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Research Article

Generating Plasma by Cumulative Detonation in a Combustion Chamber

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All combustion processes in present-day engineering applications are of the deflagration type. This character limits achievable values of parameters, such as the highest reached temperature and the corresponding degree of gas ionisation. If it were possible to increase the parameter values and reach the plasmatic state, a number of potentially useful combustion applications might be improved—like propulsion or electricity generation. Authors demonstrate a combustion chamber with detonation-type combustion that can reach, by cumulative implosion, extreme temperatures of generated thermal plasma.

1. Introduction

If it were realisable to manipulate gas flows by direct electric action, huge application potential would follow. Unfortunately, gases under usual conditions are electrically neutral. Engineering flow control applications with electric input action therefore have to operate with an intermediate conversion. Typically, the electric input is first converted into a motion of a mechanical component that in the second conversion step acts on the gas. This two-stage approach is far from satisfactory. The inertia of mechanical components limits the dynamics of the conversion. Also, poor reliability of their parts like valves, bearings, springs, and membranes is a limiting factor for useful transducer performance and operation life.

A promising solution avoiding the mechanical components is based on ionisation of the gas. It creates charge carriers that can be manipulated directly by the electric input. Problem is low concentration of generated charge carriers in thermal plasma, because it increases with rising temperarure very slowly. Obtaining a concentration at a useful level requires temperatures above those now achievable in standard engineering combustion practice.

The gas ionisation would offer a particularly important solution to generation of electricity by burning fossil fuels. Despite recent progress in renewable energy, our whole civilisation is still very much dependent on the combustible substances available in nature. Their use accounts for approximately one third of the current global 15 TWh worldwide energy production. The electricity generating process with combustion in its present version consists of a series of conversion steps. It begins with the fuel combustion followed by steam generation, driving a mechanical motion (by a turbine), and finishing with creating electricity in conductor coils rotating in a generator. All this is associated with losses that represent about two-thirds of the chemical energy theoretically available in the fuel. The least welcome among them are the mechanical motions and their losses—in principle not at all necessary.

Yet a no-moving-part electricity generation is known for quite a long time: it is the MHD generator [1] with charge carriers moving at high velocity through a stationary magnetic field. The charge carriers may be generated by the combustion process, but their concentrations in present-day achievable combustion products are insufficient. The temperature levels at which the MHD idea would become economical are so high that they are not obtainable [2] with the combustion of the degradation type. Those few MHD generators built for tests increase the ionisation level by the addition of pure oxygen and/or by seeding the gas with alkali metal droplets. This—together with the need of special

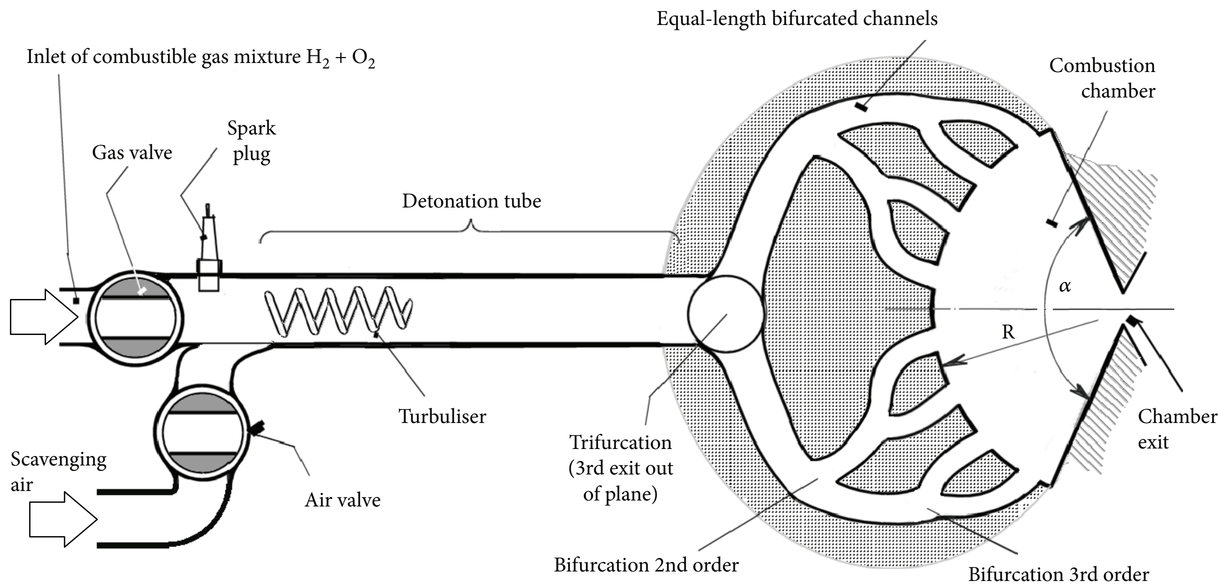

Figure 1: Schematic representation of the investigated single-shot laboratory test model. The cumulative effect is reached in the focal point near the chamber exit—where the temperature levels approach those needed for efficient thermal plasma generation.

expensive building materials—causes the present-day MHD idea to be out of question economically.

A more efficient combustion than the deflagration is in fact also known for a long time. It is detonation, involving supersonic wave accelerating so that it creates a propagating shock front. It is capable of getting nearer to the desirable high ionisation level—but difficult to exploit safely. Attempts at harnessing the detonations [3, 4], e.g., in a propulsion engine [5, 6], have not infrequently led to explosions with undesirable consequences. Moreover, the ionisation levels demonstrated so far in the successful detonation-type combustions have been lower than those needed for practical uses.

2. Cumulative Detonations

The key idea of this paper has its origin in detonation processes applied to military uses. The extremely high temperature is obtained by focusing detonation waves from many directions onto a small central region of space inside the combustion chamber which has the form of a hollow sphere. The problem is the necessity to ensure synchronisation of the detonation waves coming from many directions from the internal surface of the combustion chamber. Experience has shown practical impossibility of obtaining the synchronisation of detonation waves generated in separate sources. One reason is the sensitivity of activation energy. Generation of detonation waves is too much influenced by very small deviations of local conditions. Another reason for the sensitivity is the extreme propagation velocity of the detonation waves, of the order of kilometres per second, so that even a small disturbance prevents them from mutual meeting. Instead, the approach discussed here is based on having a single source from which the generated primary wave is distributed into the desirable large number of locations in the combustion chamber inner wall.

Literature contains descriptions of successful detonation wave generators that may be used as the source of the primary detonation wave. The most important is the detonation tube of constant internal cross section which is at the beginning of the run filled with combustible gas mixture. The wave generated in the upstream tube end propagates to the other downstream end and is converted into the detonation wave by a turbuliser. At the downstream tube end are distributors, consisting of bifurcated equal-length cavities leading to the locations on the hollow sphere surface. This is schematically presented in Figure 1, cf. also [7, 8]. Of course, the configuration with distribution channels complicates the chamber design and manufacture.

The basic idea of the cumulative detonation was first discussed very early, already in 1792 [9]. It was then aimed at applications to mining, which was not successful because gunpowder, the only explosive then available, is incapable of generating the propagating wave characteristic for the detonation. Later, in 1886, the idea was described in the US Patent [10] mentioning concentration effect in a cavity lined with solid explosive. A large-scale use of this hollow charges idea came in the 2nd World War. All cases studied then were single-shot configurations, the combustion chamber being after the detonation no more in existence for another cycle.

A device remaining not destroyed and thus available for the next detonation cycle requires operating with combustible gas mixture, scavenging the combustion residue and refilling the cavities with new charge. This was first investigated in 1972 as described in [11]. The detonation wave source there was a tube of 20 mm diameter and 1000 mm length distributed to the circumference of a 200 mm inner radius chamber. Its cavity was not a full circle but a spherical sector of angle (definition of this angle is in Figure 1) $\alpha = 11$ deg. Firing stoichiometric propane + oxygen mixture made possible in [11] reaching in the chamber exit the electron temperatures approximately $15{,}300 \pm 3{,}000$ K. This is already

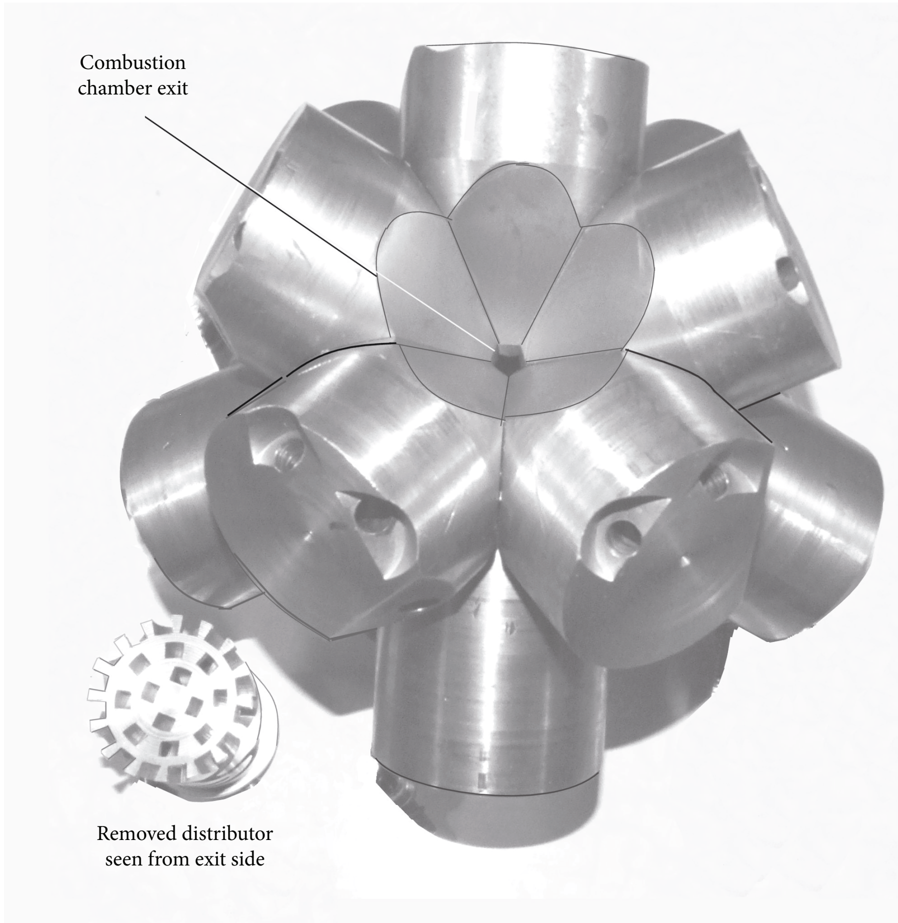

Figure 2: Photograph of the test combustion chamber—actually seen from below where there is the exit for the generated plasma. At the bottom picture on the left is one of the detonation wave distributors seen from the side of the entrances into the chamber.

a magnitude sufficient for full ionisation of the combustion products. Similar temperatures 10,000 K-13,000 K were demonstrated in another set of experiments in 1982 [12] performed with mixture $H_2 + O_2$ in a 100 mm radius hemispherical ($\alpha = 180$ deg) chamber.

3. Present Authors' Test Chamber

Schematic representation of the test setup designed and used by the present authors is in Figure 1. There are three main parts, as discussed in [7]. They are as follows:

(1) Detonation tube

(2) Chamber body

(3) Distributors: a system of progressively branched channels

In the final application considered by the authors, the exit from the chamber will be connected to yet another additional part—a more or less standard MHD electricity generator. For the reciprocating operations, the chamber must be provided with a system for scavenging the combustion products and refilling with the combustible mixture. A discussion of alternative solutions of this system using the ideas taken over from no-moving-part fluidics is in [13].

Prior to the test run, cavities of the single-shot configuration are filled, through the gas valve shown in Figure 1, by the combustible gas mixture, the fuel gas and oxygen. The detonation is then activated by the electric voltage above the dielectric strength of the mixture, applied to the spark plug. At first, the mixture starts burning in the usual deflagration regime. The transition into the detonation-type combustion is caused by interaction with the turbulence generated further downstream in the detonation tube [14] by eddy producing turbuliser. The detonation wave thus formed passes through the detonation tube to its downstream end where it is divided—first through the main trifurcation and then through the progressive bifurcations. This divides the primary detonation wave into small waves delivered through the distributor channels to the many exits into the combustion chamber inner cavity. The emergence of the simultaneous wavelets is adjusted by varying the lengths of the individual distributor channels. With the proper adjustment, a nearly smooth spherical implosion wave is formed propagating towards the common focal point at the chamber exit. The conditions there reach high concentration of charge carriers together with their extremely fast velocity. This would produce a high voltage pulse in the output electrodes, if the chamber were used as a source for driving an MHD generator. The chamber may be also used [5, 6] for aircraft propulsion. After the detonation, the air inlet valve is open and the air flow, moved by pressure as well as the expansion wave propagating inside the detonation tube, removes the combustion products. All the cavities are thus scavenged clean; their refilling with the mixture in the next cycle may start again.

While some components of the setup shown schematically in Figure 1, especially the detonation tube, e.g., [3], are not unknown and could be designed with some confidence based on previous experience in literature, the attention in the model design concentrated on the combustion chamber body and the distributor channels inside its walls. The basic information to be learned from the tests was planned to be the magnitude of the instantaneous peak temperature reached during the implosion. The other important quantity was the speed of the combustion product motion inside the chamber exit. For the purposes of obtaining an information about these two critical parameters, it was at this initial stage sufficient to perform only a single detonation.

The size of the test chamber was decided to be $R = 47.55$ mm internal radius and the apex angle $\alpha = 180$ deg, the chamber thus being hemispherical in shape. A smaller chamber, more convenient for testing, would be too likely to cool the combustion process excessively by radiative heat transfer into the chamber wall, the latter in the single-shot regime not heated by previous cycles. As seen in Figures 2 and 3, the chamber body was set up from a separately machined component parts—for ease of manufacturing and also for access to the holes for the distributor channels, incorporated inside the wall.

The detonation chamber and the wave distributors created three separate design problem areas that needed a solution, as follows:

(a) Manufacturing and testing the detonation tube for generation of the primary detonation wave

(b) Development, design, and manufacturing the combustion chamber body capable of withstanding the expected very high mechanical stresses

(c) Design, manufacturing, and testing the distributors with sequential bifurcations. The distributors were essential for converting the input planar primary detonation wave into the more or less spherical implosion. Because of the potential problems that might arise from curvature of the trajectories inside the distributor channels, the channels were arranged adjustable so that the wave travel time in them could be slightly varied

3.1. Detonation Tube. The detonation tube was made by milling from a 40 mm × 40 mm duraluminium block, 180 mm long. Its internal channel, of 8 mm × 8 mm square cross section, was also made by milling and closed from above by placing there a top cover plate. Clear axial length of the constant-section channel was 140 mm. At the inlet end was positioned an electrically operated refilling valve, opened for admission of stoichiometric mixture of hydrogen and oxygen, both obtained prior to the test by water electrolysis. As a safety measure, a flame trap was inside the detonation tube—an insert consisting of thin aluminium foils dividing the detonation tube channel cross section between them into a large number of narrow flow paths. Activation energy for starting the combustion process was provided by automobile combustion engine ignition system with spark plug in the detonation tube. Shielding around the spark plug was added to avoid electrical interference with diagnostic instrumentations. The turbuliser—for transition from initial deflagration-type burning into the detonation—was not of the usual Shchelkin spiral [14] configuration. Instead, it was a set of local increases of the channel internal width. It was made by 8 mm dia milling tool, the same as that used for making the channel. At the downstream end of the detonation tube was the flow divided (trifurcated) into three metal (copper) tubes of equal length and round cross section, curved to lead into the distributors inside the combustion chamber body.

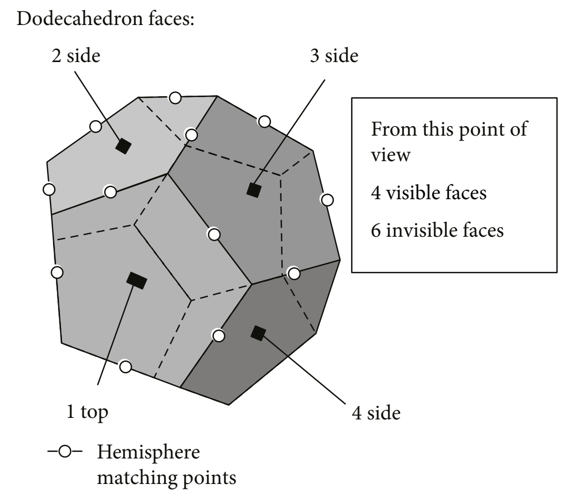

Figure 3: Approximation of the spherical inner wall of the combustion chamber by dodecahedron with pentagon-shaped flat surfaces. Distributed over them were $3 \times 2 \times (16 + 8 + 4) = 168$ exit holes. The white points are the locations of the pentagon edges corresponding to the ideal spherical surface.

3.2. Combustion Chamber Body. This most important part of the test setup consisted of twelve thick-walled cylindrical steel components with the cylinder axes arranged radially, as seen in the photograph in Figure 2. These cylinder-shaped components had their inner ends tapered by planar surfaces. As may be seen in the photograph, these planar taperings ensured mutual contacts between neighbour components. The cylindrical outer ends of the chamber components (seen in Figure 2) were extended radially outwards. These extensions provided a useful internal space for insertion of the components forming together the distributor.

The components of the combustion chamber thus exposed to the very high internal pressure only their very small tips, as is visible around the chamber exit in Figure 2,

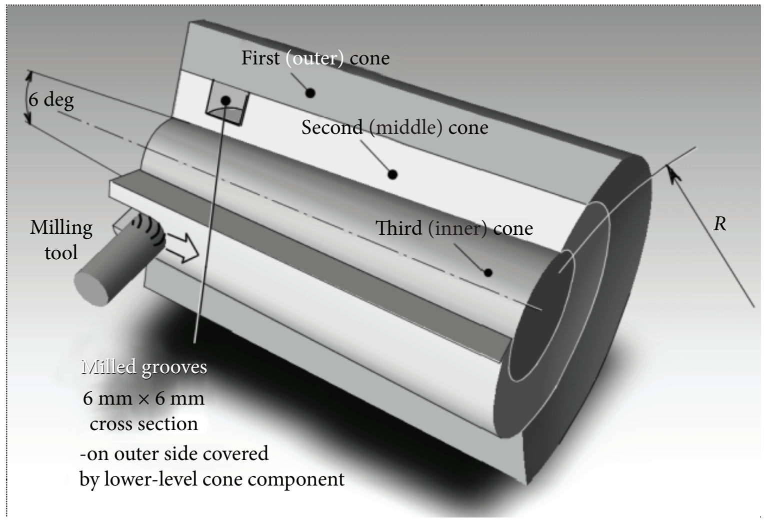

Figure 4: The basic principle of the distributor body layout. The grooves milled on the outer surface of the three 6 deg cone-shaped components, nesting one into another, are used for the role of the equal-length channels. The milling tool seen at the left follows the bifurcation trajectories such as those presented in Figure 7.

limiting the magnitude of the detonation wave forces. The surfaces of these tips in mutual contact thus had the shape of a dodecahedron (Figure 3). Of course, this geometry only approximated the ideal internal spherical shape. The keeping of an exact spherical surface geometry was unnecessary. What really mattered was the shape of the generated implosive detonation wave propagating inside the chamber cavity towards the focal point of the implosion. This wave shape depends not only on the shape of the chamber walls but also on the configurations of the mutually interacting exit ends of the distribution channels. Their number and positions were necessarily also limited.

The white points shown in Figure 3 are located in the middle of the dodecahedron inner edges. Only these points actually represent the positions at which the final assembled shape corresponds exactly to the $R = 47.55$ mm radius hemisphere so that avoiding the approximation was impossible anyway.

Left open in the assembled chamber body was the exit hole, Figure 2. The devices employing the plasma generated in the chamber (such as the MHD generator) would be later connected to this hole. In the test model, this open orifice served both as an exhaust for the combustion products and a window for access of plasma diagnostics. In the cylindrical outer ends of the chamber components, 6 deg apex angle conical cavities of 75 mm length were made (its walls decreasing in the outward direction). Into these cavities were fitted the components of distributors. They were put into the chamber walls from the inside because their conical shape was tapered towards their outer end—as seen in Figure 4.

3.3. Distributors. The task fulfilled by the 18 distributors, positioned inside the walls of the combustion chamber, is to divide the planar detonation wave arriving from the detonation tube into the total of 168 exits, all of them aimed at the focus point in the sphere centre. For this gradual division of the primary planar detonation wave, in the distributor channels the wave trajectories are progressively bifurcated into a total of 28 exits, all of them $6\,\text{mm} \times 6\,\text{mm}$ square cross sections. To resist the pressure forces generated in the detonation, the distributor components, conical in shape and tapered towards the outer side, as seen in Figure 4, are oriented so that the internal pressure forces them to sit in their conical seats.

Each distributor consists of three conical components as seen in Figure 4, fitting one into another. A photograph of a typical distributor component is presented in Figure 5. The exits into the combustion chamber are there recognisable at the bottom of the picture, at the larger-diameter end. The basic requirement for proper synchronisation of the detonations is the identical lengths of all wave paths. The channels for passage of the individual detonation waves were made as grooves by milling, as suggested by the milling tool in its position at the left side of Figure 4. From the outer side (i.e., the side from which the milling tool entered), the grooves are covered—and thus converted into the channels—by the conical internal hollow surface of another distributor component fitted from the inner end. The milling of the channels was performed on a machine with two variables defining the position of the milling tool. One variable was the linear axial position while the other was the angular rotation around the axis of the manufactured component. Plots of mutual dependence of the values of these two variables, with data point coordinates related to the tool centre, are presented in Figures 6, 7, and 8. The first division of the detonation wave was in trifurcation manner. This means flow distribution into three downstream parts. It was achieved by connecting the end of the detonation tube into three spatially carved copper tubes. This was followed by another trifurcation, on the surface of the distributor cone along the milling tool trajectories presented in Figure 6 and also seen at the top of the photograph in Figure 5. All

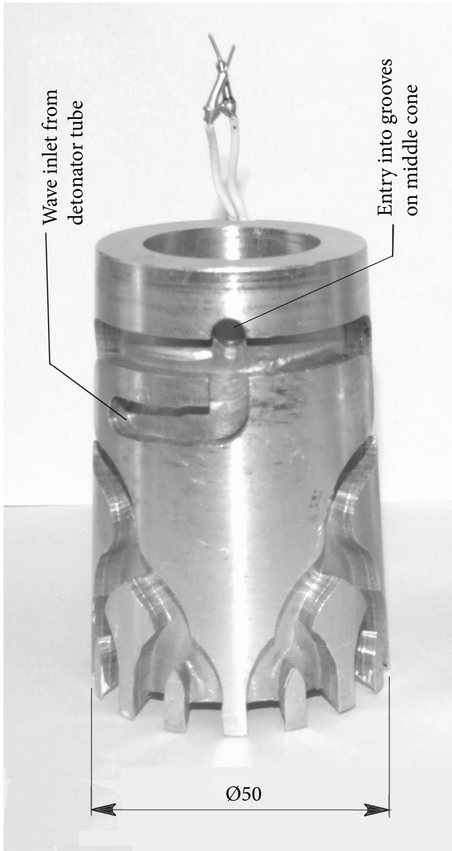

Figure 5: Photograph of the outer distributor cone. On top there is the trifurcating entrance, following the trajectories presented in Figure 6. The two electric conductors on the top of the picture lead to ionisation detectors.

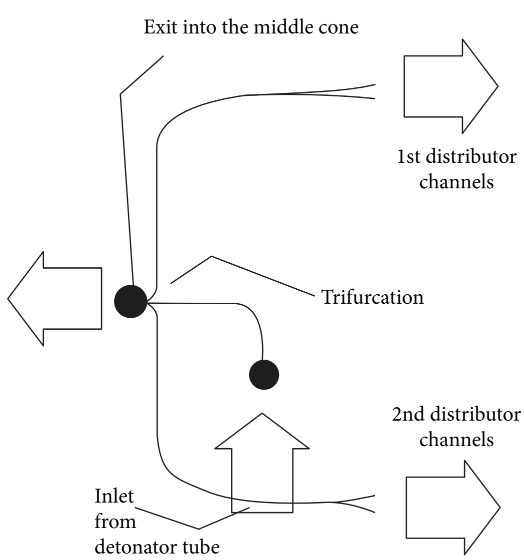

Figure 6: Milling tool trajectories of the top of outer distributor cone (Figure 5). The incoming flow trifurcates: two exits lead into the two outer cone channels. The third outlet enters the middle cone.

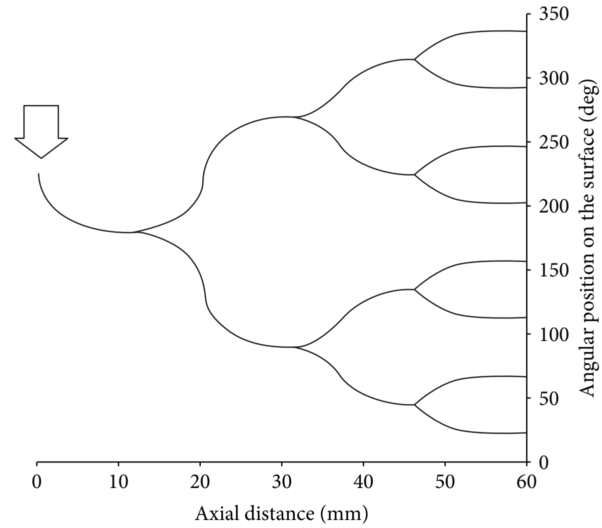

Figure 7: Trajectories of the flow in the grooves made on the surface of the middle cone. Shown here is the output from the milling machine control program. Milled grooves are made of 6 mm diameter. It distributes the detonation wave into the 8 exits into the combustion chamber.

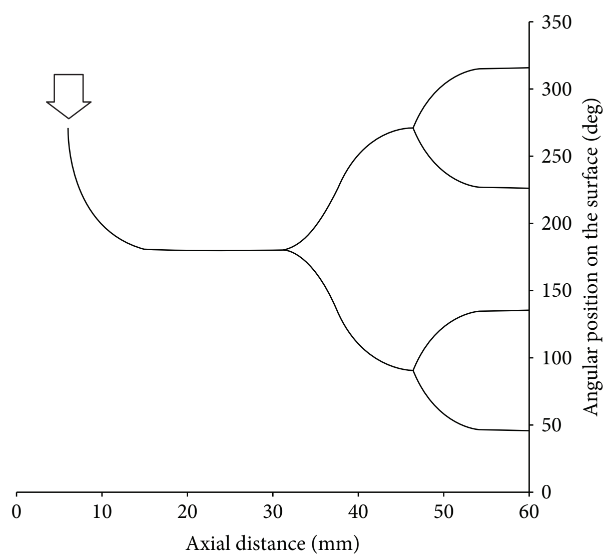

Figure 8: Trajectories of axial and angular position of the groove cutting tool used in manufacturing the inner cone body shown in Figure 10. Only four detonation wave entrances could be made on the surface of this small component.

subsequent divisions of the detonation wave are bifurcations into two downstream connected channels, as it is seen, e.g., from the trajectories in Figure 7 and the photographs in Figures 5, 9, and 10.

The conical axisymmetric shape of the distributor bodies provided an opportunity for precise adjustments of the synchronism of the distributed parts of the detonation wave. The effective channel lengths may be varied by small angular increments by rotation of the particular cone-shaped distributor component.

Figure 9: Photograph of the middle cone with the grooves according to Figure 7. Note the 6 mm dia hole near the top of this component. It leads to the inner cone shown in Figure 10.

Figure 10: Photograph of the inner cone body with the grooves distributing the detonation wave into the four exits. Bifurcating flow trajectories in this case correspond to Figure 8.

4. Feasibility Tests

Authors' experiments with gas ionisation by the cumulative detonations are still in their early phase. They have, nevertheless, already demonstrated convincingly the most important qualitative fact: the capability to reach the extreme temperature levels in the combustion chamber near its exit—and the corresponding high level of ionisation.

4.1. Ionisation Probes. Propagation of detonation waves inside the distributor cones and formation of the convergent detonation wave were monitored by an array of ionisation probes. Their concept is very simple: they are based on the fact that the detonation wave with the ionised molecules is electrically conductive so that its passing past a pair of wire electrodes connected to a charged condenser may be monitored on an oscilloscope as voltage drop on a (condenser discharge). The ionisation probes were made from copper wire of 0.75 mm diameter insulated by PTFE coating. Active parts of the probes, protruding 2 mm deep into the 6 mm $\times$ 6 mm distributor channel, had the insulation striped off. The probes were charged by way of a 48 kΩ resistor from an 80 V DC voltage source. The voltage drop across this ionisation probe was recorded on an oscilloscope. The main purpose of measurements with these probes was identification of the time delays between the propagating detonation waves in individual distributor channels. These results provided the baseline information for fine synchronisation of the distributed waves, which was done by small adjusting of the angular positions of the distributor cone bodies. The rotational adjustment can either extend or shorten the length of the auxiliary vent leading the incoming detonation wave into the first bifurcation inside the distributor. In this way, all 18 distributors could be finely tuned to microsecond range. Typical simultaneous oscilloscope traces of four probes are demonstrated in the example in Figure 11. The three probes marked B, C, and D were fully synchronised while the

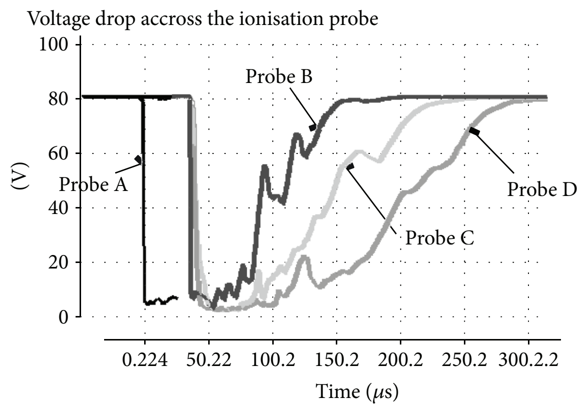

Figure 11: Records from four ionisation probes, one of them (probe A) was wrongly adjusted in this particular test (later, of course, its conical body was rotated to get the desirable full synchronisation).

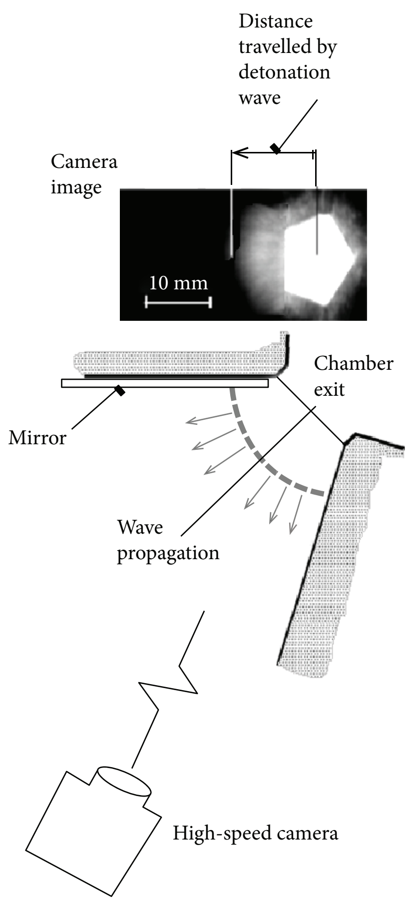

Figure 12: Schematic presentation of the setup used to measure the propagation speed of detonation waves in the chamber exit. Light-emitting wavefront position was measured in camera images. Unfortunately, the detonation progresses so fast that even with the very high-speed camera in its highest frame speed regime the timing of images was difficult.

oscilloscope trace of the wave propagation past the probe A was too short (and had to be later made longer prior to the next set of measurements).

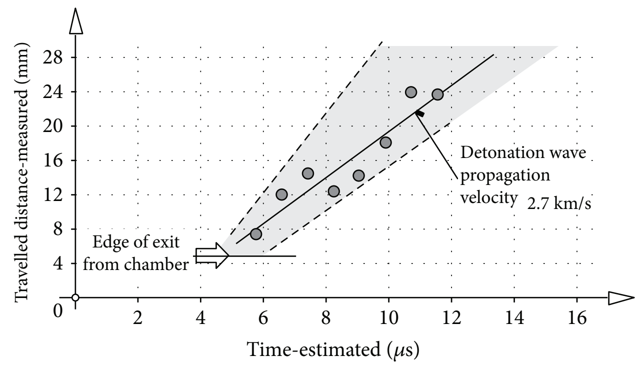

Figure 13: Evaluation of 8 camera images of the propagating wavefront has led to approximate detonation speed of the order of kilometres per second, demonstrating that the combustion was indeed of the detonation character. The grey area shows the estimated region of possible accuracy.

4.2. Detonation Wave Exit Speed. After each detonation, the combustion products leave the combustion chamber and this provided an opportunity for obtaining some information about their propagation speed. It is a quantity of considerable importance. First, it is well known that detonation waves propagate at extremely high supersonic speeds, of 3 to 5 kilometres per second—with hydrogen-air mixture detonation speed generally higher than the speeds measured with mixtures of air with hydrocarbons [15]. Although the ionisation probes themselves provided a convincing demonstration of the presence of the charge carriers, these were present due to the detonation generated upstream, in the detonation tube. It was important to know whether the wave precursor of the plasma generated in the focal point of the chamber also propagates at a velocity of similar order of magnitude. The second fact to be taken into account is the plasma generation based on the mutual collision of the detonation waves coming from the opposite sides. It seemed possible that the waves slow down (while increasing the pressure) when they approach what is nominally the stagnation point of the collision.

The layout of the propagation speed experiments is presented in Figure 12. The high-speed camera was placed at a safe distance; the generated image frames were split by a small mirror to show both the chamber exit and the space with the propagating wavefront inside. The mirror images were calibrated so that the wavefront locations were known. The problem was that the camera frame period was nearly the same as the time needed for the plasma cloud moving through almost the whole camera field of view. Thus, the time scale of the data plotted in Figure 13 has to be considered preliminary, subject to later improvement of accuracy. Nevertheless, correlating the distances and time scale, the plasma wavefront velocity was evaluated to be approximately 2.7 km/s. This is at any rate a demonstration of the detonation velocity character.

4.3. Spectroscopic Measurement of Temperature. Increasing the gas temperature means increasing the speed of particle motions. In a spectroscopic measurement [16, 17] of the emitted light, the Doppler effect (some particles moving back

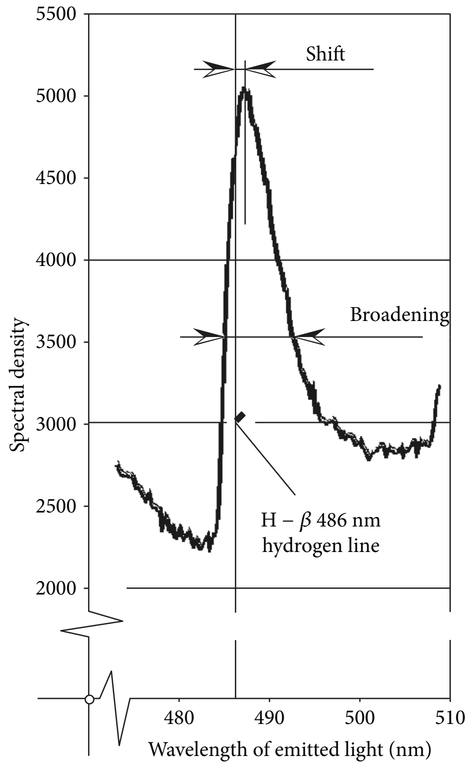

FIGURE 14: Typical example of spectroscopic measurement of combustion product temperature. Doppler effect of elementary moving light sources causes broadening of the line which in principle makes it possible [16, 17] to evaluate the temperature.

and others forward) can both increase and decrease the recorded light wavelength—and this is visible in the spectrogram as broadening of the basic line.

The temperature of the plasma is proportional to the square root of the broadening and may be thus evaluated.

In the experiment, the light emitted at the chamber exit was collected by closely positioned end of fused silica optical fibre of 100 μm diameter. It was led into the aperture of IHR370 spectroscope. The spectrum shows several contamination peaks. The most important result seen there is the H-β line for hydrogen at the nominal (stationary particles) wavelength 468 nm. Seen in Figure 14 is the profile of the H-β line shift and asymmetric broadening, apparently caused by high pressure. Analyses of the spectrum are still in progress. Rough evaluations performed so far indicate temperatures in the range from 10,000 K to 15,000 K. This suffices for a reliable conclusion of the presence of thermal plasma inside the chamber.

There may be some collision-type stagnation leading to slightly lower than expected chamber exit velocities, but this effect is not strong, no doubt due to the hemispherical (rather than the full sphere) geometry of the combustion chamber.

5. Conclusions and Discussion

Obtaining the extremely high local temperatures of combustion products necessary for reaching full ionisation was demonstrably achieved by replacing the usual deflagration combustion processes by detonation—in particular using the idea of cumulative effect of the detonation waves in the combustion chamber. The feasibility of the idea was tested in the model combustion chamber for single-shot operation. The results are satisfactory and the implosion-type detonation is shown to generate ionisation levels sufficient for most plasma applications—suitable for no-moving-part electricity generators and gas flow manipulators. The paper describes the design details of the tested model of 47.55 mm internal radius hemisphere with 168 detonation wave entrances into the chamber, each entrance with 6 mm × 6 mm size. While the laboratory model is still at an early stage of its development and evaluation of some of the accumulated experimental data is still in progress, it is already possible to state quite safely that the new method makes it possible to reach temperatures of the order ~10,000 K and, of course, the corresponding high degrees of thermal ionisation.

Data Availability

The present authors' experiment was primarily of qualitative character—feasibility study of focusing on the implosive focusing of spherical detonation waves. Whatever data are here presented here, they are of preliminary nature to be revised in future repeated measurements.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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