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150 kJ Compact Capacitive Pulsed Power System for an Electrothermal Chemical Gun

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Abstract – A 150 kJ compact capacitive pulsed power system (CCPPS) capable of delivering electrical energy into an electrothermal chemical (ETC) gun on a vehicle has been studied. The CCPPS provides pulsed electrical energy into a capillary plasma injector which generates plasma of tens of thousands °K in temperature and has a nonlinear resistance depending on the current. The design requirements of the CCPPS are as follows: the maximum power of 250 MW, the pulse width of about 0.6 ms, the volume of no more than 0.5 cubic meter, the efficiency of energy transfer over 80 % and the repetition rate of 4~5 times per minute. The constructed CCPPS is composed of four 37.5 kJ capacitor bank modules in parallel to make a trapezoid pulse shape and to satisfy the design requirements. Each module is designed to achieve high reliability, safety, efficiency and energy density to endure severe operating conditions. The results of the performance test on the CCPPS using a 120 mm ETC gun are described.

Keywords: ETC gun, Pulsed power system, Capillary plasma injector, Capacitor bank

1. Introduction

ETC propulsion is a technology improving the acceleration performance of a gun by controlling the ignition and combustion of the propellant inside a barrel with the plasma generated by an electric pulsed discharge [1]. Since the ignition of an ETC gun is controlled using an adjustable electrical power unlike a conventional chemical gun, the combustion characteristics can be kept consistently against the variation of the environmental temperature. In addition, the plasma of high temperature and energy has a capability to ignite a low vulnerable propellant [2].

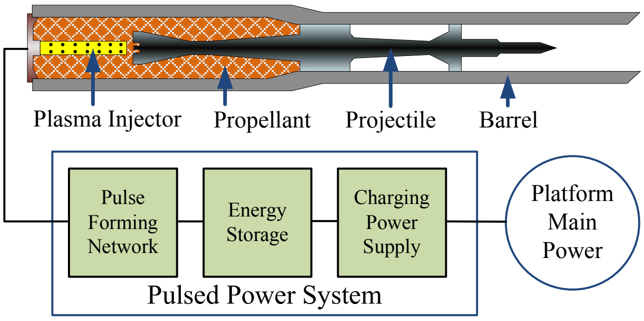

Fig. 1. A general concept of an ETC gun

Fig. 1 shows a general concept of an ETC gun consisting of a plasma injector, propellant, a projectile, a barrel and a pulsed power system (PPS). Among various types of pulsed power systems, a PPS of the capacitor bank type is the most commonly used one in the ETC gun system because of an easiness of a pulse forming, an expandability, and a maintenance. It is composed of a pulse forming network, energy storage elements and a charging power supply. Agency for Defense Development (ADD) has developed a 2.4 MJ PPS for the research of ETC technology as shown in Fig. 2 [3-5]. It consists of eight 300 kJ modules occupying a large space for an easy maintenance purpose.

Fig. 2. The 2.4 MJ pulsed power system

In this study, we intended to verify the feasibility of a compact capacitive pulsed power system that could be mounted on a military vehicle. Based on the required conditions of the pulsed power system for an ETC gun, the specifications for the CCPPS performance were decided. Electrical parameters of the circuit components were determined from a simulation code. The mechanical configuration of the main components was designed by 3D digital mock-up. After the fabrication of the CCPPS, short circuit discharges and those using plasma injector loads were tested. The repetition rate of charging and discharging

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was measured, and firing experiments using a 120mm ETC gun were conducted.

2. Design of the CCPPS

2.1 Electrical power and energy

Previously, firing experiments of the ETC gun were conducted using 2 modules of 2.4MJ PPS. The ignition of propellant was done by using the plasma injector located in the gun chamber. The injector produces a hot and dense plasma of about tens of thousands °K in temperature and several hundreds bar in pressure by capillary discharge. Fig. 3 shows the results of the experiments. The pressure of the propellant in the chamber of the gun rises fast to high peak values as the delivered electrical power or energy increases, which shows the controllability of the pressure curve by changing the condition of the electrical discharge.

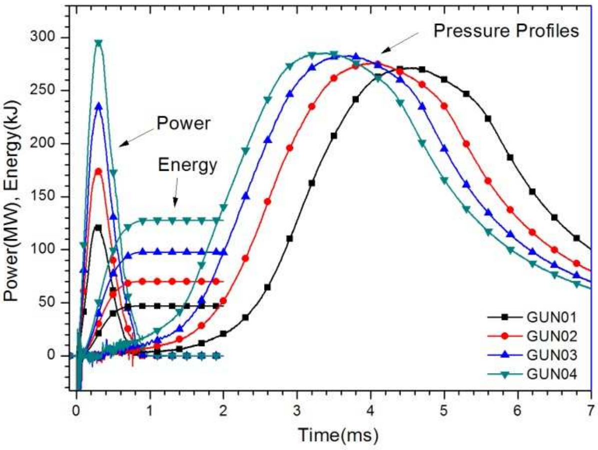

Fig. 3. Electrical power, energy, and pressure of the ETC gun using 600 kJ PPS

The required electrical power and energy of the PPS were in the range of 100~300 MW and 50~120 kJ, respectively. To achieve the performance of the experiments using the 2 modules of the 2.4 MJ PPS the newly designed CPPS should have the same capability of delivering the electrical power and energy to the gun. Thus, the maximum energy and power of the CCPPS were determined to be 150 kJ and 250 MW, respectively. From the experiences of the previous design and experiments, the required specifications of the CCPPS were determined as follows: the maximum power of 250 MW, the pulse width of about 1 ms, the maximum charging energy of 150 kJ, the volume of no more than 0.5 m^3, the efficiency of energy transfer over 80 %, and the repetition rate of the charging and discharging of 4~5 times per minute.

2.2 Detailed design of the CCPPS

The detailed performance specifications of the CCPPS are summarized in Table 1. The maximum charging and operating voltage of the CCPPS was determined to be 7 kV to save the space occupied by the components and to achieve a good insulation. Generally, higher voltage operation requires more serial connections of semiconductor switches and crowbar diodes.

Table 1. Performance Specifications of the CCPPS

Parameter	Specification
Maximum Charging Energy	150 kJ
Maximum Peak Power	250 MW
Maximum Charging Voltage	7 kV
Pulse Shape (Rise time, Pulse width)	Trapezoid Shape (<0.2 ms , > 0.6 ms)
Efficiency	> 80 %
Volume	< 0.5 m^3
Repetition Rate	4~5 times per minute

The possible circuit topologies of the CCPPS are an LC ladder, a single module and a multi-module circuit. Circuit simulations have been done for each topology to find the parameters satisfying the required performance specifications of Table 1. In the circuit simulation, the capillary plasma injector used in the previous ETC gun experiment played the role of a load. Though the resistance of the plasma injector depends on the temperature and pressure of the produced plasma, it can be modeled as a function of the delivered current for a simplified calculation [6]. Among them, the 4-module circuit was selected for the design of CPPS since the LC ladder type produced a low efficiency of 60~70 % and the current waveform of the single module could not be easily modified to the required rising time and pulse width. In the case of the 4-module circuit, the current waveform of a trapezoid pulse shape produced an efficiency over 80 %. Also, the current ratings of the devices could be alleviated. On the other hand, the measurement and control of the CCPPS became more complicated. The detailed design results of the 150 kJ CCPPS are summarized as follows:

- 4 parallel modules
- The same capacitance and charging voltage
- The same inductance
- Pulse forming by sequential triggering

The designed 150 kJ CCPPS consists of four 37.5 kJ unit modules, a capacitor charging power supply, a Light Triggered Thyristor (LTT) driver, a charge-dump circuit and a cable collector. A schematic diagram of the CCPPS is shown in Fig. 4.

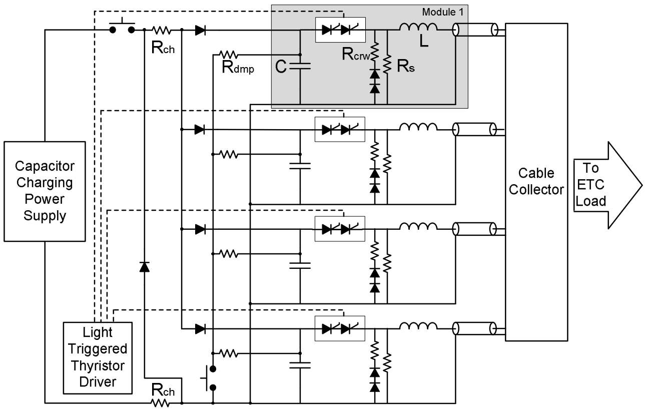

Fig. 4. A schematic diagram of the 150 kJ CCPPS

Target values of the main and sub parameters for a unit module were chosen based on the feasibility of fabrication as shown in Table 2.

Table 2. Target parameter values of a unit module

	Parameter	Target Value
Main Parameter	Operating voltage, V_C	7 kV
	Main capacitance, C	1530 μF
	Pulse forming inductance, L	11 μH
	Trigger time, t_1, t_2, t_3, t_4	0, 40, 240, 360 μs
Sub Parameter	Capacitor-switch resistance	6 mΩ
	Capacitor-switch inductance	0.6 μH
	Inductor resistance	2 mΩ
	Crowbar resistance	20 mΩ
	Crowbar inductance	0.15 μH
	Cable resistance	2 mΩ

To minimize the stray resistance and inductance of the module assembly, the conductors connecting the electrical components were prepared as wide as possible and to have coaxial structures. Fig. 5 shows the result of the simulation using the values referred in Table 2. The peak current and power were 108 kA and 220 MW, respectively. The rising time was 0.18 ms. The transferred energy was 122 kJ with an efficiency of 81%. The result shows that the selected parameters satisfy the required specifications. Using the selected parameters a short circuit simulation has been done to determine the detailed electrical requirement of the main devices. In the short circuit condition of the load, the current of a unit module was about 70 kA and the maximum total current was 208 kA as shown in Fig. 6.

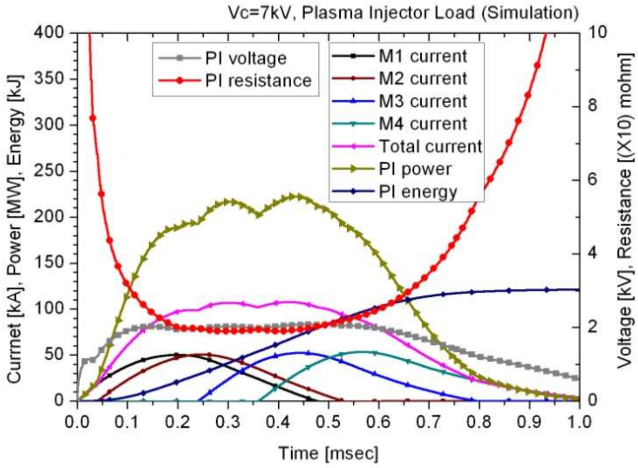

Fig. 5. A simulation result using 4-module circuit

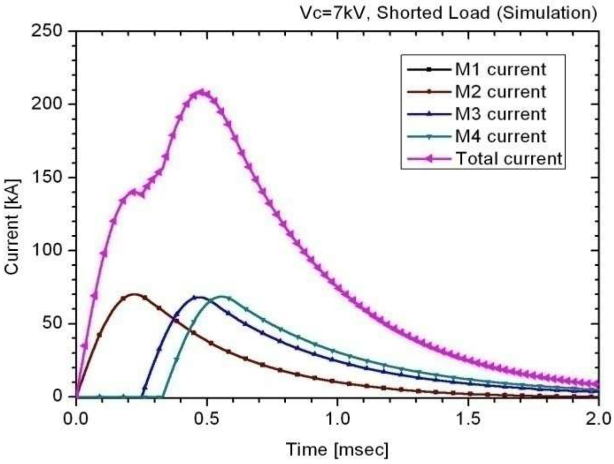

Fig. 6. A simulation result using a shorted load

From this result, the allowed maximum current, action integral and di/dt of the switch and the diode in each module are summarized in Table 3 for the appropriate choice of products.

Table 3. Required values of ratings of a switch and a diode

Switch	Maximum peak current		73 kA
	Action Integral		0.74 MA^2s
	Rising di/dt	Maximum	570 MA/s
		Average	348 MA/s
	Falling di/dt	Maximum	-1365 MA/s
		Average	-1040 MA/s
Diode	Maximum peak current		69 kA
	Action Integral		1.50 MA^2s
	Rising di/dt	Maximum	1304 MA/s
		Average	1000 MA/s

From the arrangement of the components using a 3D digital mock-up, the final configuration with the volume below 0.5 m^3 was obtained as shown in Fig. 7.

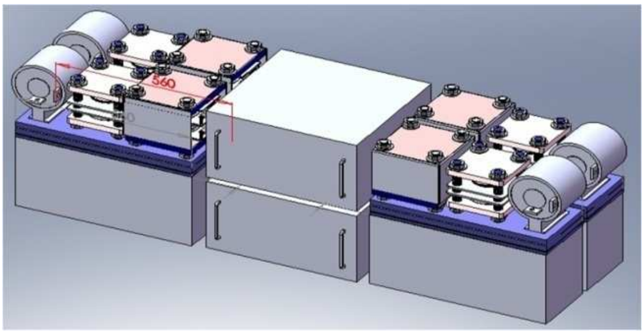

Fig. 7. The 3D mock-up of the CCPPS

3. Setup of the CCPPS

The main components of the CCPPS are a capacitor, a switch, a crowbar diode, an inductor, a capacitor charger and a controller. The capacitors are manufactured by ICAR. Its dimension is 225×560×265 mm (W×D×H). Its shape was determined considering overall energy density of the CCPPS. The salient electrode is electrically positive and the body is negative. It has the energy density of 1.12 J/cm^3, the operating voltage of 7 kV, the capacitance of 1640 μF, the ESR of 1.2 mΩ, the ESL of 41 nH and the maximum current of 100 kA. The Light Triggered Thyristor (LTT) manufactured by Infineon was adopted as a switch of the CCPPS. To turn on the LTT, a light pulse from a laser diode of 40 mW in power and 904 nm in wavelength was used. This optical switch has several advantages. The LTT operates with reduced susceptibility to electromagnetic interferences. Furthermore, the LTT has an integrated protection function for a forward overvoltage and a high dv/dt. Thus, the additional protection circuit required in an electrically triggered thyristor is not necessary in the LTT. The adopted LTT has a wafer diameter of 100 mm, the DC forward blocking voltage of 6 kV, the repetitive peak reverse voltage of 7.5 kV, the surge on-state current of 100 kA and the action integral of 8 MA^{2}s. Two switches were connected in series considering the operating voltage and voltage spikes generated in the multi-module discharge. For the crowbar purpose, two diodes with wafer diameter of 80 mm and electrical specifications similar to the LTT were connected in series. In addition, a crowbar resistor of 15 mΩ was inserted to avoid the resonant current generated between the capacitor and the crowbar diode. To reduce the amplitude and the rate of the load current an inductor of a pancake type was fabricated. It was tested up to the voltage of DC 20 kV with the peak current of 100 kA. The internal resistance was about 1.5 mΩ. Fig. 8 shows the 37.5 kJ unit module of the CCPPS.

The conducting plates connecting the switch and the crowbar diode had coaxial structures. Two conducting plates connected to the electrodes of the capacitor were mounted above the capacitor in parallel. The switch, the crowbar diode and the inductor were mounted on the upper plate. The conducting plates provide current paths to the mounted components. After the preliminary design using the 3D digital mock-up shown in Fig. 7, overall system of the CCPPS was fabricated as shown in Fig. 9. The dimension of the CCPPS is 470×1740×610 mm (W×D×H) which satisfies the specification of the volume (0.5 m^3).

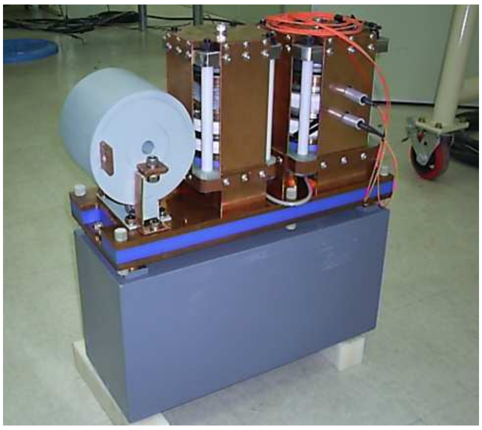

Fig. 8. The unit module of a 150 kJ CCPPS

Fig. 9. Overall system of the 150 kJ CCPPS

4. Experimental Results

Parameters shown in Table 2 were revised to real values shown in Table 4 through the test of the unit module and 2 modules.

Table 4. Real parameter values of a unit module

	Parameter	Real Value
Main Parameter	Operating voltage, V_C	7 kV
	Main capacitance, C	1640 μF
	Pulse forming inductance, L	12 μH
	Trigger time, t_1, t_2, t_3, t_4	0, 0, 250, 330 μs
Sub Parameter	Capacitor-switch resistance	2 mΩ
	Capacitor-switch inductance	0.1 μH
	Inductor resistance	1.5 mΩ
	Crowbar resistance	15 mΩ
	Crowbar inductance	0.15 μH
	Cable resistance	2 mΩ

Fig. 10 and Fig. 11 show the comparison between the simulation and the test result in the short circuit condition with the charging voltage of 7 kV for a unit module and 6.7 kV for 2 parallel modules, respectively. The peak currents of 75 kA and 100 kA guarantee safe operations of the components.

The CCPPS discharge tests at 5.6 ~ 7.0 kV using the plasma injector loads are shown in Fig. 12 and Table 5.

Peak powers were 159~250 MW, and the transferred energy were 87.8~137.9 kJ. The pulse rising time less than

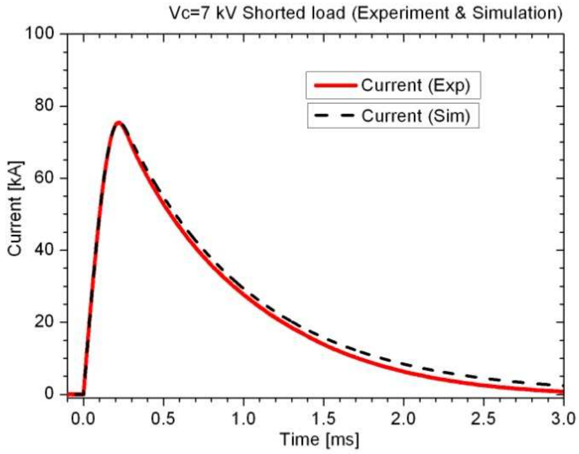

Fig. 10. Short circuit current of a unit module

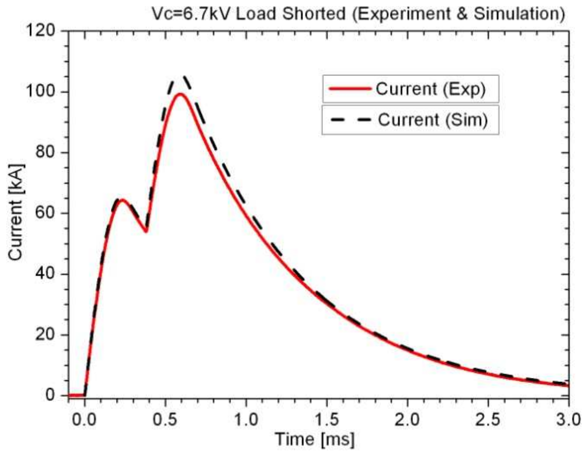

Fig. 11. Short circuit current of 2 modules

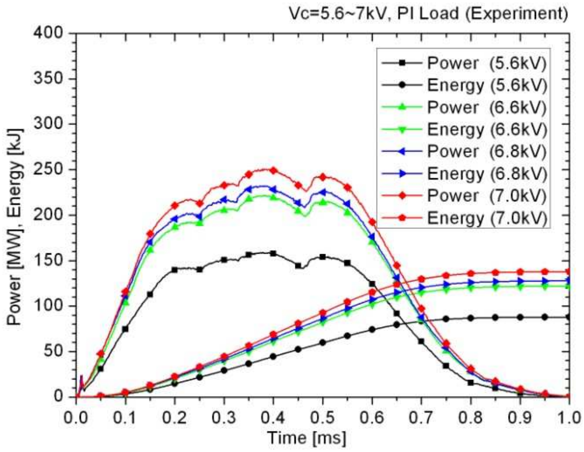

Fig. 12. Power and transferred energy at the 150 kJ CCPPS

Table 5. Measured values of the CCPPS discharge

V_C (kV)	5.6	6.6	6.8	7.0
Input Energy (kJ)	102.5	144.2	151.2	163.0
Peak Current (kA)	64.7	82.3	85.0	88.7
Peak Power (MW)	159	221	232	250
Output Energy (kJ)	87.8	122.1	127.8	137.9
Efficiency (%)	85.6	84.7	84.5	84.4

0.2 ms and the pulse width of about 1 ms were achieved. The efficiency of the energy transfer was over 84.4 % which is 4~5 % higher than that anticipated. The repetition rate depends on the charging speed of the capacitor charger. The capacitor charger was manufactured by PulseCon in Korea. Its maximum charging rate is 35 kJ/s and its output voltage can be adjusted to 25 kV. Repetitive discharges at 6.5 kV have been done manually using a 52 mΩ resistive

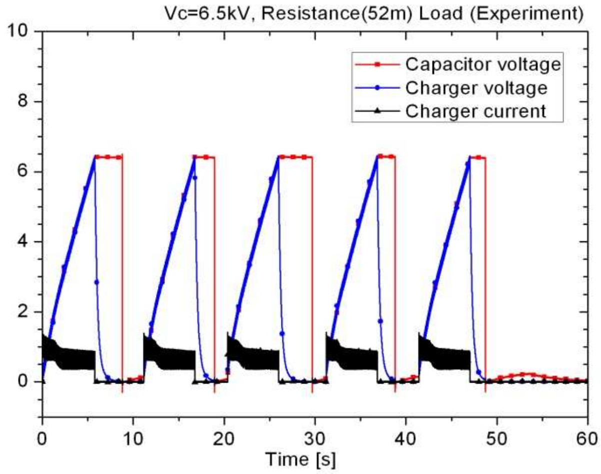

Fig. 13. The capacitor voltage, the charger voltage and the charger current at repetition rate test of the 150 kJ CCPPS

Fig. 14. Firing experiment of the ETC gun using the 150 kJ CCPPS

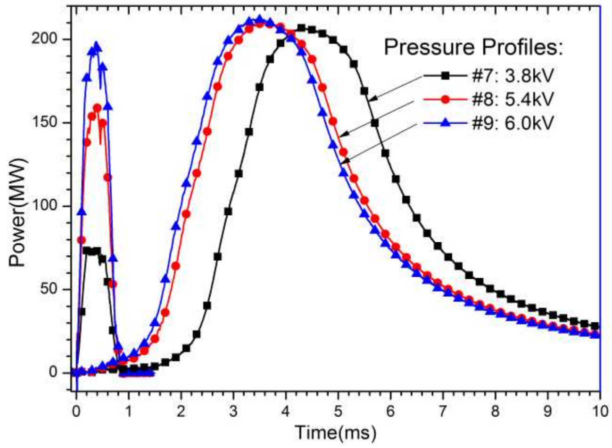

Fig. 15. The electric power of the CCPPS and a pressure profile in the ETC gun

load. As shown in Fig. 13, it took about 48 seconds for the repetitive charging and discharging of 5 times. If the repetitive operation is done automatically, it is possible to obtain the rate of 7~8 times per minute.

Fig. 14 shows the firing experiments of the 120 mm ETC gun using the CCPPS. In the result shown in Fig. 15, as the input power increased from 75 MW to 198 MW, the peak pressure inside the gun chamber increased a little, but the time to reach the peak pressure was reduced from 4.5 ms to 3.5 ms. It was verified that the 150 kJ CCPPS operated stably for the ignition of low vulnerable propellant as well as conventional propellant in the ETC gun.

5. Conclusion

To verify the possibility of developing a compact pulsed power system suitable to be mounted on a vehicle the required specifications were investigated. The performance specifications of the CCPPS for an ETC gun were determined as follows: Maximum charging energy of 150 kJ, maximum peak power of 250 MW, the volume of less than 0.5 m^3, the efficiency of energy transfer over 80 % and the repetition rate of 4~5 times per minute. Using the SPICE code and 3D digital mock-up detailed electrical parameters and spatial configuration were determined.

Using the fabricated 150kJ CCPPS, short circuit discharges of a unit module, discharges using the plasma injector load, repetitive discharge operations and firing experiments of the ETC gun have been done. From the test results, the required performance specifications of the CCPPS were achieved.

References

[1] J.W. Jung, S.H. Kim and K.S. Yang, "Overview of ETC Research in Korea," *IEEE Trans. Magnetics*, Vol. 39, No. 1, pp. 22-23, Jan. 2003.

[2] S.H. Kim, K.S. Yang, Y.H. Lee, J.S. Kim and B.H. Lee, "Electrothermal-Chemical Ignition Research on 120- mm Gun in Korea," *IEEE Trans. Magnetics*, Vol. 45, No. 1, pp. 341-346, Jan. 2009.

[3] Y.S. Jin, H.S. Lee, G.H. Rim, J.S. Kim, J.S. Kim, J.H. Chu, J.S. Jung and D.W. Hwang, "Design and Performance of a 300 kJ Pulsed Power Module for ETC Application," *IEEE Trans. Magnetics*, Vol. 37, No. 1, pp. 165-168, Jan. 2001.

[4] G.Y. Sung, J.S. Kim, J.H. Chu and J.W. Jung, "Development of 2.4-MJ Capacitor Bank for Electrothermal Propulsion Technology," *IEEE Trans. Plasma Science*, Vol. 30, No. 5, pp. 1789-1792, Oct. 2002.

[5] J.S. Kim, Y.H. Choi, J.H. Chu and G.Y. Sung, "Analysis on High Surge Voltages Generated in Paralleled Capacitor Banks," *IEEE Trans. Magnetics*, Vol. 39, No. 1, pp. 422-426, Jan. 2003.

[6] S.H. Kim, K.S. Yang, J.S. Kim, And Y.H Lee, "Comparison of Plastic Ablation Materials of Capillary Discharge," *in Proceedings of 16th IEEE International Pulsed Power Conference*, Albuquerque, New Mexico, 2007.

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