NUMERICAL SIMULATION OF HEAT TRANSFER IN ELECTRICAL RESISTANCE MICRO-THRUSTER

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A micro-propulsion system can be used in micro satellites for orbit lifting, speed adjusting, gravitation compensation, station keeping, attitude control and so on. It mainly consists of a nozzle, a micro thrust chamber, micro valve(s), micro pump(s), micro channel(s), micro pressure and temperature sensors and a control circuit, etc. A chemical micro-propulsion systems with high performance and a low power-consuming electric system was developed in [1,2].

A single electrical resistance micro-thruster fabricated at Tsinghua University in China using MEMS technology consists of a micro-resistor (820μm long × 440μm wide × 2μm thick), a vaporizing chamber (1000μm long × 500μm wide × 10μm thick), a nozzle, a propellant inlet and a micro channel, with two silicon wafers bonded together. The water (propellant) is fed into the chamber from a propellant storing tank through the propellant inlet and the micro channel. The micro-thruster is designed to operate in pulse mode. A pulsed electric current, with high voltage but very short pulse duration of a few microseconds, is applied to the heating resistor. Consequently, the propellant in the chamber is vaporized into vapor with high temperature and high pressure in a very short time. Then the vapor exits through the specially shaped nozzle with high speed, and thus producing thrust in a reversed direction.

Rapid boiling is a transient heat transfer phenomenon with phase change under special conditions. The most common rapid boiling appears when the high heat fluxes pulsatively act on a very thin film or wire which immersed in liquids. Their two main characters are the strong non-equilibrium of liquid-vapor and transience of processes. The following assumptions are made: 1) heat transfer is pure heat conduction by neglecting the convective effects in liquid but with phase change [3]; 2) there is an internal heat source in heat resistor. Hence, it is a two-dimensional transient conduction problem with internal heat source and with phase change.

Up till now, the scientists of Russia, Japan and USA have carried out some works on rapid boiling phenomena. However there is not any appropriate and exact theory on rapid boiling heat transfer in micro size and it is demanded to investigate heat and mass transfer in rapid boiling systematically and in detail. In this study, the beginning moment of heat transfer in electrical micro-thruster is described by the classical model of Fourier’s law, the non-Fourier “Cattaneo-Vernotte” (C-V) model and the non-Fourier “dual phase lag” (DPL) model of heat conduction, respectively, and with consideration of the phase change.

The basic idea of DPL model was represented by Tzou's formula [4]:

$$\rho c_p\left(\frac{\partial T}{\partial t}+\tau_q\frac{\partial^2 T}{\partial t^2}\right)=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}+\lambda\cdot\tau_T\frac{\partial^2 T}{\partial t\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}+\lambda\cdot\tau_T\frac{\partial^2 T}{\partial t\partial y}\right)+q_v$$

where τ_q and τ_T are the delay times in establishing heat flux and temperature, respectively. The tendency of the delay time is to induce thermal wave with sharp wave front separating heated and unheated zones. And the delay time is necessary to establish steeper temperature gradient across the solid. They are also interpreted as the effects of "thermal inertia" and "microstructure interaction", respectively [5]. Only when applied very high heat flux and rapid heating conditions exist in thermal process, the lag effects of τ_q and τ_T are obvious. When τ_q and τ_T equals zero, the model is degenerated into classical thermal wave model.

The traditional heat conduction equation implies an infinite speed of propagation of the thermal signal, indicating that a local change of temperature causes an instantaneous perturbation in the temperature at each point of the medium, even if the intervening distances are very large. For homogeneous materials, such as pure liquids, gases and dielectric solids, the values of thermal relaxation time range from 10^{-14} to 10^{-6} s [6,7]. However, the values of thermal relaxation time might be significantly larger for materials with a non-homogeneous inner structure. This small value of relaxation time indicates that if the physical time scales are of the order of microsecond or larger, then non-Fourier effects will not be significant. While most traditional thermal engineering applications have time scales in excess of milliseconds, few modern technological processes such as laser melting deliver large values of heat fluxes in very short pulses, sometimes as short as femtoseconds. For such processes the non-Fourier conduction would certainly be very important and the Fourier formulation could conceivably be in great error.

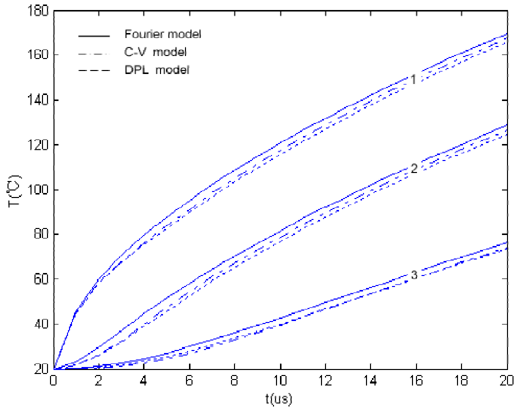

Fig. 1. Comparison of different models

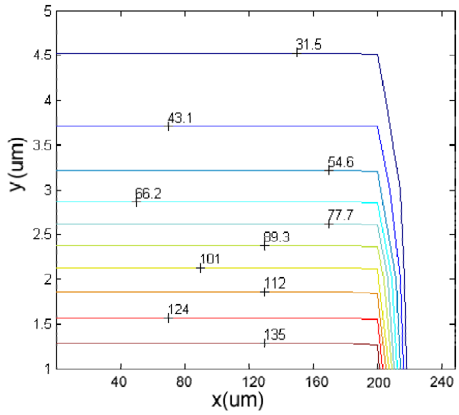

Fig.2. Temperature distribution after 15μs

Fig. 1 compares three different heat conduction models. The Fourier's equation was calculated by setting $\tau_q = \tau_T = 0$ for heat resistor and water; the C-V equation $\tau_q = 10^{-8}$ s for heat resistor, $\tau_q = 10^{-6}$ s for water, and $\tau_T = 0$ for both media; while the DPL equation $\tau_q = \tau_T = 10^{-8}$ s for heat resistor, and $\tau_q =$

$\tau_T = 10^{-6}$ s for water. The result showed there was a certain time delay between non-Fourier models and Fourier model. The calculation results of non-Fourier models with τ_q and τ_T less than the above values showed no obvious differences with Fourier model. Hence the non-Fourier effect could be neglected if the thermal relaxation time was small enough. The temperature distribution after 15 μs is showed in Fig. 2. Having been heated for 15 μs, a little amount of water had reached the temperature of 100℃. However, the most of water is still in a comparatively lower temperature, especially those far away from the heat resistor. The temperature rising rate reached the maximum value at the beginning. The further from the heating resistor, the lower the temperature rising rate. As time passed, the temperature rising rates trended to be constant.

CONCLUSIONS

There was a certain time delay between non-Fourier models and Fourier model. The calculation results of non-Fourier models with τ_q and τ_T less than the above values showed no obvious differences with Fourier model. Hence the non-Fourier effect could be neglected if the thermal relaxation time was small enough.

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