A COMSOL modeling of the pre-breakdown heating phase in the electro-thermal breakdown of conductive water

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Abstract. By using the multi-physics simulation software COMSOL, the pre-breakdown-heating phase in the electro-thermal breakdown of conductive water is modeled. In this COMSOL model, the Joule-heating module (*jh*) and the electric circuit module (*cir*) are used together to simulate the time-evolution of the temperature in the central axis of the underwater gap.

1. Introduction

Discovered by Russian scientist Yutkin in 1938, an underwater arc can be generated in underwater pulse discharge. The underwater arc can drive an intense shockwave and then form a mechanic destruction, which is called “water hammer effect”. Based on this water hammer effect, the underwater discharge devices have wide applications in many fields, such as shockwave lithotrity [1], impulse forming [2], rock fragmentation[3] and pipe cleaning [4].

According to our previous study[5], most of the underwater discharge devices are operated in a “electro-thermal breakdown” mode, which usually happens in conductive water under a weak electric field of 10 kV/cm order. The characteristic of the electro-thermal breakdown is that there exists a pre-breakdown-heating phase before breakdown, which may last 100μs~1ms. In the pre-breakdown-heating phase, an amount of energy must be deposited to the underwater gap from the external circuit, and the temperature of the gap water must be raised to a threshold value, which can be regarded as one of the necessary conditions for the succeeding breakdown. In our previous study[6], that threshold temperature is estimated to be 800K. However, that estimation is not accurate, because the figure of the electrode is out of consideration and the electric field in the underwater gap is assumed to be a homogeneous field. In order to get a more accurate estimation of the threshold temperature from the experiment data and the simulation data, a more accurate model for the pre-breakdown-heating phase is needed.

2. Physics modeling

The basic setup of the underwater pulse discharge device is shown in Fig.1. The C is the pulse capacitor, which service as an energy storage device. The G is the underwater gap, which provides a pulse electric field for electro-thermal breakdown. In electro-thermal breakdown, the evolution of the voltage on the underwater gap is shown in Fig.2[7]. From Fig.2, the discharge can mainly be divided to two phase. The first phase, which experiences an exponential decrease, is the pre-breakdown-heating phase. The second phase, which shows an intense oscillation, is the post-breakdown-discharge phase. According to our previous study[6], when the gap interval is fixed, the intensity of the shockwave in electro-thermal breakdown mainly lies on the temperature of the discharge arc, which mainly lies on the remaining voltage after the pre-breakdown-heating phase (U_B in Fig.2).

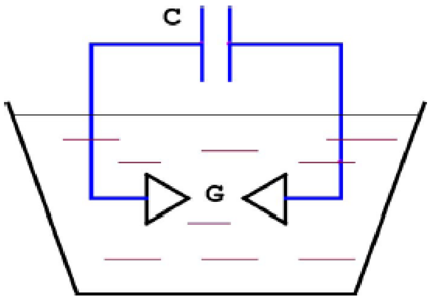

Fig.1 The main setup of the underwater puse discharge device

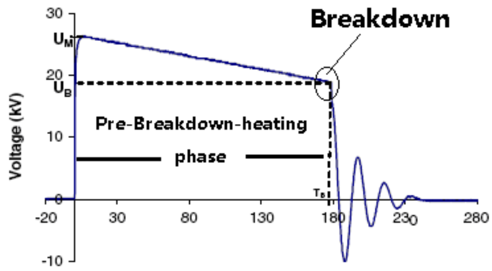

Fig.2 The evolution of the voltage on the underwater gap[7]

A good electrode for the electro-thermal breakdown with a fixed gap interval, should reduces the energy leakage in its affiliate area and raise the remaining voltage. The most common electrode is shown in Fig.3, in which the insulator cone with a cone figure is to achieve a full release of the discharge shockwave.

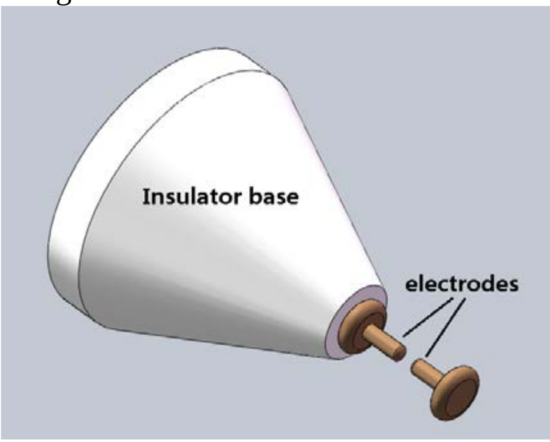

Fig.3 The most common electrode for eletro-thermal breakdown.

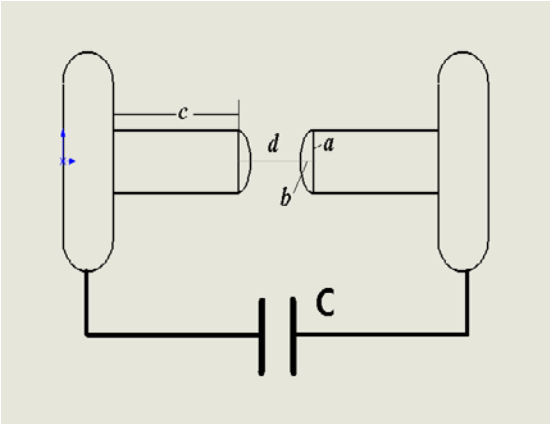

Fig.4 The basic setup and parameters of the electrodes

The basic setup of the electrodes are shown in Fig.4. It consists of a cylinder, of which the length is *c* and the diameter is 2*a*, and a half-ellipse, of which the semimajor axis is *a* and the semiminor axis is *b*. The most important parameter of the electrodes, named *d*, is the gap interval, which mainly decides the strength of the electric field. In this paper, we set: a = 2mm, b = 1mm, c = 10mm, d = 4mm.

To build the physics model for the pre-breakdown-heating phase, the multi-physics simulation software, COMSOL (Ver 4.3b), is used. Firstly, for the electrodes shown in Fig.3, the geometric modeling is shown in Fig.5.

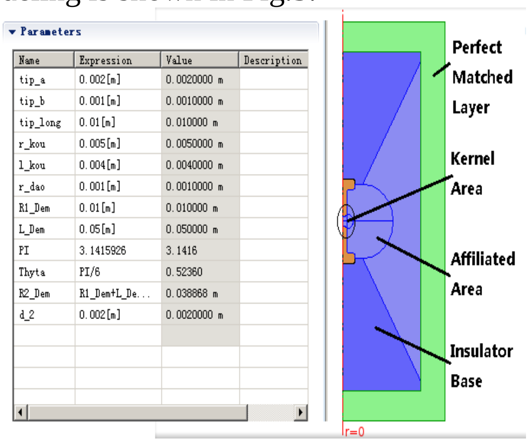

Fig.5 The geometric modeling for the pre-breakdown-heating phase

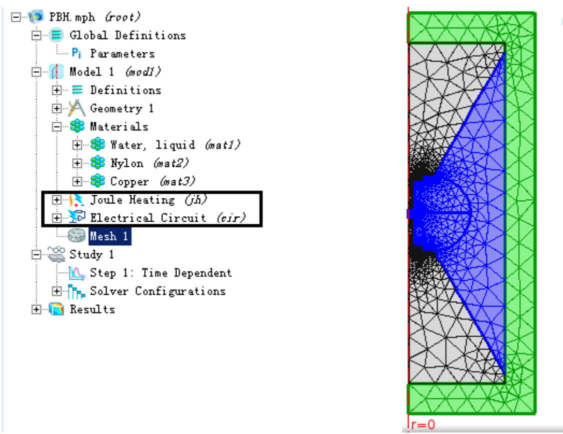

Fig.6 The mesh and the choice of multi- phyics modules

As shown in Fig.5, the computation domain is mainly divided to the kernel are, the affiliate area, the insulator area and the perfect matched layer (PML). The PML realized a full absorption-boundary-condition, which represents for an unlimited far-field domain. The key parameters for the kernel area, which is formed by the electrodes, are recorded in a global parameter list. The re-building of the geometric model can be easily realized by an adjustment to these key parameters.

As shown in Fig.6, when the geometric modeling is finished, the COMSOL can generate a triangular mesh set, of which the density can be adjusted according to the different importance of different computation areas. After meshing, the corresponding physics modules should be added to the “Model 1” root. In this case, the Joule-heating module (*jh*) and the electric circuit (*cir*) are chosen. For the new added Joule-heating module, two electric terminals need to be added, as shown in Fig.7.

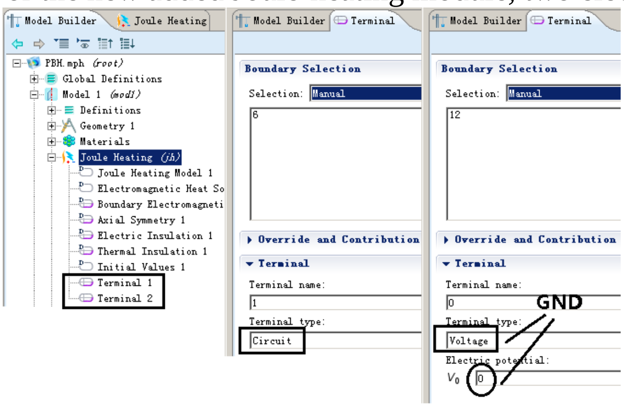

Fig.7 The setup of the Joule-heating module

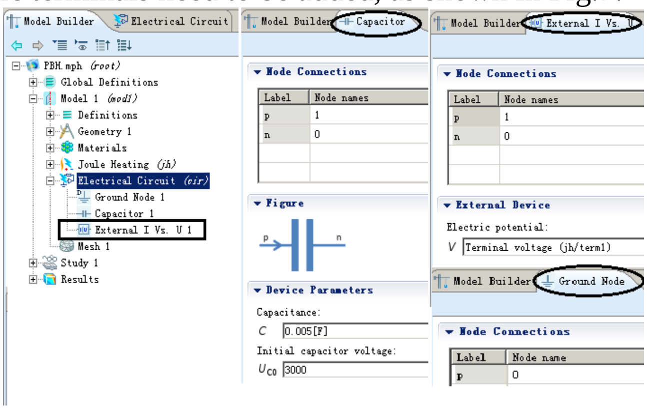

Fig.8 The setup of the circuit module

In the setup of the Joule-heating module, the terminal names should be identical to that in the circuit module. The terminal names can be any integal numbers, but the terminal ”0” is strongly advised to be reserved for the ground node. For the terminal 0, which serves as the ground, the ”Terminal type” should choose ”Voltage”, and the corresponding ”Electric potential” is usually set to be 0. For the other terminal 1, the ”Terminal type” should choose ”Circuit”.

For the new added circuit module, three items are added: the ”Ground Node”, the ”Capacitor” and the ”External I Vs U”. In the ”Ground Node” , the terminal name of is set to be ”0”. In the ”Capacitor”, the value for the capacitance and the initial voltage are setup. In the ”External I Vs U”, which in fact stands for the gap water, the two terminal names should be identical to that in the Joule-heating module, and the ”Electric potential” should choose ”Terminal voltage (jh/term 1)”.

3. Simulation results

Before the simulation, a solver of ”Time dependent” must be added to the ”Study” root, as shown in Fig.9.

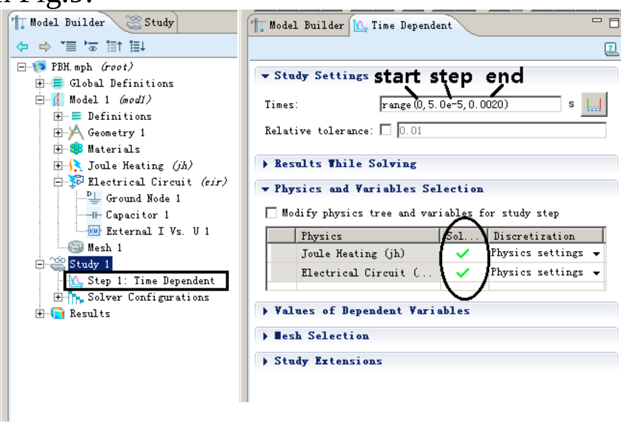

Fig.9 The setup of the time dependent solver

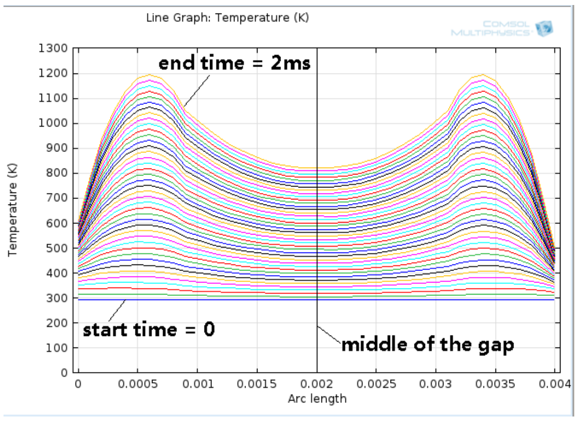

Fig.10 The time evolution of the gap water

In the time dependent solver, the start time (0) , the time step (50μs) and the end time (2ms) are added to the ”range( )” function. In addition, in the ” Physics and Variables Selection” column, both of two physics modules (“*jh*” and “*cir*”) should be activated.

After above setup, we set the capacitance C = 5mF, the initial voltage U_0 = 3000V， the water conductivity G = 3S/m，the gap interval d = 4mm，the diameter of electrode 2a = 4mm，the semiminor axis of the tip ellipse b = 1mm。Then, after a short computation period of several seconds, we get the simulation result for the time evolution of the water temperature along the central axis between two electrodes, as shwon in Fig.10.

4. Summary

From the simulation result for the time evolution of the temperature, the capacitor(C = 5mF, U_0 = 3000V) can make a Joule-heating on the gap water (G = 3S/m) from 300 K to 800 K, which reaches our initial expectancy.

Acknowledgments

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