Development of Corona Discharge Apparatus for Supersonic Flow

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This paper describes an apparatus developed for ionizing supersonic air by means of corona discharge. The corona discharge is induced in a test section that contains suitably shaped electrodes that maximize electric field intensity in the flow and also withstand the aerodynamic loading. The test section is designed to fit into a shock tube. The corona is created by means of a 12 kV dc source. Static tests using room air revealed visible corona for about 6 to 9.5 kV and arcing at higher voltages.

Introduction

Ignition of air fuel mixture in supersonic combustion engines is brought about by a high intensity arc from a spark plug. Supersonic flows are inherently at high pressures and densities, and thus arc discharge breakdown occurs at higher voltages, requiring higher energy for ignition. This can lead to diminished life of the spark plugs and associated equipment. Also, leaner fuel-air mixtures, that would produce less noxious emissions and more efficient combustion, are more difficult to ignite. These shortcomings may be remedied by pre-ionizing the fuel-air mixture prior to combustion, which results in the creation of ions and electrons in the flow, thus achieving a reduction in the ignition energy. It is proposed that corona discharge be used to ionize supersonic flow.

Corona is observed as a luminous glow on the surface of certain high voltage electrodes that have a high potential gradient around them. The color of corona varies with the constituents of the gas. In air, corona appears as a faint bluish white emanation. Corona is caused when a high potential density around an electrode excites the valence electrons of the gaseous atoms and molecules, leading to electro-luminescence. This excitation is accompanied by ionization of the gas around the electrode. Corona discharge is highly dependent on the geometry of the electrode. If Q is the total charge stored in a conductor and r is the conductor's radius of curvature, the electric field intensity E is inversely proportional to the radius, as given by

$$E = \frac{Q}{4\pi\,\varepsilon_0\, r} \tag{1}$$

where ε_0 is the permittivity of free space (and air) and is equal to 8.852×10^{-12} F/m.

Equation (1) demonstrates that the electric field is stronger around sharp conductors or those with low radii of curvature.[1] In cases where one electrode has a much lower radius than the other, the corona will be present around the smaller or sharper electrode. This is then referred to as the active electrode. The active electrode can be made the anode (positive corona) or the cathode (negative corona) in a bipolar dc configuration. Corona discharge occurs with both dc and ac voltages. For this study, only dc power is used.

Visible corona discharge occurs from the surface of a high voltage (HV) electrode when the surface voltage gradient reaches a critical value that is dependent on the polarity, fluid pressure, temperature and other factors such as the presence of impurities.[2] The magnitude of the onset voltage is called the corona threshold voltage. If the applied voltage is increased, the intensity of the corona and current flow are increased. Finally, a point is reached when the resistance of the air gap between the electrodes breaks down completely and strong arcing occurs. Arcing is a high current, high power dissipative phenomenon and is mostly short lived, as the charge is quickly extinguished in the arcing process. Thus, spark ignition of a fuel-air mixture is administered by an arc across a spark plug. Corona, on the other hand, is a longer sustained low current, high volt-

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age effect, consuming very little energy, of the order of mW.

A byproduct of corona discharge in air is ozone. Oxygen molecules are split into ions and unstable oxygen atoms in the presence of the electric field. The ions and oxygen radicals combine with other oxygen molecules to form ozone. The presence of ozone in a fuel-air mixture can enhance the combustion process.

Several experimental studies have been carried out previously at the Aerodynamic Research Center (ARC) of the University of Texas at Arlington involving high voltages, plasma and supersonic flows including one in which the products of hydrogen-oxygen detonation were seeded with potassium or cesium carbonate along with the application of high electric fields, to study the conductivity of the gases.[3] These tests were performed in a detonation-driven shock tube.[4] The present study is designed for the same shock tube, but at lower Mach numbers.

Experimental Setup

The apparatus consists of the test section which includes the corona discharge electrodes and a high voltage dc power supply.

Test Section

The test section has been designed to fit onto the ARC's present shock tube configuration, which has a 2 in. (54 mm) o.d. 304 SS tube section, with an i.d. of $1^5/_8$ in. (41.275 mm). The test section essentially comprises of a 15 in. (38 cm) long 2 in. o.d. stainless steel tube. Type 316 SS 2 in. union coupling nuts are mounted on both ends of the tube to attach the test section to the shock tube. Elongated circular cut-outs were made in the tube, through which a 316 SS triangular wedge, with a sharp edge, is inserted, as shown in Fig. 1. The wedge is held in place by means of press-fit manufactured blocks made out of Lexan.[5] The wedge forms the active electrode while the steel tube itself is the passive electrode. The test section is electrically insulated from the rest of the shock tube by means of Lexan isolation blocks. Lexan is a plastic that is a good electrical insulator and has favorable mechanical properties, such as rigidity, resistance to impacts and ease of machining.

The sharp-edged wedge shape of the active electrode offered more electrical and mechanical advantages over other shapes that were considered, such as a flat dual-sided knife or a cylindrical wire element. The knife edge concentrates the electric field while the angular shape gives structural stability. The electric field distribution for this electrode gap is governed by Laplace's equation $\nabla^2\phi = 0$, where ϕ is the electric potential. The solution of this equation for this particular geometry would involve complex FEM analysis and is not intended for this project. Apart from the electric field effects within the test section, there exists the interaction of the electric field between the exterior surfaces of the test section and the ground or the ambient air. This effect has been experimentally found to be negligible.

Mechanically, the wedge is stronger than a thin

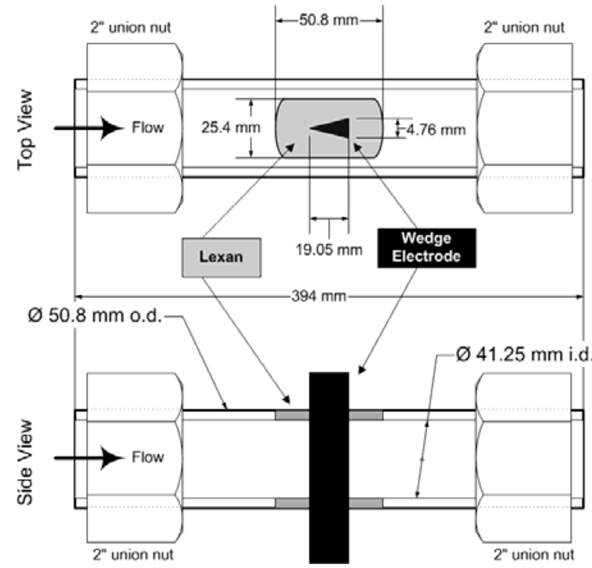

Figure 1: The test section showing the electrode geometry and direction of supersonic air flow.

wire that could get damaged by the impact of debris or by aerodynamic loading. Also, a cylindrical wire presents a blunt body profile that would create strong bow shocks in front of it. The triangular wedge would only have a weak oblique shock formation. The wedge would receive lower aerodynamic loading and the total pressure losses would be lower. The internal geometry of the test section is complex as the top and bottom surfaces of the wedge are closer to the curved tube walls, with a minimum separation of 11 mm. As a result, in static air, arcing occurs at about 9.5 kV between the rear edges of the wedge and the points of the tube close to it. Although Lexan can withstand temperatures up to 125 ^{o}C, the heat generated by the arcs is high enough to char the top surface of the Lexan block. This causes it to carbonize, thereby reducing its electrical resistance. This proved to be an impediment to the initial tests, requiring several dismantling and cleaning of the Lexan blocks and was overcome by coating the surface of the Lexan blocks with a thin layer of ceramic cement, namely, Sauereiesen Electrotemp Cement No. 8, which is composed of silica (SiO_2), zirconium silicate ($ZrSiO_4$), magnesium oxide (MgO) and magnesium phosphate ($MgPO_4$).[6] This cement is off white in color, has a dielectric strength rated at 2900–3900

V/mm at 21 °C and can withstand temperatures up to 1400 °C. A small sample of this cement was subjected to a HV dc test to check for conductivity. It was found to have zero conductivity up to the maximum output of the HV power supply of about 12 kV. However, after applying the cement coating, corona discharge currents have increased significantly, as will be explained in the next section. Electrical leads are attached to the wedge and the pipe section and the polarity of the applied voltage can be easily switched as desired, such as with the wedge made negative with respect to the pipe (negative corona) or positive with respect to the pipe (positive corona).

The HV Power Supply

A high voltage, dc power supply was assembled for this project. It is a simple design consisting of a step-up transformer, a HV diode bridge rectifier and a capacitor filter. It is capable of supplying up to 12 kV dc. Figure 2 shows the basic circuit setup. The step up transformer is a neon transformer that is used to power commercial neon light displays.[7] These transformers are available with secondary windings rated at 9 kV, 12 kV and 15 kV at 30 mA or 60 mA full load and primaries rated at 120V, 60Hz for the US market and 240 V, 50 Hz for the European market. The model used in this power supply is a 120 V/12 kV/720 VA transformer that has an effective primary-to-secondary turns-ratio of 100. The input to the neon transformer is supplied by a variable autotransformer and it can be varied from 0 to 100% of line voltage (120 V, 60 Hz). Thus the voltage across the secondary winding of the neon transformer is 100 times the output of the autotransformer.

The output of the neon transformer is rectified by means of the full wave bridge rectifier assembly. The diodes used for the rectifier assembly have a peak inverse voltage rating of 125 kV. A 1 μF, 50 kV capacitor is used to store and filter the output. The current flow during the corona discharge process is in the tens of μA range and therefore regulation of the power supply is not critical. The power supply is thus continuously variable from 0–12 kVdc. The potential of the capacitor is measured by means of a voltage divider as shown in Fig. 3. The total resistance used is 500 MΩ. A precision high input impedance digital dc voltmeter measures the voltage across the 5 MΩ resistor, giving a voltage division of 1/100 as shown. The reading on the voltmeter is multiplied by 100 to get the actual capacitor voltage. The 500 MΩ resistance ensures that the capacitor is not discharged quickly if the power from the neon transformer is cut off. The RC time constant, for the capacitor voltage divider network, is found to be 500 s. The output of the capacitor is controlled by means of electromechanical high voltage relays.[8] These relays were used in place of solid state switches because of lower cost and easier operations. (Solid state devices such as Silicon Controlled Rectifiers or Thyristors have faster switching times, of the order of μs. The relays have operating times of about 15 ms. However, they are very expensive and need complicated control and commutation circuits. Also semiconductor devices have leakage currents in the range of nA and sometimes as high as μA, which are the expected range of the corona current.) One drawback of electromechanical relays is that their contact capacitance can allow the transfer of high frequency noise to the output in the open position. Sixty Hz noise from the mains and the transformer is carried through to the test section. This common mode noise can be eliminated by employing appropriate amplifier circuits in the diagnostic instruments. This noise is not expected to affect the corona discharge, as the capacitor and voltage divider resistors

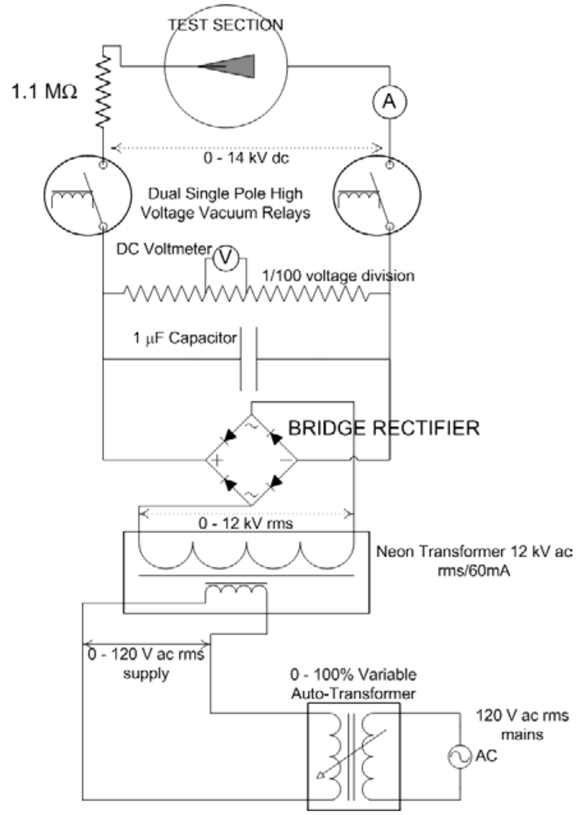

Figure 2: A schematic circuit diagram of the HV power supply.

effectively form a low pass filter. During eventual supersonic corona tests, the power to the test section is expected to be on continuously through the short test period. Thus, fast and accurate switching was deemed unnecessary. Relays labeled Re_1 are used to switch the power output to the source.

The current limiting resistor marked R_{CL1} on the output side of the capacitor prevents arcing. This resis-

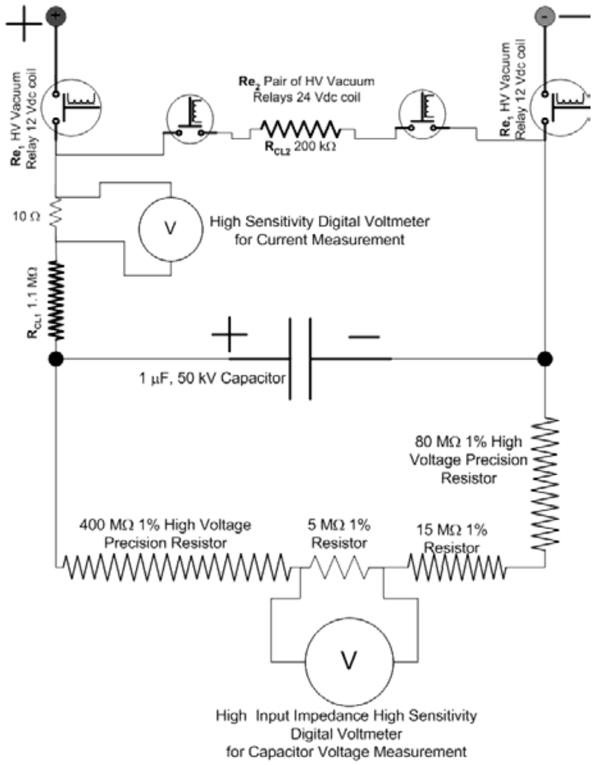

Figure 3: Circuit diagram of the voltage divider, the control relays, current limiting resistors and the voltmeter and current measuring instrument.

tor has a value of 1.1 MΩ. Thus at a voltage of 12 kVdc, the maximum current that it will pass is 10.9 mA. With current dissipation during corona discharge being in the order of μA, there will be a small voltage drop across the resistors that will have to be accounted for. For example, with the capacitor charged to 9 kV, if the corona discharge is drawing a current of 50 μA, the voltage drop across the resistor R_{CL1} is found using Ohm's law to be 55 V and thus the actual voltage applied across the test section electrodes is 8.945 kV. This is a small price to pay for protection to the test section and the capacitor from arc damage.

The capacitor can be discharged by activating the relays Re_2. This brings the 200 kΩ resistor R_{CL2} in series with R_{CL1} across the capacitor, amounting to a total of 1.3 MΩ. The capacitor now has a RC time constant of about 1.3 s. Thus the capacitor discharges quickly and safely. (Shorting capacitors can shorten their lives and should be avoided.)

Safety features are built into the power supply, including line filters on the ac input side, an isolation transformer to isolate the HV power supply circuits from the ac mains, line fuses to protect against over current, etc. All the HV leads are covered in thick insulation material for safe handling and the HV components are housed in separate boxes. Currents and voltages can be monitored and the controls can be activated from a remote location.

Results

The test section was tested with a continuously applied voltage, which was increased in steps, in static ambient air at STP. The results presented in Fig. 4 were obtained from tests that were carried out after the application of a coat of ceramic cement on the Lexan. Both negative and positive corona discharge show similar currents at the lower voltages. There is an initial linear phase where the current is directly proportional to the voltage, followed by a knee point after which current increases sharply. The linear phase is also called the Ohm's law phase. For negative corona, the knee voltage is about 6.5 kV. For positive corona, the linear phase extends up to about 9 kV. Testing is carried out until intermittent sparking occurs. If voltages are increased beyond sparking, spark gap breakdown occurs and strong arcing can occur that can damage the insulation and cause pitting of the electrodes. Also the test section becomes contaminated, which can cause increase in currents.

For negative corona, a faint buzzing starts at around 6 kV which gets louder with increasing voltage followed by the appearance of a visible glowing spot on the knife edge at about 6.5 kV. It was also observed that there are faintly glowing spots on the surface of the ceramic cement itself. The cement layer did not have a smooth surface and had tiny protrusions and holes on the surface. Insulators between highly stressed electrodes will develop a static charge build up on their surfaces of opposite polarity to that of the electrodes near them due to induction. The regions of micro-roughness with static charge build up have a high concentration of electric fields around them, causing glow discharges to occur on their surfaces. As the voltage increases, more and more glowing spots appear on the knife edge, the buzzing gets louder and the smell of ozone is detectable in the air. At about 8 kV, a gentle breeze can be felt upstream of the knife edge. Between 8 and 9.5 kV, the corona spots increases in brightness and in number. The corona discharge is not a steady process, as the spots appear and disappear within this voltage range. This can also be verified by the current draw, which correspondingly varies with the appearance of the corona spots. At about 10 kV, sparks are seen to be discharged between the rear edges of the wedge to the steel pipe surface. The rear of the wedge is the closest to the pipe surface and this is where sparks are seen to appear first, while corona is only seen on the knife edge in front. The sparks are seen to be intermittent, with a few seconds gap between each strike and the discharge current spikes up sharply during the sparks, which last only a fraction of a second.

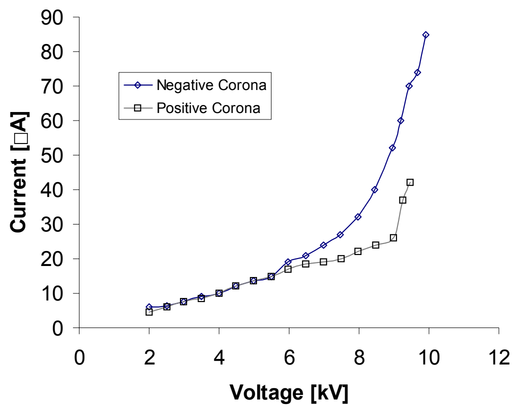

Figure 4: Voltage and current characteristics of negative and positive corona discharge. The uncertainty of the voltage reading has been calculated to be 1.4 % of the voltmeter reading. The uncertainty of the current measurement is estimated to be ±5%.

The positive corona does not yield any visible corona on the wedge up till 7.5 kV. A faint buzzing only started at 6.5 kV. A few more corona spots appear on the knife edge up to about 9.5 kV when sparking occurs from the rear of the wedge to the steel pipe surface. However, the discharge activity is not visibly as intense as for the negative corona. The corona wind is also not as strong in this case. For the geometry of this test section, negative corona presents more favorable corona discharge activity. This is contrary to many experiments performed earlier by other investigators, where positive corona is preferred.

Some other findings are that when the test section is contaminated with dust, such as cement dust or soot, the discharge current is many times over that of the clean configuration and corona is found to be more intense. When hot air is blown through the test section with a hot air blower, the current rises slowly. This agrees with literature.[2]

The power consumed during corona discharge is very small. For negative corona at 10 kV, with a current flow of 85 μA, the power drawn is only 850 mW. For positive corona, the maximum tested voltage of 9.5 kV at 42 μA resulted in a power consumption of about 400 mW. This shows that corona discharge utilizes very small amounts of energy.

Following the ionization of gas during the discharge is a deionization process. Ionization in air creates positive and negative atomic or molecular ions and free electrons. Electron drift velocity being very high, electrons are absorbed readily due to collisions with atoms, molecules and ions or by the anode.[9] The heavier ions linger a short time longer and are then deionized by recombination, electron attachment or diffusion..

Conclusions and Future Work

The test section was bench tested using static ambient air. The corona discharge current and voltage characteristics were obtained. Corona spots were seen on the sharp edge starting at 6.5 kV for negative corona and 7.5 kV for positive corona. Results show a linear "Ohm's Law" phase where current increases linearly with voltage, followed by a sharp increase in current leading up quickly to the spark over voltage of around 10 kV for negative corona and 9.5 kV for positive corona. The sharp smell of ozone, buzzing sounds and a soft corona wind in the upstream direction of the sharp edge is detected at voltages greater than 8 kV for negative corona. The region between 8.5 and 9.25 kV is a favorable and safe voltage range at which further static and supersonic tests can be carried out because this range gives steady currents between 40 and 55 μA with strong visible corona activity, while remaining below the spark over voltage. At these voltages, corona is seen to cover the entire sharp edge.

Ion detection methods have to be resolved to detect the presence of ions downstream of the test section in both static and supersonic tests. Instrumentation for measurement of properties of the supersonic shock tube experiments has to be designed and set up. The properties of the corona wind have to be examined. The corona discharge has been largely subjected to anthropomorphic examination only. A more thorough investigation involving sensitive instruments would be valuable. Corona discharges for AC voltages have been found by previous investigators to be more intense. The efficacy of AC corona for ionization of supersonic flow needs to be investigated. High voltage ac is easier to generate and the equipment can be made smaller and lighter than high voltage dc generators. This can be advantageous for flight vehicles in terms of space and weight savings. Another interesting study could be the spectroscopic analysis of the ionized flow to study the species.

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