (CI) engines [16]-[18]. In recent years, advanced gas sampling techniques have been developed with the aim of comprehensively understanding the in-cylinder processes which lead to pollutant emissions such as NO_x and PM, and therefore develop methods of reducing the formation of these emissions. Heywood et al. [19] carried out in-cylinder gas sampling experiments in a single cylinder CFR engine in order to investigate the contribution of unburned hydrocarbons, from the quench layers on the cylinder head and upper portion of the cylinder liner, to the exhaust emissions. Matsui and Tanaka [20] developed a special gas sampling cylinder head insert (with dual functionality as both a spark plug and a gas sampling valve) and used it to measure local fuel mixture concentrations within the spark electrode spacing, at the instant of spark discharge. Helium gas was used as a carrier gas for the collected gas sample and it was observed that the cyclic variation in fuel concentration at the electrode spacing increased with increasing percentage of EGR supplied to the engine. Turns and Borman [21] investigated, in a steady flow rig, the extent to which a sampling valve can disturb the in-cylinder gas motion. Two types of in-cylinder gas sampling probes were used, one having intermittent and the other continuous sampling flow action. It was observed that the probe diameter affected the measured species concentration, by altering the fuel diffusion process. It was also reported that, when sampling in low velocity streams having a species concentration gradient, an intermittent sampling probe produced less concentration profile-smearing than a steady-flow probe, as the sampled gas was collected and averaged over a smaller sampling region. These results are in agreement with similar studies carried out previously by various other investigators [22]-[24].

Aoyagi et al. [25] used an electro-magnetic needle-type sampling valve (Tsukasa Sokken GSD-1A) in a direct injection compression-ignition (CI) engine to investigate the effects of injection timing, swirl ratio and combustion chamber shape on the formation processes of NO and soot. NO was observed to form during the early and middle stages of combustion at high in-cylinder pressures and temperatures, and peak NO concentrations were reached as in-cylinder mixture ratios neared stoichiometric conditions. Soot was reported to form rapidly during the initial stages of combustion in fuel rich zones within the flame, and was later oxidized due to the entrainment of air in the flame. Optimum swirl conditions were found to produce a more homogenous distribution of fuel and air throughout the combustion chamber, resulting in lower soot levels. Similar studies were conducted by Fujiwara et al. [26] in which gas composition analysis was performed using gas chromatographic techniques, while a transmission electron microscope was employed to examine soot concentration and size distribution, and the spatial dispersion of soot particulates. Zhao et al. [27] developed an in-cylinder poppet-type gas sampling valve, based on the percussion principle, with an electromagnetically actuated armature and a proximity sensor to measure valve lift. This sampling valve was used to extract in-cylinder gaseous samples from a direct injection CI

engine, at various instants during the engine cycle, so as to follow the in-cylinder composition histories of NO_x , CO, CO_2 and soot emissions. NO_x concentrations were found to increase rapidly after combustion and reached peak levels within 1 ms of the start of combustion before subsequently declining to similar concentration levels as those measured in the engine exhaust. Peak particulate concentration in the cylinder was found to be at least 20 times greater than the exhaust particulate concentration. Electron microscopy and chemical speciation techniques were also employed to assess soot particulate sizing; individual soot spherules appeared to be larger at 40 CAD ATDC relative to those observed at 10 CAD ATDC and 150 CAD ATDC. Kato et al. [28] applied an in-cylinder gas sampling technique to determine the concentrations of the soluble organic fractions (SOF) and the insoluble fractions (ISF) of PM at different locations within the combustion chamber. High concentrations of SOF and ISF were reported when sampling along the spray flame axis, as compared to when sampling closer to the chamber wall.

More recently, Nowak et al. [1] utilized a gas sampling technique to measure the in-cylinder concentrations of various stable intermediate species during the HCCI combustion cycle and provide insights on fuel oxidation. The sampling probe featured an in-built N_2 dilution system and channels for oil circulation to regulate valve temperature, and was installed in the spark plug hole of a CFR engine; sampling times of 0.6 ms were achieved with satisfactory repeatability. The maximum concentration of combustion products observed during the high temperature reaction regime, and the major species produced during these reactions, were found to be the same as those measured in the exhaust gas. Of the exhaust THC concentrations, 70% were reported to be unburned fuel species mostly from the in-cylinder surface boundary layer, where low temperatures prevent oxidation. Dumitrescu et al. [29] carried out a computational study to determine the optimum sampling valve design (including the method of surface cooling and inert gas flow specification) required to arrest the reaction chemistry in an extracted sample for high resolution determination of particulate loading. The authors suggested that the sample valve length should be kept as short as possible to prevent adherence of soot on the valve inner walls, and the flow of an inert gas was necessary to quench sample reactions as valve wall cooling alone was insufficient in this respect.

A fairly high resolution gas sampling system to analyse engine incylinder gas composition would help enhance our understanding of incylinder processes that lead to the formation of pollutant emissions, especially when using future 'green' fuels. In previous work done by investigators [1], [13], [27], the engine in-cylinder gas sample was collected in a bag, requiring a significant volume of sample to be collected (approx. 10 litres) so as to achieve steady readings from typical gas analysers. Since the volume of sample extracted from the cylinder every engine cycle is relatively small (approx. 4-6 cm^3) [27], filling a bag with sufficient volume can take considerable time. Furthermore, in the time interval between filling up a bag and analysing the collected gas sample, the sample cools down to room temperature, causing condensation of high boiling point species in the sample.

The first part of this paper gives a detailed account of the development of a novel in-cylinder gas sampling system consisting of an intermittent, timed, fast-acting, electromagnetically actuated, poppet-type sampling valve and a heated dilution tunnel. The various attributes of the sampling system have been described in relation to the literature available on the subject. The sampling system described in this paper was developed to make the extraction and analysis of engine in-cylinder gas samples more efficient and accurate. The gas sample was kept at about 200°C from the point at which the sample was extracted from the cylinder to the point at which the sample entered the analysers. The dilution tunnel system also allowed gas composition data to be obtained faster than with the use of a bag, as no buffer time was needed to collect the gas sample, and the gas sample flowed directly from the sampling valve to the analysers. The sampling valve was extensively bench-tested for repeatability and durability, and to calibrate the valve at optimum operating conditions, the procedures for which have been outlined in this paper.

As a demonstration of the sampling system capability, the second part of the paper reports a series of experiments in which gas samples were extracted from two in-cylinder locations (from within the core of the diesel fuel spray and between two of the sprays) while the engine was operating on H₂-diesel fuel and CH₄-diesel fuel mixtures. The samples were collected at different instants during the engine cycle in order to monitor the change in in-cylinder gas composition as combustion progressed. It is hoped that the results obtained from this study will not only complement optical analysis undertaken using in-cylinder laser diagnostic techniques, but also contribute towards the validation of incylinder kinetic models based on computational modelling.

PART 1: DEVELOPMENT OF THE IN-CYLINDER GAS SAMPLING SYSTEM

Sampling Valve Tip

Gas sampling valves can be broadly categorised in terms of the type of valve tip used. The most commonly used type of valve openings are the outward opening poppet-type valve and the inward opening needle-type valves. In a poppet-type valve, the poppet is firmly seated in its seat due to the force provided by a pre-compressed return spring, with the in-cylinder gas pressure acting on the valve face providing an additional force and improving the seal at the valve inlet. An actuation mechanism pushes open the poppet valve, allowing gas to flow from the cylinder into the valve. Conversely, needle-type valves use the incylinder gas pressure to push the valve open against the return spring force [3]; the force provided by the return spring must be sufficient to keep the needle-valve firmly shut against the high pressures of the combustion chamber. Both valves possess relative advantage and disadvantage; crevices in the sampling valve are avoidable in poppet-type valves as they can be machined flush with the combustion chamber surface, something which is not possible entirely in a needle-type valve [27]. However, needle-type valves have smaller tip diameters [17], [28], [30] compared to poppet-type valves [27], [31], an advantage where access to the combustion chamber is difficult. A smaller tip diameter is also less likely to interfere with the gas flow inside the combustion chamber. The gas sampling valve used in the present study has a poppet-type

opening at the valve tip (Figure 1) as there was adequate space for access to the engine cylinder, but it was critical to seal the valve tip against the high in-cylinder gas pressures.

Valve Actuation System

In a poppet-type valve, the actuation force required to open the valve must be sufficient to counter, and overcome the in-cylinder gas pressure and the compression force of the return spring. Most early examples of in-cylinder sampling valves were mechanically actuated by linkages using pushrods and rockers, driven by the engine crankshaft or camshaft [15], [31]-[34]. Hydraulic actuation systems were also utilised in several investigations [35]-[39] as they are relatively space efficient, can provide forces sufficient to open the valve, are precisely controllable and have a short response time (between 0.8 to 2 ms). In particular, the work done by LoRusso et al [35], [36] using the electro-hydraulic gas sampling valve led to new insight regarding unburned hydrocarbon emissions from the quench layer of cylinder walls in SI engines. However, the setup of hydraulic actuation systems tends to be more complicated than other actuation methods [3].

An electromagnetic actuation mechanism was employed in the gas sampling valve presented in this paper. In an electromagnetically actuated poppet-type sampling valve (Figure 1), as soon as current is supplied to the electromagnet solenoid, the magnetic flux build up in the solenoid causes the armature to move, thereby opening the valve. In order to ensure a very short opening interval of the sampling valve, a large electromagnetic traction force and high armature acceleration are required. The traction force can be increased by increasing the thickness of the armature allowing it to build up a greater amount of magnetic flux; however, this increases the weight of the armature and therefore lowers armature acceleration [40]. Kajima & Kawamura [41] investigated this trade-off and established that the magnetic flux does not have time to penetrate deeply due to the transient operation of the electromagnet and, therefore, the armature thickness could be reduced without significantly affecting the performance of the solenoid. For the sampling valve design described in this paper, the centre volume of the armature was bored out to carry the hardened end of the armature shaft. To assist the rapid build-up of magnetic flux and provide a faster valve response, investigators have suggested reducing the number of winding turns on the electromagnet coil to reduce self-inductance [41] and slitting the armature to minimize eddy currents [42]. However, these techniques were not used in the current design, as the armature also acted as the actuating shaft and slitting it would have introduced further design complications. Ohdachi et al. [42] reported a considerable improvement in armature acceleration with increasing voltage supplied to the electromagnet, attributable to significantly increased initial flux accumulation in the armature. It should be noted, however, that the maximum voltage that can be supplied to the electromagnet is limited by the dielectric strength of the winding insulation, magnetic saturation and overheating of the coil [3]. For the design described in this paper, since the electromagnet was switched on for a much smaller period than it was “off” (“on” period was $\approx 10\%$ of the “off” period), it was possible to supply voltages considerably higher (up to 100 V) than the continuous voltage rating of the coil (24 V).

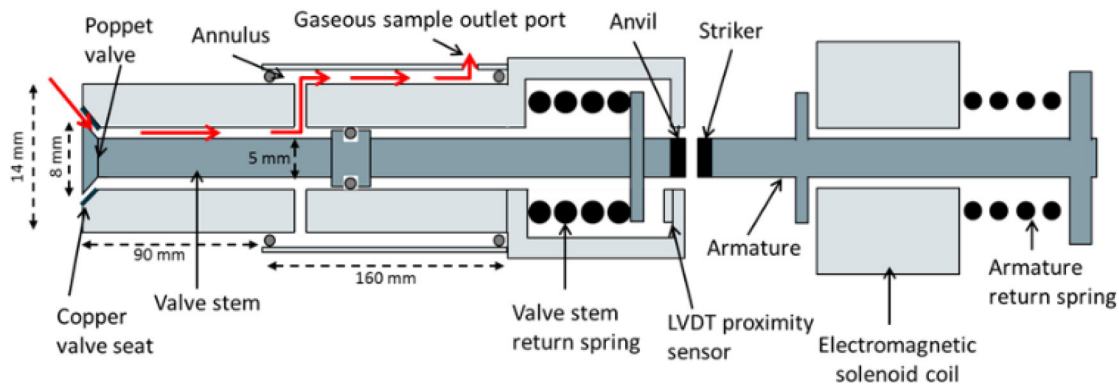


Figure 1. Simplified diagram of the in-cylinder sampling valve showing the gas flow from within the cylinder to the sample outlet port.

While an electromagnet actuation system can be controlled with great flexibility, the response of typical electromagnets is slow [3], as time is required for the build-up of magnetic flux in the coil. To overcome this issue, the sampling valve design described in this paper was based on the 'percussion' principle, where the armature is not rigidly joined to the valve stem (Figure 1), as first described by Yates [43] and successfully implemented by several other investigators [27], [32], [44]. In the current design a small gap, of about 3–4 mm, existed between the striker of the armature and the anvil of the valve stem (Figure 1). When switched on, the electromagnet caused the armature to accelerate and travel at high speed towards the valve stem and impact the stem, imparting a large enough force to open the poppet valve very briefly. The compressive force of the return spring shut the valve after the impact and a second armature spring returned the armature and striker back to the initial position. An important characteristic of the percussion type sampling valve is that because the valve has to be open for only a very brief period of the engine cycle, the electromagnet can be switched on well before the valve is required to be opened, so that a sufficient amount of flux can build up in the electromagnet. The armature-striker can travel across the gap gaining speed, and building up a substantial amount of kinetic energy, before striking the valve stem. Therefore a strong compressive force of the return spring can be overcome by a relatively small electromagnet size, improving acceleration of the valve stem [3].

An important design consideration in the 'percussion' system is to ensure that the armature return spring (Figure 1) should be able to rapidly withdraw the armature away from the valve stem and anvil. This is so as to prevent collision between the anvil and the striker which could delay the poppet valve closing. Zhao et al. [27] discussed this in great detail and concluded that subsequent collisions were difficult to avoid due to the following reasons. First, the natural frequency of valve return spring is greater than the armature return spring. Values of 35 Hz for the valve return spring and 10 Hz for the armature return spring were calculated for the sampling valve described in this paper. This is because the valve return spring constant has to be quite large to ensure proper sealing at the seat. Secondly, the armature spring constant has to be kept low so as not to significantly impede the momentum being gained by the armature as it moves to strike open the valve. For the sampling valve in the present study, high-speed imaging was performed to monitor the collisions between the armature-striker and the anvil of valve stem. It was observed that, even though the anvil collided with the striker

during valve closure, the striker was pushed out of the way by the valve stem due to the high incylinder pressures acting on the face of the valve and thus it did not appear to obstruct the closure of the poppet valve significantly.

For the current design, extensive bench tests were conducted with the sampling valve using springs of various stiffnesses in the valve stem, with a range of voltages being applied to the electromagnet. Parameters such as the maximum valve lift, valve open duration and the flow rate through the valve opening were monitored. Figure 2 shows the linear relationship between the duration of the signal sent to the electromagnet and valve lift duration and gas flow rate through the valve when the sampling valve was operated at a frequency of 10 Hz (representative of 1200 rpm engine speed, with every successive engine cycle being sampled), with a constant air pressure of 40 bar being applied to the valve face.

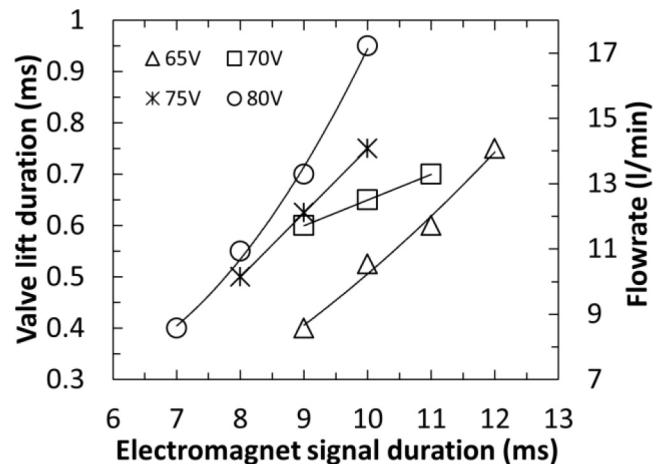


Figure 2. Valve lift duration and gas flow rate through the valve of the gas sampling valve at 10Hz operating frequency and 40 bar air pressure on the valve face. Natural frequencies; valve return spring - 35 Hz, armature spring - 10 Hz (for the sampling valve being discussed in this paper).

Construction Materials

The outer body of the sampling valve tip, including the annulus casing, and the striker were manufactured from stainless steel (grade 304) (also utilized in several previous investigations [20], [27], [37]) due to its generally non-corrosive properties and high oxidation and thermal resistance [3]. The valve poppet was machined from

silver-steel while copper was used to form the valve seat. Repeated impacts by the silver-steel poppet onto a square-edged copper seat allowed the poppet to hammer a bespoke seat matched to the poppet, thereby forming a good seal. The hot in-cylinder temperatures of a running engine (800-2000 K) assisted this process though thermal softening of the copper seat, with subsequent work-hardening of the copper seat resulting in a durable surface. The housing of the LVDT (linear variable differential transformer) proximity sensor was made out of a polymer material so as to isolate the sensor from any interfering signals from the electromagnet voltage.

Installation of the sampling Valve in the Engine Head

The sampling valve was installed in the engine head in place of one of the two inlet valves. The inlet valve was replaced with a dummy valve with a thread on the inner hollow surface; the sampling valve was screwed into this thread of the dummy valve. The sampling valve tip penetration into the combustion chamber could be varied from 0 mm (flush with the engine head) to a maximum penetration of 9 mm. To prevent the sampling valve from hitting the piston crown, at the sampling valve's maximum penetration, a small part of the piston at the edge of the bowl was cut out. Figure 3 shows the relative positions of the piston bowl cut-out, the diesel injector and the sampling valve inside the engine head with respect to the piston position at TDC.

An additional set of cursory tests were performed whereby the centrally located diesel fuel injector was rotated in order to move the diesel fuel spray relative to the sampling valve position and investigate the transport delay in the diesel fuel hydrocarbons reaching the sampling valve. The gas sample was collected and passed on to an FID analyser to measure the level of unburned hydrocarbons in the sample. It was hoped that these tests would give a preliminary idea of the charge motion inside the combustion chamber; however, it was observed that the hydrocarbons reached the sampling valve at the same time, irrespective of the position of the diesel fuel spray relative to the valve. It is therefore speculatively suggested that the swirl rate has decreased significantly due to the removal of one of the intake valves. It could be expected that a reduction in swirl might create asymmetrical charge motion inside the combustion chamber, leading to reduced combustion efficiency and increased unburned hydrocarbon and particulate emissions. However, a reduction in peak hydrocarbon concentration was observed with increasing distance between the spray and the valve, suggesting dispersion of the diesel spray to have taken place due to mixing and diffusion (despite the reduction in swirl rates).

Shape and Volume of an Engine In-Cylinder Gas Sample

The shape and volume of the in-cylinder gas sampling region are important factors that determine the spatial resolution of the sampling valve. Through their investigations on gas sampling valves, Zhao & Ladommatos [3] concluded that due to distortion as a result of fluid friction at the chamber wall and the presence of a boundary layer, the gas sampling region tends towards a hemispherical shape as shown in Figure 4.

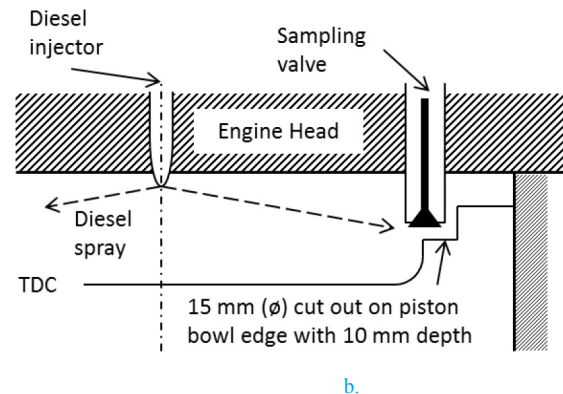
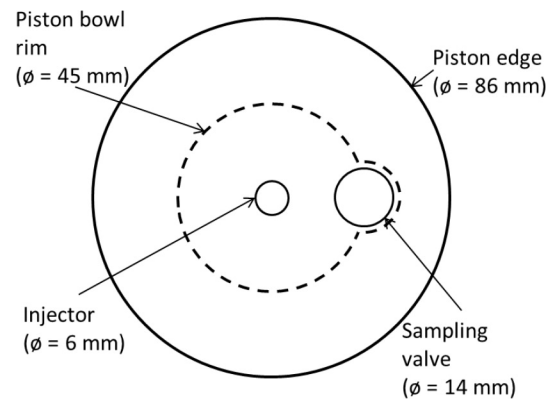


Figure 3. Schematic showing (a) plan view and (b) cross-sectional side view of the relative locations of the injector, the sampling valve at maximum in-cylinder penetration and the piston at TDC.

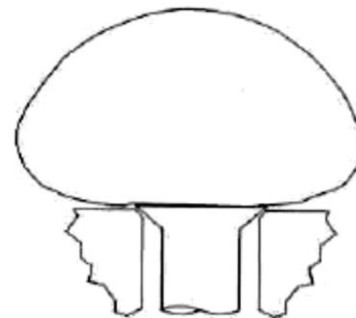


Figure 4. Actual sample volume shape at inlet of a poppet-type sampling valve, adapted from Zhao & Ladommatos [3].

Weiss & Keck [45] carried out a two-dimensional numerical analysis on the hemispherical shape of a gas sample volume around the inlet of a poppet-type sampling valve, which was extended by Zhao & Ladommatos [3] to three-dimensional hemispherical shapes. The volume of a sample shape attaining a roughly hemispherical shape, $\Delta V_{C,H}$, and assuming axial symmetry about the axes of the hemisphere, is approximately given by,

$$\Delta V_{C,H} = \frac{P_O T_C}{P_C T_O} V_O \frac{60\pi}{N} \quad (1)$$