High-temperature generation of a diode-laser coupled fiber-tip heat source

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Abstract: **In this study, characteristics of high-temperature generation mechanism of a laser-diode (LD) coupled fiber-tip heat source for novel laser-thermal microthruster applications were investigated. To investigate physical mechanism of the high-temperature generation of the fiber-tip heat source, a numerical simulation for heat transfer phenomena in a near tip region of a quartz fiber with laser irradiation was conducted using a commercial CFD code. From the results, it was shown that the high-temperature region was very limited in a thin layer at the tip. Considering the maximum temperature at the tip in both measured and calculated results, exceeding a melting point of quartz, the high-temperature layer must be in a liquid phase at this short period of less than 0.2 s. In addition, it was shown that in smaller fiber cases, much lower laser powers were required for the fiber-tips to be heated over 3,000 K within 0.2 s.**

I. Introduction

Feasibility studies of micro-spacecraft are currently under significant development for a mass less than 100 kg with an available power level for propulsion of less than 100 watts.[1-4] The significance in reducing launch masses has attracted growing interests in regard to a decrease in mission cost and an increase in launch rate. The micro-spacecraft segments of the satellite launch industry have been growing rapidly in recent years. Development activity for a mass less than 50 kg range has been significantly exceeding that in the 50 ~ 100 kg range. In the smaller range alone, there were fewer than 15 satellites launched annually in 2000 to 2005, and 34 satellites in 2006. Then there were fewer than 30 launches annually during 2007 to 2011, and 34 satellites in 2012. The launch rate rapidly rose up to 92 satellites in 2013, and then 158 in 2014, which included some of more practical missions .[5,6]

Although, in the past, many very small spacecraft lacked propulsion systems, future micro-spacecraft will require significant propulsion capability to provide a high degree of maneuverability and capability. The benefit of using electric propulsion for the reduction of spacecraft mass will likely be even more significant for mass limited micro-spacecraft missions.[2-4] Various potential propulsion systems for micro-spacecraft applications, such as ion thrusters, field emission thrusters (FEEPs), colloid thrusters, pulsed plasma thrusters (PPTs), etc., have been proposed and are under significant development for primary and attitude control applications.[4]

On the other hand, small-sized onboard laser plasma thrusters are also under significant development with rapid evolutions of novel compact laser systems.[8] One of the advantages of the laser thrusters is that they can induce high specific impulses. In addition, the system can be very simple and small with significant controllability of the thrust.

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In this study, characteristics of high-temperature generation mechanism of a laser-diode (LD) coupled fiber-tip heat source for novel laser-thermal microthruster applications were investigated. The LD-coupled fiber-tip heat source can generate a high temperature spot, and is currently used as a novel high-temperature heat source for skin surgery applications.[9] However, detailed physical mechanism of the high temperature generation is still not well-known.[10] An objective of this study is to characterize the temperature generation and to understand its physical mechanism for the future application of microthrusters.

II. A Fiber-tip Heat Source Coupled with a Laser Diode.[10]

A high-temperature micro-heat source made from a fiber-tip heat source coupled with a low-power laser-diode can generate a thin high-temperature layer with a diameter of that of the fiber. Currently, the LD-coupled fiber-tip heat source is used as a novel high-temperature heat source for skin surgery applications.[9,10]

Before its operation, a tip of the optical fiber is treated as follows. Figure 1 shows how the fiber tip is processed using titanium dioxide powder. Coherent light from the LD source is directed through the fiber as the tip is pressed into the TiO_2 powder. The laser beam from the fiber is absorbed by the TiO_2 in the powder granules and the heat generated there partly fuse the fiber tip, which then resolidifies with a coating of Ti containing material over it.

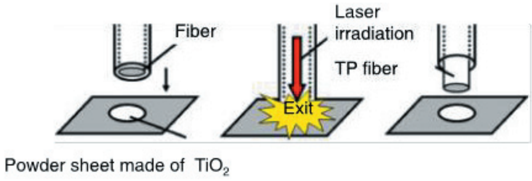


Fig.1. Conceptual drawing of fiber tip processing withTiO_2 powder.

From the SEM and EPMA analysis, it is shown that the heat generated in the fiber tip burns the primary coating on the fiber exterior with stripping off the clad and exposing the core.[10]A portion of the tip is melted portion in the tip due to high temperature exceeding the material melting point. A Ti layer is distributed to a depth of about 0.1 mm beneath the surface of the fiber tip, for a fiber of 0.4 mm in diameter, LD power of 6 W, wavelength of 908 nm.

Figure 2 shows temporal variation of fiber-tip temperature estimated with two-color radiation thermometryanalysis.[10] The fine heat source on the fiber-tip was found to be capable of elevating temperatures as high as 3100 K. Typical temperatures for 80, 110, 140, and 170 ms after excitation laser pulse was triggered were measured to be 2540, 2710,2940 and 3110 K, respectively, for a fiber of 0.4 mm in diameter, LD power of 6 W,wavelength of 908 nm.

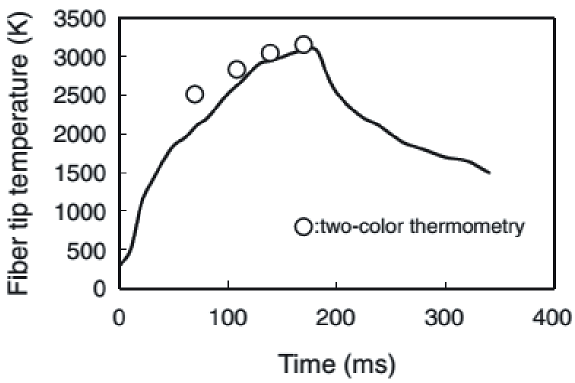


Fig.2. Results of fiber-tip temperature.

Solid curve shows full temporal behavior after the infrared radiation intensity of the pump laser had been calibrated with a two-color radiation thermometry at a time of 170 ms, assuming the fiber-tip to have a blackbody radiation spectral distribution. Also, round plots other than one at 170 ms indicate analysis with the two-color radiation thermometry at times of 80, 110, and 140 ms.

III. A Novel Laser-thermal Microthruster Concept using LD-coupled Fiber-tip Heat Source

In this study, to characterize the temperature generation and to understand its physical mechanism, characteristics of high-temperature generation mechanism of the LD-coupled fiber-tip heat source for novel laser-thermal microthruster applications were investigated.

A schematic illustration of a laser microthruster with the LD-coupled fiber-tip heat source is shown in Fig.3. As shown in this illustration, the fiber is simply installed

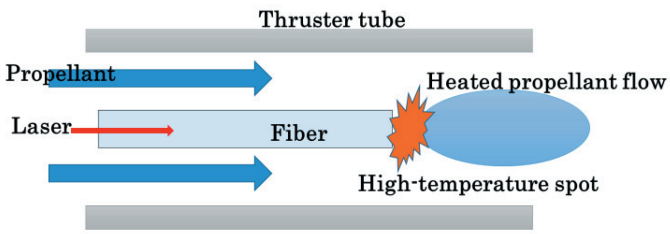


Fig.3. A schematic illustration of a laser microthruster with the LD-coupled fiber-tip heat source.

coaxially in a thruster tube in which liquid propellant is fed. Since the structure of the thruster head is very simple, it can be miniaturized as small as possible, depending on the diameters of a tube and a fiber. To heat the propellant flow, the laser power output from the fiber tip must be absorbed either by the tip (and then transferred to the propellant) or directly by the propellant with absorber additives. Then, the heated propellant gas is exhausted through an exhaust nozzle aerodynamically accelerating the propellant and generating a thrust as a reaction force.

IV. Heat Transfer Simulation of an LD-coupled Fiber-tip Heat Source

To investigate physical mechanism of the high-temperature generation of the fiber-tip heat source, a numerical simulation for heat transfer phenomena in a near tip region of a quartz fiber with laser irradiation was conducted using a commercial CFD code (Autodesk Simulation CFD 2015 (Autodesk, Inc.)). A typical simulation model is shown in Fig.4. The original model and its experimental result are corresponding to those explained in Sec.2 and Fig.2, respectively. As shown in Fig.4, a cylindrical fiber made of quartz with the core diameter of 0.4 mm is assumed to be receiving (or absorbing) laser irradiation on a tip, which is simply assumed to be an arbitrary heat flux input into the tip surface. The fiber is assumed to be surrounded by ambient air of atmospheric pressure at 298 K, and convective and radiative heat transfer phenomena are occurring in the boundary between the fiber surface and ambient air. An emissivity of the quartz surface is assumed to be 0.92. Typical laser power and duration are 6 W and 180 ms, respectively.

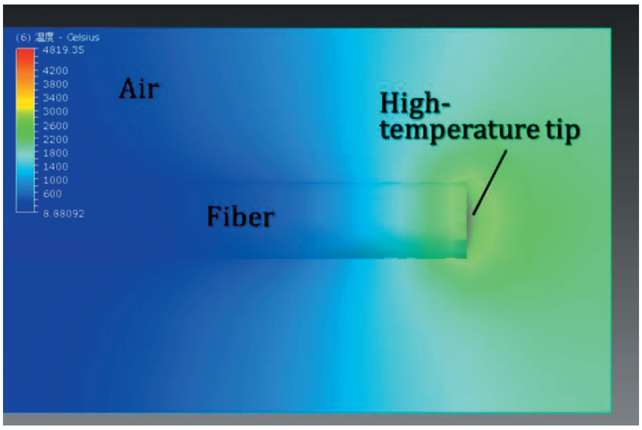


Figure 4. Simulation model

An example of 3-D surface temperature distribution in a near tip region of the fiber after 160 ms laser irradiation is shown in Fig.5 for laser power of 6 W, duration of 180 ms an absorption rate of 100%. As shown in this figure, the maximum temperature region, over 4,000 K, is generated and also is significantly limited in a thin layer on the surface. Since a given absorption efficiency is too high, the maximum temperature is much higher than those measured in the previous study shown in Fig.2, where the measured maximum temperature is 3,110 K.

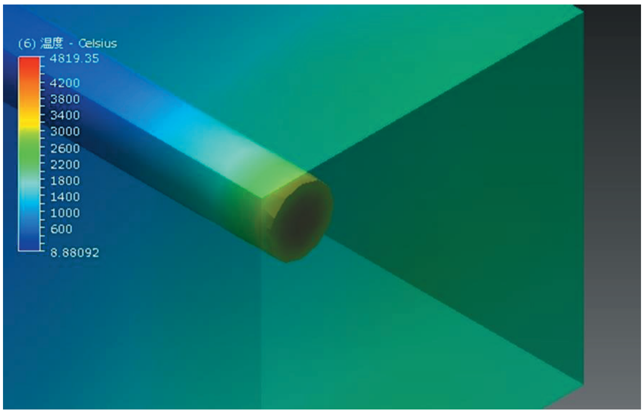
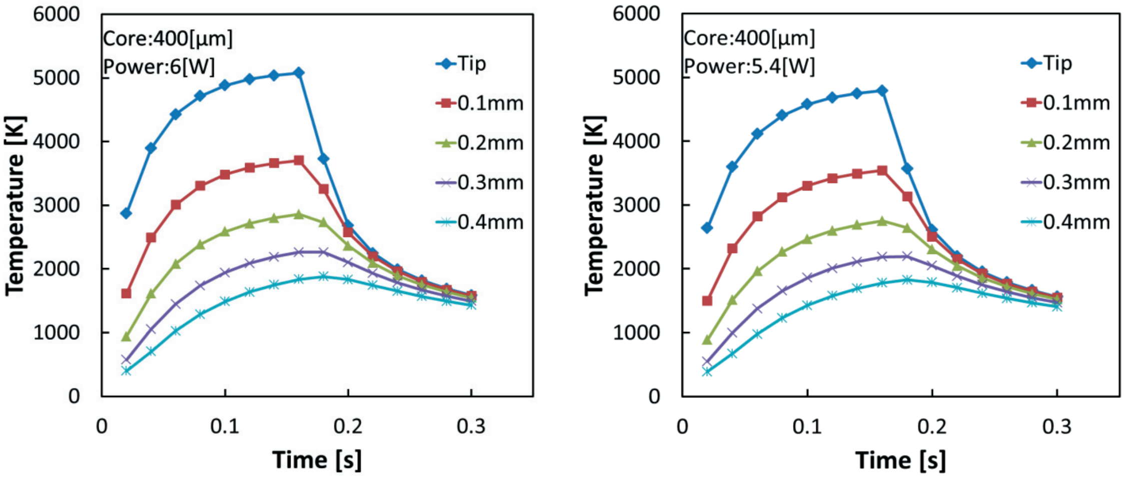


Figure 5. 3-D temperature distribution in near tip region of a fiber after 160 ms laser input.

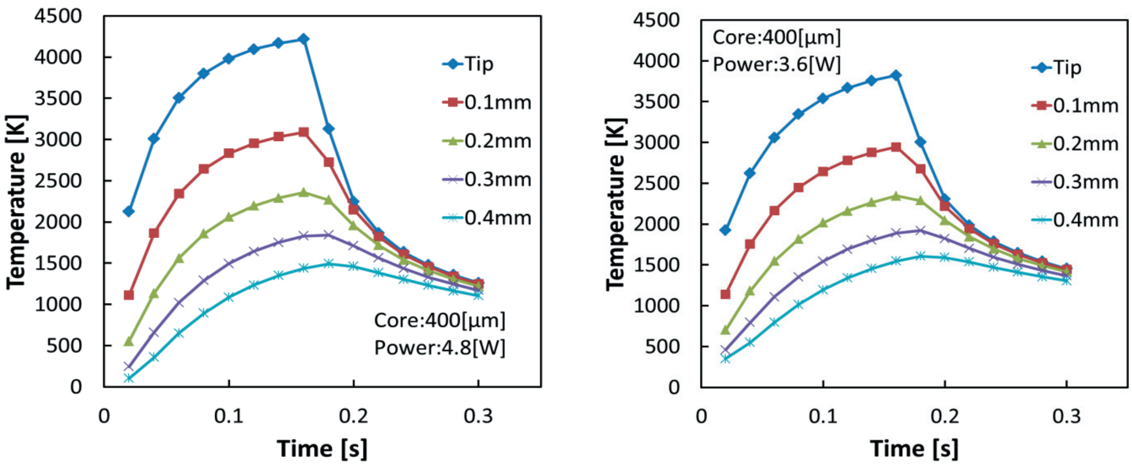
To visualize the temporal variation and detailed structure of the high-temperature region of the fiber-tip, temporal variation of axial distribution of temperature along longitudinal surface of a fiber in a near tip region are shown in Figs.6 to 8, for various absorption rates ranging 40% ~ 100%. Similar to measured temperature in Fig.2, except the maximum temperatures being estimated much higher than measured value, the tip temperature of the fiber abruptly increases with over 4,000 K by 100 ms. After 100 ms, the temperature gradually increases and reaches peak value at the end of laser duration. Then, the tip temperature rapidly falls with time. At 0.1 mm away from the tip, the maximum temperature is much lower than the tip with a large gap of about 1,500 K. The temperature decreases with distance from the tip. From the results, it is shown that the high-temperature region is very limited in a thin layer at the tip. Considering the maximum temperature at the tip in both measured and calculated results, exceeding a melting point of quartz, the high-temperature layer must be in a liquid phase at this short period.

From the Figs.6 to 8, the maximum temperatures decrease with decreasing the absorption rate of the laser at the tip. From the comparison of the temperatures between measured and predicted results, the absorption rate must be about 40%, which is shown in Fig.8 (b).



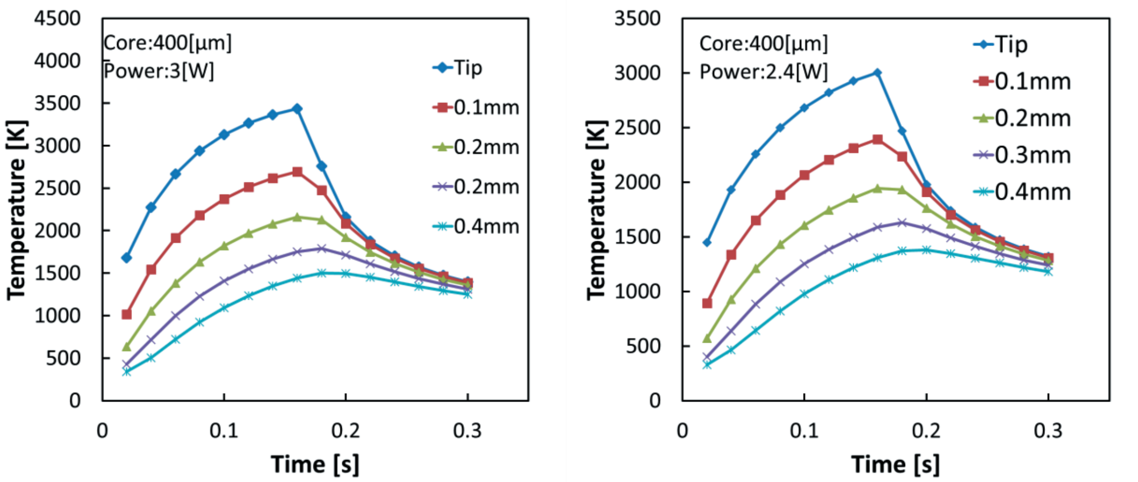
(a) 100% **(b) 90%**

Figure 6. Temporal variation of axial distribution of temperature on along longitudinal surface of afiber in a near tip region, for laser power of 6 W, duration of 180 ms, and various absorption rates (a) 100%, and (b) 90%.



(a) 80% **(b) 60%**

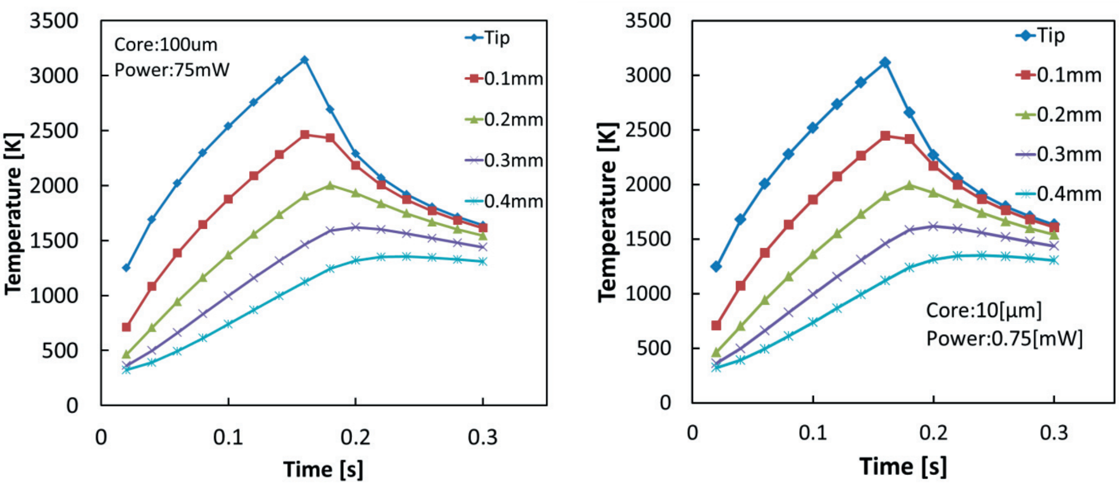
Figure 7. Temporal variation of axial distribution of temperature on along longitudinal surface of a fiber in a near tip region, for laser power of 6 W, duration of 180 ms, and various absorption rates (a) 80%, and (b) 60%.



(a) 50% **(b) 40%**

Figure 8. Temporal variation of axial distribution of temperature on along longitudinal surface of a fiber in a near tip region, for laser power of 6 W, duration of 180 ms, and various absorption rates (a) 50%, and (b) 40%.

Temporal variations of fiber-tip temperatures for smaller diameters of fibers and lower laser powers are shown in Fig.9 for (a) fiber diameter of 0.1 mm and laser power of 75 mW, and (b) fiber diameter of 0.01 mm and laser power of 0.75 mW. It is shown that in smaller fiber cases, much lower laser powers are required for the fiber-tips to be heated over 3,000 K within 200 s. Even a laser power of 0.75 mW can generate high-temperature tip of over 3,000 K for a fiber diameter of 0.01 mm.



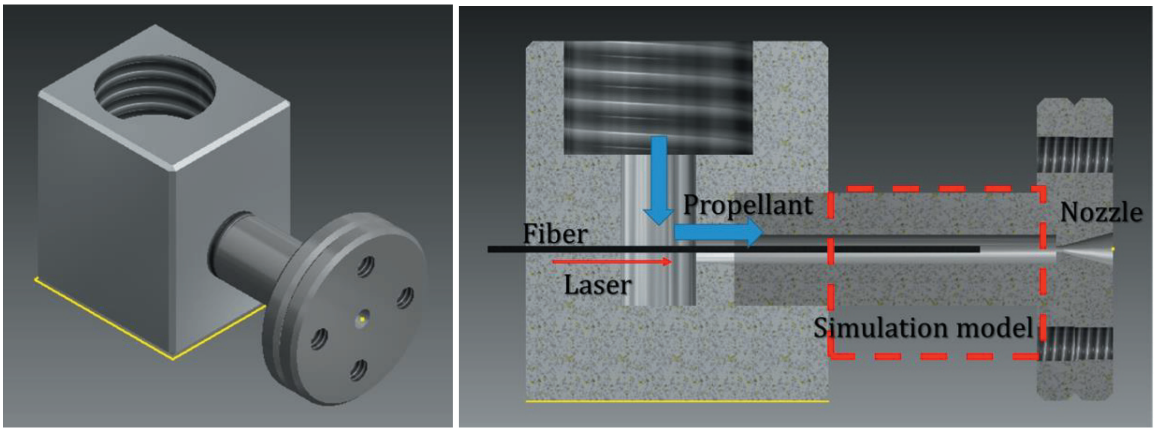
(a) 0.1 mm fiber, 75 mW laser **(b) 0.01 mm fiber, 0.75 mW laser**

Figure 9. Temporal variation of axial distribution of temperature along longitudinal surface of a fiber in a near tip region for various fiber diameters and laser powers.

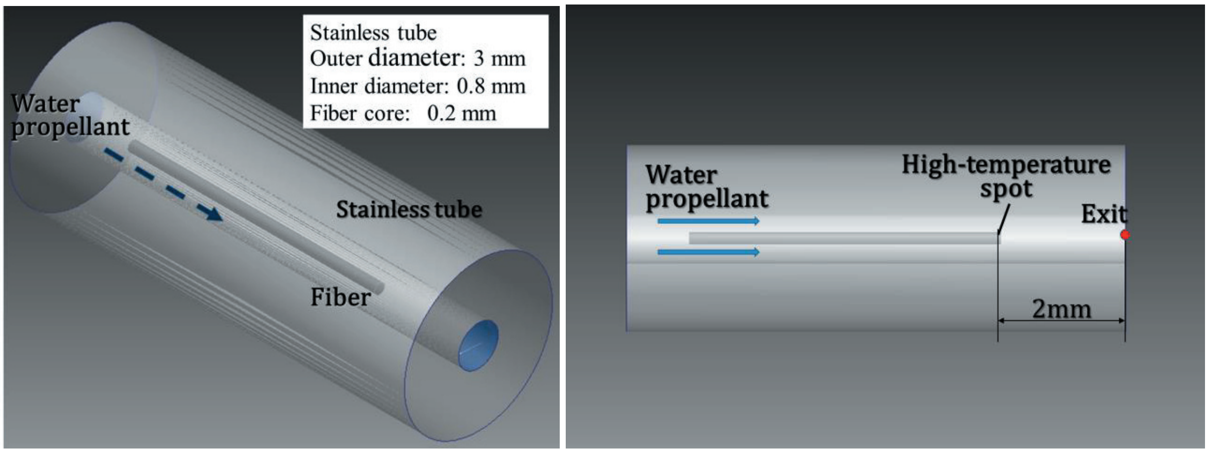
V. Numerical Heat Transfer Simulation of a Laser-thermal Microthruster using LD-coupled Fiber-tip Heat Source

Currently, authors are developing a laser-thermal microthruster using LD-coupled fiber-tip heat source shown in Fig.10 (a) and conducting preliminary operational tests including thrust performance measurement. The thruster main body is made of stainless steel and a nozzle of molybdenum. A throat diameter of the nozzle is 0.2 mm with a half-cone angle of 15 degrees. In this thruster, a CW laser beam from a laser diode of 3 W in power is coupled to an optical fiber of 0.2 mm in diameter is irradiated. As for the liquid propellant, pure water is employed. As shown in this figure, the fiber is placed coaxially along the center line in a thruster tube made of stainless steel (3 mm in outer diameter, 0.8 mm in outer diameter).

In this report, a simulation domain is limited to a region inside of the dotted line in Fig.10 (a). Details of the domain consisting of a thruster tube and fiber-tip are illustrated in Fig.10 (b), and heating characteristics and optimum heating conditions are investigated numerically for the fiber-tip heat source. In this numerical simulation, a commercial CFD code (Autodesk Simulation CFD 2015 (Autodesk, Inc.)) is employed. Similar to that assumed in the previous section, a fiber-tip heat source in this case is assumed to be a heat flux as high as the laser input power in the edge surface area of the fiber. The thruster tube is assumed an adiabatic wall and an emissivity of tip- and side-wall surfaces of the fiber is assumed 0.92.



(a) Thruster head under development



(b) Simulation model

Figure.10 Details of thruster head and simulation model

Temporal variations of temperatures of a fiber-tip and propellant at tube exit, or an upstream point of a throat, temperatures for propellant mass flow rates of 8.0 mg/s and 2.0 mg/s are shown in Figs.11 and 12, respectively.

From the figures, with higher mass flow rate (8.0 mg/s), a variation, or oscillation, of propellant temperature is severe at initial 10 s, including some lower temperate times below a boiling point of water. This initial instability is probably caused by a spatial distribution and temporal variation of the temperature in the flow primarily due to convection, since the temperature is observed at a fixed point. After that, the oscillation of the temperature is dumped, and then the temperature gradually increases with time.

On the other hand, the fiber-tip temperature is more stable and tends to converge into a constant value. From these results, it is shown that the fiber-tip temperature is controllable to some extent. Namely, a condition giving too high temperature for the tip to be biled and damaged can easily be avoided. For lower propellant flow case (2.0 mg/s), propellant temperature is relatively stable even from an initial phase, and higher temperatures can be generated.

From these results, for a given laser power case, the reduction of propellant mass flow will result in perfect vaporization and further heating of the propellant. If the mass flow is too small for the laser power, the fiber-tip temperature will exceed a boiling point of quartz and then will be damaged. This phenomenon is already observed in our preliminary experiment. Our future work will include, optimization of laser power, propellant mass flow rate, fiber diameter, nozzle sizes, etc.

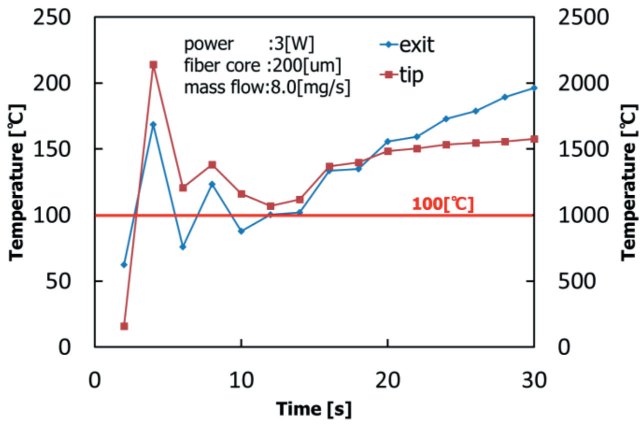


Figure.11 Temporal variation of fiber-tip and nozzle exit temperatures for propellant mass flow rate of 8.0 mg/s.

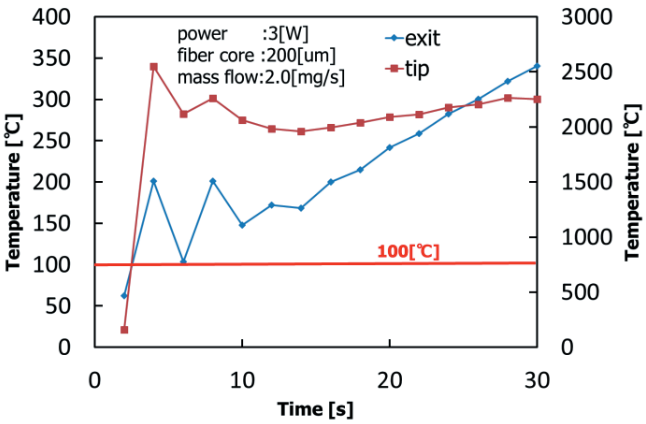


Figure.12 Temporal variation of fiber-tip and nozzle exit temperatures for propellant mass flow rate of 2.0 mg/s.

VI. Conclusion

In this study, characteristics of high-temperature generation mechanism of a laser-diode (LD) coupled fiber-tip heat source for novel laser-thermal microthruster applications were investigated. To investigate physical mechanism of the high-temperature generation of the fiber-tip heat source, a numerical simulation for heat transfer phenomena in a near tip region of a quartz fiber with laser irradiation was conducted using a commercial CFD code. The following results were obtained.

1) It was shown that the high-temperature region was very limited in a thin layer at the tip. Considering the maximum temperature at the tip in both measured and calculated results, exceeding a melting point of quartz, the high-temperature layer must be in a liquid phase at this short period of less than 200 ms.

2) The maximum temperatures decreased with decreasing the absorption rate of the laser at the tip. From the comparison of the temperatures between measured and predicted results, the absorption rate at the tip must be about 40%.

3) It was shown that in smaller fiber cases, much lower laser powers were required for the fiber-tips to be heated over 3,000 K within 200 ms.

4) A simulation including a thruster tube, where water propellant was fed, and a fiber-tip was additionally conducted to investigate heating characteristics and optimum heating conditions. From the results, for a given laser power case, the reduction of propellant mass flow resulted in perfect vaporization and further heating of the propellant. However, if the mass flow was too small for the laser power, the fiber-tip temperature will exceed a boiling point of quartz and then will be damaged.

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