Numerical Simulation of a 1 kW-Class CW Laser Thruster

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Numerical analyses were performed to clarify the power conversion mechanisms in a 1 kW-class continuous-wave laser thruster. Laser plasma heating and radiation emission from the plasma, which dominate in the power conversion balance, were the focus of this analysis. The calculation results show that low laser power absorption and large radiation loss from the plasma result in low thruster performance. The results also show that optimization of the nozzle shape and use of regenerative-cooling can substantially improve thruster performance.

Key Words: Simulation, Advanced Propulsion, Laser Propulsion

Nomenclature

\( D \): diameter
\( e \): energy per volume
\( F, G \): axial and radial numerical flux vectors
\( I_\lambda \): spectral radiation intensity at wavelength \( \lambda \)
\( k \): Boltzmann constant
\( m \): mass
\( M, N \): axial and radial diffusion vectors
\( p \): pressure
\( q \): heat flux
\( q_{\text{laser}} \): absorbed laser power
\( q_{\text{rad}} \): radiation heat flux
\( Q \): conservation vector
\( R \): random number
\( s \): distance
\( S \): source term
\( t \): time
\( T \): temperature
\( u, v \): axial and radial velocities
\( z, r, \theta \): components in a cylindrical coordinate system
\( \rho \): density
\( \kappa \): absorption coefficient or thermal conductivity
\( \tau \): viscosity

Subscripts
\( b \): black body
\( \text{rad} \): radiation
\( z, r, \theta \): components in a cylindrical coordinate system
\( \lambda \): wavelength

1. Introduction

Laser propulsion can be used to propel a spacecraft using the power of laser beams.\(^1,2\) There are two types of laser propulsion, depending on whether the laser is continuous or repetitively pulsed. The former is called continuous-wave (CW) laser propulsion and the latter is called repetitive-pulse (RP) laser propulsion. By employing a large laser power, laser propulsion removes the need for a spacecraft to carry its own power source. Consequently, laser propulsion has the advantages of having higher specific impulse and larger payload fractions when compared to chemical and electrical propulsion systems. Another advantage of laser propulsion over other propulsion systems is that it requires less propellant since it can use the surrounding atmosphere as a propellant in the case of launch applications. This paper investigates CW laser propulsion using air as the propellant.

Figure 1 shows a schematic view of a CW laser thruster. The incident laser beam is focused by a mirror (or lens) to produce a high-temperature plasma. The plasma absorbs the laser power and heats the surrounding propellant gas, which then expands through a convergent-divergent nozzle to produce thrust. In the following, the plasma created and sustained by the laser beam is referred to as laser-sustained plasma (LSP).

Fundamental experiments and numerical simulations have been performed by Keefer et al.,\(^3\) and similar experiments have been conducted by Mazumder et al.\(^4\) using a high-power laser. In Japan, fundamental experiments\(^5\) and numerical simulations\(^6\) have also been performed using a low-power (1–2 kW) laser. These studies revealed that the power conversion efficiency of the CW laser thruster is relatively low and the heat loss associated with it is quite significant. Thus, clarifying the power conversion mechanisms and establishing the reason for the large heat loss of the CW laser thruster are important issues to address in order to improve thruster performance.

The main reason for the large heat loss is that the radiation emission from the LSP is relatively high due to the high temperature of the LSP. This is unavoidable since laser power can only be absorbed at high temperatures. In addition, the fraction of the radiation power loss to the incident laser power has not been accurately measured because direct measurement of radiation power loss is difficult. Therefore, numerical simulations are potentially very helpful for identifying the power loss mechanisms and for investigating
each power loss mechanism in detail.

Numerical investigations of the power conversion of CW laser thrusters have been conducted by several researchers. In these studies, however, radiation transport was treated as diffusion and not analyzed in detail. Therefore, laser plasma heating and radiation emission from the plasma, which dominate the power conversion balance, are the focus of analysis in this paper.

This study attempts to clarify the power conversion mechanisms in a 1 kW-class CW laser thruster and to propose strategies for improving its performance. Numerical analyses were performed that investigated the effects of changing the nozzle shape and using regenerative-cooling in order to improve the thruster performance.

2. Physical Model

2.1. Propellant

Air was used as the propellant in the calculations in order to evaluate the performance of CW laser propulsion for launch applications. The 11-species air model (N₂, O₂, N, O, NO, NO⁺, e⁻, N⁺, O⁺, N₂⁺ and O₂⁺) was employed in the calculations since air plasma contains several radiators such as O₂ molecules, N atoms, N⁺ ions, O⁺ and N₂⁺ molecular ions.

Local thermal equilibrium was assumed because the LSP is sustained in a subsonic region in which the pressure is on the order of 1 to 10 atm and the flow speed is on the order of 0.1 to 10 m/s. The equilibrium constants, internal energies, specific heats and transport properties between 1,000 K and 30,000 K were calculated using polynomial forms. The Sutherland formula was employed for temperatures under 1,000 K. The diffusion of the plasma is assumed to be ambipolar.

2.2. Convection

Compressible two-dimensional axisymmetric Navier-Stokes equations were used for the following reasons: 1) the density of the propellant gas is changed dramatically by the high-temperature plasma, 2) laser heating and radiation emission are strongly dependent on the plasma density, and 3) the LSP is sustained by the balance between the convection and energy transport process. The equations are given as follows:

\[
\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial z} = \frac{\partial M}{\partial x} + \frac{\partial N}{\partial z} + A + S \tag{1}
\]

where

\[
Q = \begin{pmatrix}
\rho \\
\rho u \\
\rho v \\
e
\end{pmatrix}, \quad F = \begin{pmatrix}
\rho u \\
\rho u^2 + p \\
\rho u v \\
(e + p)u
\end{pmatrix}, \quad G = \begin{pmatrix}
\rho v \\
\rho v u \\
\rho v v + p \\
(e + p)v
\end{pmatrix}, \\
M = \begin{pmatrix}
0 \\
\tau_{ee} \\
\tau_{ez} \\
ur_{ez} + v\tau_{ee} - q_e
\end{pmatrix}, \quad N = \begin{pmatrix}
0 \\
\tau_{er} \\
\tau_{rr} \\
ur_{rr} + v\tau_{er} - q_r
\end{pmatrix}, \quad A = \frac{1}{r} \begin{pmatrix}
-\rho v \\
-\rho u + \tau_e \\
-\rho v^2 + \tau_r - \tau_\theta \\
-(e + p)v + ur_{er} + v\tau_{ee} - q_e
\end{pmatrix}, \quad S = \begin{pmatrix}
0 \\
0 \\
0 \\
q_{\text{laser}} - q_{\text{rad}}
\end{pmatrix}.
\]

The r and z axes are defined as shown in Fig. 1.

2.3. Radiation

Radiation transport inside and near the LSP becomes dominant because the temperature of the LSP reaches approximately 20,000 K. Radiation transport obeys the following equation when scattering and dissipation are negligible,

\[
\frac{\partial I}{\partial s} = -\kappa_s (I_e - I_{bs}). \tag{2}
\]

In general, calculating radiation transport is time-consuming. If the plasma is optically thick, however, the calculation can be simplified using the diffusion approximation \(q_{\text{rad}} = k_{\text{rad}} \nabla T\). Most of the numerical investigations employed this approximation. However, the outer region of the LSP is optically thin. Kemp et al. evaluated radiation transport by subdividing the LSP into optically thick and thin regions, and determining the boundary between them.
by trial and error. This means that the diffusion approximation is not self-consistent. In addition, the validity of the method used for determining the diffusion coefficients in the above studies is questionable since it used data for arc columns, which are sustained by a different mechanism.

In this investigation, Eq. (2) is solved directly using the Direct Simulation Monte Carlo (DSMC) method to analyze radiation transport in detail. Because radiation emission and absorption are strongly dependent on wavelength, the emission and absorption coefficients at each wavelength were calculated using the SPRADIAN radiation analysis code.

2.4. Heat transfer to the nozzle wall
Heat transfer from the hot propellant gas to the nozzle wall is estimated using the Bartz formula, however, it accounts for less than 1% of the total power loss since the LSP is surrounded by cold gas flow. For this reason, heat transfer to the nozzle wall was ignored in this study.

2.5. Laser absorption
Laser absorption was evaluated using the ray tracing method. The incident laser beam was divided into many beamlets along the radial direction and each beamlet propagated towards the focal point while obeying Beer’s law. Figure 2 shows the radial intensity distribution of the laser beam measured experimentally. The simulation results obtained in this study were compared with these experimental results.

The intensity of each beamlet was evaluated by integrating the following equation along the laser beam path,

$$\frac{dI}{ds} = -\kappa I, \quad (3)$$

where the absorption coefficient was calculated by considering the inverse Bremsstrahlung reactions given in Table 1, in which the reactions between ions and electrons are taken from Kemp, and the reactions between neutrals and electrons are taken from John.

In general, the laser beam is refracted by the plasma. For a CO2 laser having a wavelength of 10.6 \textmu m, this effect is taken into account by solving the following equation,

$$\Delta \theta = 5.01 \times 10^{-15} \int_{\Delta R} \left( \frac{\partial n_e}{\partial r} \right) ds \ \text{rad} \quad (4)$$

At the beginning of the calculation, a plasma seed having a diameter of about 2 mm and a temperature of approximately 18,000 K was located near the focal position to initiate laser power absorption. The effect of the plasma seed on the computational result was eliminated by varying its size and temperature prior to commencing practical calculations.

Table 1. Inverse Bremsstrahlung reactions.

<table>
<thead>
<tr>
<th>Absorption reaction</th>
<th>( \text{O}^- + h\nu \rightarrow e^- + \text{O}_2^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{O}_2^- + \text{e}^- \rightarrow \text{O}_2 )</td>
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3. Numerical Method

3.1. Computation procedure
In the simulation, the flow solver and ray-tracing modules were called in each iteration while the radiation calculation module was called after every several hundreds of iterations since radiation computation requires much computational time.

The convergence criterion was selected such that all the residuals of the following parameters were within \( 10^{-4} \): 1) the absorbed laser power, 2) the radiation loss from the LSP, and 3) the kinetic energy of the outflow.

3.2. Flow scheme
The scheme used for the flow solver is the 2nd-order TVD scheme for the inviscid flux terms using the Minimod limiter. The LU-ADI time integration method was used with a local time step to accelerate convergence. Second-order central differencing was employed for the viscous and diffusion flux terms.

At the nozzle inlet, the stagnation temperature and mass flow rate were fixed, and the pressure was extrapolated. On the nozzle wall, a non-slip, adiabatic and catalytic wall condition was applied. All variables were extrapolated at the nozzle exit.

3.3. Radiation calculation scheme
The radiation energy transport was evaluated by the DSMC method where the radiation emission and absorption processes were simulated on the basis of many sample photons. The initial positions and velocities of the sample photons were assigned randomly and their energies were determined from the emission coefficient and the volume of the computational cell. The sample photons propagated until they were stopped by absorption, which is calculated using the following equation,

$$\int_{s} \kappa_s ds = -\log(1 - R). \quad (5)$$

The emission and absorption coefficients were calculated...
by SPRADIAN using the temperature and density profiles obtained by the flow solver.

Radiation calculations were conducted inside the cylinder, shown in Fig. 3 that surrounds the region having temperatures higher than 5,000 K, because emission and absorption at temperatures below 5,000 K are negligible. The cylinder was divided into 128 × 64 computational cells and each computational cell had between 64 and 128 sample photons at the beginning of the calculation. The wavelength of the radiation was divided into about 5,000 bands, ranging from ultraviolet to near-infrared (500–15,000 Å).

Sample photons that reached the nozzle inlet or outlet were considered to be radiation power loss. The boundary condition on the nozzle wall was assumed to be black, however, this condition could be easily changed to analyze different nozzle wall conditions.

4. Results and Discussion

4.1. Effect of focus position

4.1.1. Calculation conditions

The effect of focus position on the LSP position, temperature and energy conversion were investigated using a convergent-divergent nozzle that had a 1-mm diameter throat and energy conversion were investigated using a convergent section. The focal positions were selected from the range 2.73 mm to 250 mm. The f-numbers of the optics were selected to be 2.5 for nitrogen and 2.7 for air as propellants.

Sample photons that reached the nozzle inlet or outlet were considered to be radiation power loss. The boundary condition on the nozzle wall was assumed to be black, however, this condition could be easily changed to analyze different nozzle wall conditions.

4.1.2. Temperature and ionization contours

The temperature and ionization contours when nitrogen was used as the propellant are shown in Fig. 4, where the ionization fractions are defined as \( \alpha = \frac{n_{O^+} + n_{N_2^+} + n_{O_2^+}}{n_{N_2} + n_{O_2} + n_N + n_O + n_{NO} + n_{NO^+} + n_{N_2^+} + n_{O_2^+} + n_{N_3^+}} \). In the figure, the propellant flows from left to right and the circles indicate the focal positions. The figure shows that the maximum temperatures of the LSP are about 19,000 K when the focal points were located upstream of the throat. In contrast, the maximum temperature exceeded 20,000 K when the focal point was located downstream from the throat for the case 2.73 mm. The same trends were seen in the ionization fractions that have a maximum between 0.76 and 0.88.

As Fig. 4 shows, the LSPs are sustained upstream of the focal point with a tail towards the downstream direction and the distances between the LSP and the focal point are almost constant. In experiments, it has been reported that axial 1-mm oscillations of the LSP were seen having a frequency between 400 Hz and 500 Hz, however, no oscillations were found in the steady-state solutions.

A comparison of the calculated and experimental LSP positions is shown in Fig. 5. When f7.4 optics were used, the LSPs were sustained approximately 12 mm upstream of the focal point, which agreed well with experimental results. When f7.4 optics were used, the LSPs moved about 2–2.5 mm upstream. The reason for this is that higher laser beam intensities are produced when using f7.4 optics than when using f8 optics.

Calculation results when using air as the propellant are shown in Fig. 6. The temperatures of the LSP are 1,000–2,000 K lower than those when nitrogen is used as the propellant, and the LSPs are located further downstream (see Fig. 5.) This decrease in temperature is caused by the decrease in heating power that is required to ionize oxygen, since oxygen has a lower ionization temperature than nitrogen. The movement of the LSP downstream is explained by the compensation of the decreased heat conduction by pushing the LSP to a higher laser intensity region. It should be noted that the LSP has two hot regions, one located near its top and the other near the focal point for the case when the focal point is located at −6.27 mm, due to the existence of oxygen ions.

4.1.3. Effect of incident laser beam refraction

The effect of incident laser beam refraction was evaluated because it may reduce laser absorption. The laser beam path and the LSP at the focal point of −3.27 mm when nitrogen was used as the propellant are shown in Fig. 7. Here, the laser beam was divided into 16 beamlets to better visualize the refraction.

Figure 7 shows that the laser beam is slightly refracted by the LSP and its focal point moves 0.3 mm upstream. The effect is stronger in the outer region of the LSP because the gradient of plasma density perpendicular to the laser beam path is steeper in the outer region. However, the effect of laser beam refraction is negligible in a 1 kW-class CW laser thruster.

4.1.4. Conversion of incident laser power

The conversion of the incident laser power was calculated by varying the focal point. The results using nitrogen and air as propellants are shown in Figs. 8 and 9, respectively. In
both figures, the transmitted laser power was evaluated by summing the residual power of the beamlets in ray-tracing, and the radiation power loss was evaluated by considering the self-absorption of the plasma. The kinetic energy of the outflow refers to the flow energy at the nozzle exit and the remaining energies are regarded as frozen flow losses.

For comparison, the experimental results of Toyoda\textsuperscript{13} using nitrogen as the propellant are also shown in Fig. 8, where the thermal losses include both the radiation and heat transfer losses. Optical loss was not considered in these calculations.

In Fig. 8, the calculated kinetic energies of the outflow are approximately 30%, which agrees reasonably well with the experimentally measured value. In addition, there is satisfactory agreement between the calculated and experimental transmitted laser power and thermal heat loss.

Figure 9 shows that the kinetic energies of the outflow are about 30% when using air as the propellant. This is almost the same as when using nitrogen as the propellant. Although laser absorption increased due to the existence of oxygen ions, this effect was cancelled by the increase in frozen flow losses.

The following results can be deduced from Figs. 8 and 9:

- The transmitted laser power loss, radiation power loss and frozen flow losses comprise most of the power loss of the CW laser thruster.
- Laser power absorption is increased when the focal point is moved near the throat or further upstream from the throat.
- The kinetic energies of the outflow depend very little on the position of the focal point because the increased laser power absorption is cancelled by the increased frozen flow losses that occur when the focal point is
near the throat. The same result is seen in the upstream focal point case where increased laser power absorption is cancelled by the increased radiation power loss.

Figure 9 shows that laser power absorption is enhanced as the focal point is moved from $-3.27$ mm to $-4.27$ mm. This is explained by the fact that the LSP has two peak regions of high laser power absorption when the focal point is moved.

Fig. 6. Temperature and ionization fraction contours using air as the propellant.

Fig. 7. Effect of laser beam refraction.

Fig. 8. Effect of focal position on power conversion using nitrogen as the propellant.

Fig. 9. Effect of focal point on power conversion using air as the propellant.

near the throat. The same result is seen in the upstream focal point case where increased laser power absorption is cancelled by the increased radiation power loss. Figure 9 shows that laser power absorption is enhanced as the focal point is moved from $-3.27$ mm to $-4.27$ mm. This is explained by the fact that the LSP has two peak regions of high laser power absorption when the focal point is moved.
is located further downstream than \(-4.27\) mm, as is seen in the case of the \(-6.27\) mm focal point in Fig. 6. The second peak region is produced because air plasma has oxygen ions that can be sustained at lower temperatures than nitrogen ions.

### 4.1.5. Relationship between radiation power loss, temperature and LSP position

In this section, we discuss the relationship between radiation power loss, temperature and LSP position based upon the calculation results presented in previous sections. Because the intensity of the radiation emission from a black body is proportional to \(T^4\) and the volume of the LSP is proportional to \(D^3\), the following relations are obtained if the radiation is in equilibrium,

\[
q_{\text{rad}} \propto T^4 D^3 \quad (6)
\]

\[
D \propto (q_{\text{rad}}/T^4)^{1/3}. \quad (7)
\]

The diameter of the LSP is assumed to be proportional to the distance between the LSP and the focal point \(\Delta z\) so that

\[
\Delta z \propto D \propto (q_{\text{rad}}/T^4)^{1/3}. \quad (8)
\]

From the above relations, the following simple relation is deduced

\[
(q_{\text{rad}}/T^4)^{1/3}/\Delta z = \text{const.} \quad (9)
\]

To confirm the validity of Eq. (9), the values of \((q_{\text{rad}}/T^4)^{1/3}/\Delta z\) are plotted as a function of the focal point in Fig. 10. As Fig. 10 shows, the curves of \((q_{\text{rad}}/T^4)^{1/3}/\Delta z\) are almost flat as a function of the focal point, both for the nitrogen and air calculation results. Therefore, the relationship between radiation power loss, temperature and LSP position can be described using Eq. (9).

### 4.2. Effect of nozzle geometry

Experiments by Toyoda et al.\(^5\) showed that high conversion efficiencies can be obtained using a nozzle that has a small chamber in the upstream side of the throat of a convergent-divergent nozzle (i.e., referred to as a sub-chamber nozzle in the following). Calculations were performed to clarify the reason for this.

The calculation conditions are the same as previously described except that the nozzle geometry has a 6-mm-diameter cylindrical chamber in the upstream side of the convergent-divergent nozzle as shown in Fig. 11. The cylindrical chamber has a 3-mm-diameter throat, with the converging section having a half-cone angle of 25° and the diverging section having a half-cone angle of 45°. The propellant is air and the focal points were located at \(-3.27\) mm and \(-6.27\) mm.

Figure 11 shows the temperature contours using the normal and sub-chamber nozzles with the focal point located at \(-3.27\) mm. The LSP produced using the sub-chamber nozzle is sustained further downstream compared to that produced using the normal nozzle. Because the flow speed in front of the LSP is approximately 0.3 m/s for the normal nozzle and increases to about 3 m/s for the sub-chamber nozzle, the LSP moves downstream to increase its temperature and heat conduction to compensate for the high flow speed. The maximum temperature of the LSP is approximately 24,000 K, which is about 6,400 K higher than that using the normal nozzle because the laser beam intensity in the LSP is higher when using the sub-chamber nozzle.

The conversion of the incident laser power is shown in Fig. 12. The laser power absorption for the sub-chamber nozzle is increased compared with that for the normal nozzle. In contrast, the radiation power loss is the same as that for the normal nozzle even though the temperatures of the LSP are higher. This is explained by the small volume of the LSP produced in the sub-chamber nozzle. However, the frozen flow losses are higher in the sub-chamber nozzle because the temperatures of the LSP are higher and they are sustained closer to the nozzle exit. Therefore, although laser power absorption is higher in the sub-chamber nozzle, its effect is cancelled by the increased frozen flow losses, and as a result, the kinetic energy of the outflow does not increase.
Figure 13 shows that the temperature contours for the case of when the focal point is $\frac{C_0}{27}$ mm. The LSP using the sub-chamber nozzle is further downstream than the LSP for the normal nozzle, which is same as that seen for the case of when the focal point is located at $\frac{C_0}{3}$ mm. The maximum temperature is approximately 16,900 K using the normal nozzle and becomes about 22,000 K using the sub-chamber nozzle.

Figure 14 shows the conversion of the incident laser power for the case of when the focal point is at $\frac{C_0}{6}$ mm. The laser power absorption using the sub-chamber nozzle is almost same as that using the normal nozzle even though the LSP for the normal nozzle has two peak regions of high laser power absorption. Therefore, on the basis of the results for when the focal points were located at $\frac{C_0}{3}$ mm and $\frac{C_0}{6}$ mm, we found that using the sub-chamber nozzle can increase laser power absorption. Figure 14 shows that the radiation power loss for the sub-chamber nozzle is less than that for using the normal nozzle even though the maximum temperature of the LSP is about 5,000 K higher. The reason for this is the same as that for when the focal point was located at $\frac{C_0}{3}$ mm. The frozen flow losses for the sub-chamber nozzle are higher than those for the normal nozzle. However, the kinetic energy of the outflow is higher because of the lower radiation power loss.

From these results, we find that laser power absorption can be increased by using a sub-chamber nozzle, however, the kinetic energy of the outflow is not increased.

4.3. Effect of regenerative cooling

The above results revealed that laser power absorption can be increased by changing the focal point and the flow section profile; however, the increase will be cancelled by the increased radiation power loss and frozen flow losses. Therefore, the best strategy for improving the power conversion of the CW laser thruster is to recover the radiation power loss from the LSP, because it is quite difficult to reduce frozen flow losses. The radiation power loss can be recovered using regenerative cooling.

To evaluate the improvement in power conversion by regenerative cooling, calculations were performed using normal and sub-chamber nozzles when the focal point was located at $\frac{C_0}{6}$ mm. In the calculations, radiation that escapes from the inlet or outlet of the nozzle was assumed to be non-recoverable, while radiation that impinges on the nozzle wall was assumed to be fully recoverable. For simplicity, regenerative cooling was modeled by increasing the inflow stagnation temperature by $\Delta T = P_{\text{loss,rad}}/mC_p$, where $P_{\text{loss,rad}}$ is the radiation power loss recovered.

Figure 15 shows the conversion of the incident laser power for four cases, namely: 1) a normal nozzle without regenerative cooling, 2) a normal nozzle with regenerative cooling, 3) a sub-chamber nozzle without regenerative cooling and 4) a sub-chamber nozzle with regenerative cooling. This figure shows that the use of regenerative cooling increased the kinetic energies of the outflow by about 15% for both normal and sub-chamber nozzles.
As seen in Fig. 12, the laser power absorption using the sub-chamber nozzle tends to be larger than that of the normal nozzle. Thus, the best strategy for increasing the kinetic energy of the outflow is to increase laser power absorption using the sub-chamber nozzle and to recover the radiation power loss using regenerative cooling.

5. Summary

Numerical analyses were performed to clarify the power conversion mechanisms in a 1 kW-class continuous-wave (CW) laser thruster. Laser absorption, convection, thermal conduction and radiation were accounted for in the calculations. Laser plasma heating and radiation emission from the plasma, which dominate in the power conversion balance, were the focus in this analysis. The calculation results showed good agreement with experimental results. The results are summarized as follows.

- The transmitted laser power loss, radiation power loss and frozen flow losses comprise most of the power losses of a 1 kW-class CW laser thruster.
- Laser power absorption can be increased by varying the focal point and the nozzle geometry. However, the effecting increase in laser power absorption is nullified by the increased radiation power loss and frozen flow losses.
- Radiation power loss can be successfully recovered using regenerative cooling.
- The best strategy for increasing the kinetic energy of the outflow is to increase the laser power absorption by optimizing the nozzle geometry and recovering the radiation power loss using regenerative cooling.

References