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Improved Efficiency in Rocket Engine Performance via a Laser Kinetic Energy Transfer Chamber Allowing Single Vehicle Orbital Flights

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Abstract

Although the proposal of applying lasers to the exhaust plasma of rockets to increase thrust and fuel efficiency is not original, directions in rocket propulsion which incorporate lasers that are simplistic, inexpensive, practical, and efficient are over looked. Conversely, the consideration of rocket propulsion methods using lasers has a focus on extravagant, complex, and expensive directions that are difficult to develop in both cost and available technology. Hence, a review of two current popular published proposals and developments in rocket propulsion systems that use lasers are given. Thereafter, the theoretical laser kinetic energy transfer (LKET) concept is introduced and described in mathematical detail. The LKET propulsion concept and system is a simple and inexpensive method where the exhaust plasma, after leaving the combustion chamber of a conventional rocket engine, is subjected to the bombardment of photons that compose a laser beam within a specialized chamber built into the rocket engine referred to as an LKET chamber. Therefore, within the LKET chamber, the lasers transfer additional kinetic energy to the molecules of the exhaust plasma resultantly increasing the efficiency and thrust value of the engine specifically in reference to “delta v” or change in velocity which corresponds to a value of specific impulse. The notion of the LKET rocket propulsion concept that gives it an advantage over other more complex laser propulsion concept proposals is the idea of replacing the weight of rocket boosters for orbital flights with the weight of a laser power source (e.g. battery, fuel cell, reactor, etc.). This will prospectively allow the design of orbital (as opposed to sub-orbital) vehicles that can achieve lift-off to

orbit and to re-entry without booster rockets. Essentially, a single vehicle will have the fuel efficiency and power to carry out an entire orbital flight. Such a vehicle would be reusable, economical, and valuable to the private space-flight sector and more.

Keywords: Rocket engine; laser; exhaust plasma; space propulsion; fuel efficiency; specific impulse

Introduction

The idea of using lasers to transfer energy to a rocket's exhaust plasma to increase its thrust and fuel efficiency is not an original one. A Russian team of scientist led by physicist/engineer Yuri Resunkov of the *institute of optoelectronic instrument engineering* developed a method of using lasers to improve the efficiency of conventional rockets [1]. As proposed in their 2014 paper titled "supersonic laser propulsion", Rezunkoz and Schmidt introduced a method of using lasers to heat and thus energize the exhaust plasma of conventional rockets which will increase their efficiency and thrust level [5-7]. In the proposal by Rezunkoz and Schmidt, the laser source would be kept in a remote location to reduce the weight of fuel and equipment used to generate the laser beam [5]. Moreover, laser ablation (i.e. the irradiation of the exhaust plasma via laser) would prevent the reduction of thrust due to shock waves produced by the supersonic flow of the exhaust plasma (which causes a narrow flow stream) by forcing the gases to expand to the walls of the nozzle [5-7]. We must note here that this (the prevention of thrust reduction due to shockwaves within the exhaust plasma) characteristic will be applied to the assertion of this paper. Additionally, the assertion of this paper will be shown to be a slight nuance from this proposal.

Another significant proposal of a rocket engine incorporating lasers is the idea of the laser irradiation of fuel pellets which cause a fusion reaction where the resultant heat and energy is transferred to a gas generating a flow of plasma which was published in the *plasma and fusion research Journal of the Japan society of plasma science and nuclear fusion research* [4]. More specifically, the fuel pellet will be surrounded by a moderator or chemical propellant where the laser ignited fusion reaction of the fuel pellet will collide or interact with the moderator producing an enhanced or more energetic plasma flow [4]. Thus, the enhanced or more energetic plasma flow is directed toward a magnetic coil which compresses the plasma allowing more power and efficiency for a hypothetical vehicle incorporating the system [4].

As conveyed by the aforementioned second proposal in laser-rocket propulsion, the field of applied mechanics and engineering is focused on more elaborate and complex directions and approaches to advancing rocket and space propulsion. A pivotal aspect in Elon Musk's SpaceX's success is the consideration of more practical and less expensive approaches to accomplishing its goals in launching and operating vehicles in orbit and beyond whereas top organizations like NASA overlook simpler directions in favor of more popular or complex mainstream directions. For instance, SpaceX uses the C++ programming language, a common syntax, to operate software that guides the telemetry of its spacecraft as opposed to a more expensive specialized syntax [3]. This approach has allowed spaceX to pay less expensive engineer salaries, as opposed to paying more expensive salaries for programmers with specialized skill and experience in less ubiquitous specialized syntax commonly used in space systems. Hence, this paper's objective is to introduce a more practical, simplistic, and price efficient propulsion concept in laser based propulsion and design. Moreover, the goal of this paper is to redirect the attention of the engineering community to the efficiency of laser propulsion and to inspire further research, development, and application to space travel. Thence, we introduce the concept and design of the laser kinetic energy transfer chamber or LKET chamber. The LKET chamber is simply an additional chamber where exhaust plasma egressing from a conventional combustion chamber is channeled into and bombarded by photons emitted by high powered laser emitters. Therefore, heat and thus the kinetic energy of the photons composing the laser beam is directly transferred to the exhaust gases, resultantly, adding energy to the rocket improving the thrust and velocity values of the vehicle. As with previous proposals of laser propulsion to improve the efficiency of a rocket, a rocket incorporating an LKET chamber will produce more thrust with less fuel or propellant. Furthermore, as previously communicated, the LKET chamber's irradiation of the exhaust plasma from the combustion chamber will expand the exhaust plasma forcing the plasma to the edges of the exhaust nozzle preventing thrust loss due to shock waves within the accelerated propellant causing a narrow flow stream [5-7].

The pertinent question is then "how is the proposal of and design of an LKET chamber on conventional rockets novel from previous proposals?". The first advantage over previous proposals and designs is that the LKET propulsion concept is simplistic and will be more price efficient to develop, construct, and test as compared to other designs and concepts. Additionally, the goal of the LKET chamber will be more conducive to private and industrial space travel. As opposed to external laser emission sources, as previously proposed [4], the LKET chamber employs a hybrid design where the laser power source (e.g. battery, fuel cell, reactor, etc.) and the LKET chamber are built in with the combustion chamber and other components of the rocket engine. Furthermore, as opposed to the laser propulsion method proposed by Rezunkoz and Schmidt [7], the LKET chamber and its power source are housed by the vehicle and not in a remote location. Thus, the weight of rocket boosters will be replaced by the weight of the laser power source and the LKET chamber which are projected to be comparatively lighter than the weight of a booster or booster rockets.

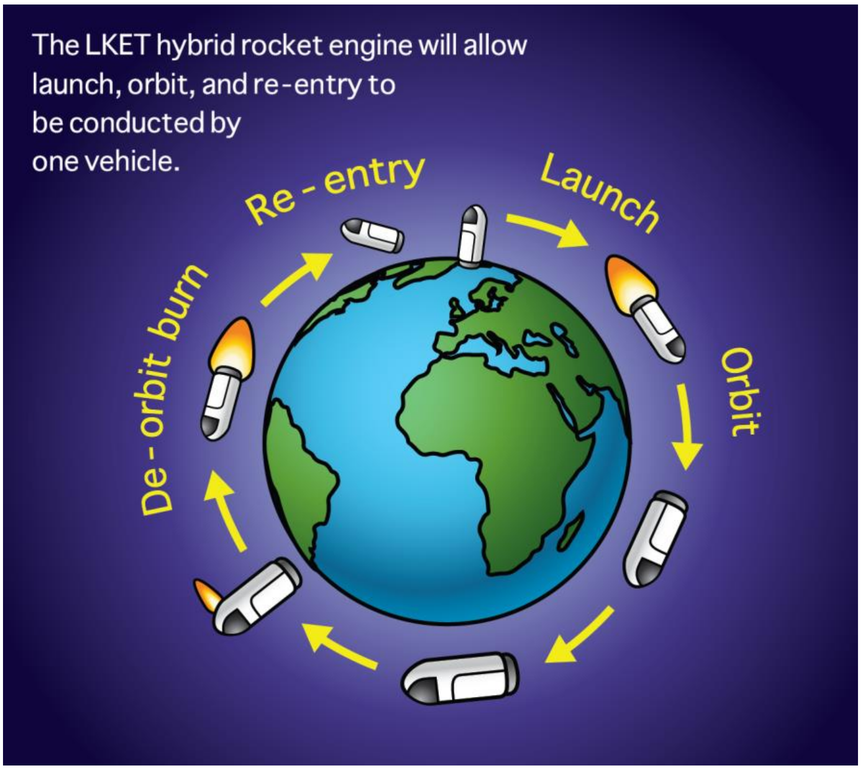

Diagram 1

Therefore, if the LKET chamber can produce a sufficient level of fuel efficiency for a given value of "delta v" (Δv) and specific impulse, then it will permit launch to orbit to re-entry to be achieved with a single spacecraft or vehicle as depicted in diagram 1 above. Currently, most launch vehicles designed by private companies for private space-flight like Virgin Galactic's space-ship two[8] and Blue Origin's New Shepard and New Glenn vehicles [2] are limited to suborbital flights unless they incorporate booster rockets (hence 2 or more stages) to propel them into orbit due to power and fuel requirements to attain orbital velocities and altitudes. The prospective efficiency of an LKET rocket propulsion concept will allow this to be achieved with a single vehicle. Hence, routine flights into orbit and back will be a matter of refueling (and re-charging) a single spacecraft similarly to commercial airliners.

The mathematical description of LKET Chamber

We begin the formulations of mathematical expressions and equations describing the theoretical LKET propulsion concept with the rocket velocity equation as expressed by Young & Freedman such that [9]:

$$v - v_0 = v_{ex} \ln\left(\frac{m_0}{m}\right) \equiv \int_{m_0}^{m} v_{ex} \frac{dm'}{m'} \tag{1}$$

Where velocity v_{ex} denotes the constant exhaust plasma velocity, v denotes the vehicles final velocity, v_0 denotes the vehicle's initial velocity, m_0 denotes the vehicle's mass prior to loss of exhaust mass, and m denotes the exhaust mass lost by the vehicle. Figure 1 below, depicts a hybrid rocket engine that features a laser kinetic energy transfer chamber or LKET chamber.

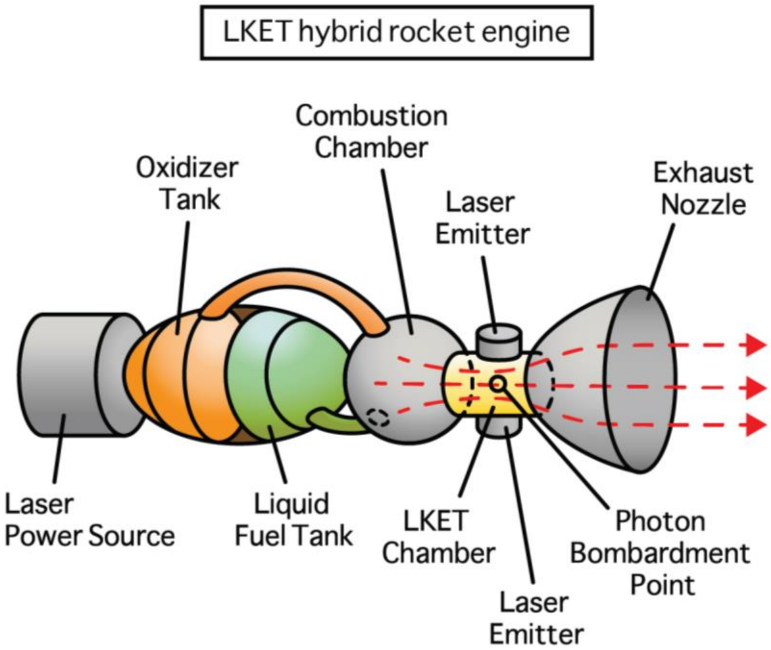

Figure 1

As shown in figure 1, the oxidizer tank and the liquid fuel tank feed into the combustion chamber where ignition and combustion occurs. The accelerated exhaust plasma egresses to the LKET chamber equipped with laser emitters which are powered by the laser power source shown to the far left of figure 1. The photon bombardment point depicted in Figure 1 is the point where the photons of the emitted radiation transfer their energy to the molecules of the exhaust plasma. As conveyed in Figure 1, the energetic exhaust exits the system via the exhaust nozzle. As stated in the introduction, the additional kinetic energy induced by the lasers within the LKET chamber cause the exhaust gases to expand to the edges or walls of the exhaust nozzle allowing more thrust efficiency in the vacuum of space as opposed to a narrow flow stream caused by supersonic fluid velocities[4].

Thus in continuing the mathematical description of the LKET propulsion concept, the exhaust gases have a constant velocity denoted v_{ex0} as they exit the combustion chamber and enter the LKET chamber. Energy E_L is the energy that the laser imparts on the exhaust gases as they pass through the LKET chamber. The process to which the lasers of the LKET chamber transfer their energy (energy E_L) to the passing exhaust plasma will now be described mathematically.

In order to effectively describe the transfer of energy from the lasers to the exhaust plasma egressing from the combustion chamber, one must begin with a description of energy on the molecular level. The formulations begin with the total translational kinetic energy denoted K_{tr} which pertains to the total molecular energy of the exhaust gases passing through the LKET chamber shown below [9].

$$K_{tr} = \frac{(Nm_a)(v_{av})^2}{2} \equiv \frac{3nR}{2N} \tag{2}$$

Where N denotes the number of molecules composing the exhaust plasma, R denotes the ideal gas constant, n denotes the number moles, m_a is the mass of each molecule, and v_{av} is the average velocity of molecules of the exhaust gases [9].The number of molecules N has a value such that [9]:

$$N = nN_a \tag{3}$$

Where N_a is Avogadro's number, the total translational kinetic energy denoted K_{tr} of Eq.2 is set equal to energy E_L (to be defined in more detail in the next section) emitted by the lasers such that:

$$E_L = K_{tr} \tag{4}$$

This can alternatively be expressed such that:

$$E_L = \frac{(Nm_a)(v_{av})^2}{2} \tag{5}$$

This implies that the average velocity of molecules of the exhaust gases v_{av} after contact with the photons emitted by the laser beams within the LKET chamber assumes a value such that:

$$v_{av} = \sqrt{\frac{2E_L}{Nm_a}} \tag{6}$$

We now introduce pressure P where pressure P is equal to the energy density as shown by the equation below [9]:

$$P = \frac{E}{V} \tag{7}$$

Where E is energy and V is volume, the dynamic pressure in the LKET chamber can be expressed within energy density such that:

$$P = \frac{K_{tr}}{V_{LC}} = \frac{E_L}{V_{LC}} \tag{8}$$

Where V_{LC} denotes the volume of the LKET chamber, pressure P can alternatively be expressed such that:

$$P = \frac{\rho_{LC}(v_{av})^2}{2} \tag{9}$$

Where the value of density ρ_{LC} in Eq.8 above can be expressed such that:

$$\rho_{LC} = \frac{Nm_a}{V_{LC}} \tag{10}$$

Hence, Eq.8 implies the equivalence of:

$$\frac{\rho_{LC}(v_{av})^2}{2} = \frac{E_L}{V_{LC}} \tag{11}$$

Dynamic pressure P_0 is the pressure value of the exhaust after it leaves the combustion chamber to enter the LKET chamber. Dynamic pressure P_0 is the pressure value at exhaust velocity v_{ex0} where exhaust velocity v_{ex0} is the *initial* constant exhaust velocity after leaving the combustion chamber. At density ρ_{LC}, dynamic pressure P_0can be expressed such that:

$$P_0 = \frac{\rho_{LC}(v_{ex0})^2}{2} \tag{12}$$

Dynamic pressure P_{Total} is the sum of initial pressure P_0 of Eq.12 and pressure P of Eq.9 corresponding to the LKET chamber, hence, pressure P_{Total} is the total pressure resulting from both the combustion chamber and the LKET chamber. Dynamic pressure P_{Total} is expressed as the sum of:

$$P_{Total} = P_0 + P \tag{13}$$

Substituting the values of pressure P_0 and P into Eq.13 gives:

$$P_{Total} = \frac{\rho_{LC}(v_{ex0})^2}{2} + \frac{\rho_{LC}(v_{av})^2}{2} \tag{14}$$

Inserting the value of the average velocity of molecules of the exhaust gases $v_{av}$of Eq.6 (which is the average molecular velocity as a result of laser photon bombardment) into Eq.14 above gives:

$$P_{Total} = \frac{\rho_{LC}(v_{ex0})^2}{2} + \frac{\rho_{LC}E_L}{Nm_a} \tag{15}$$

Thus, Eq.15 can alternatively be expressed such that (where $P_{Total} = \rho_{LC}(v_{total})^2/2$):

$$\frac{\rho_{LC}(v_{total})^2}{2} = \frac{\rho_{LC}(v_{ex0})^2}{2} + \frac{\rho_{LC}E_L}{Nm_a} \tag{16}$$

Therefore, solving Eq.16 for the value of total velocity v_{total} such that:

$$v_{total} = \sqrt{(v_{ex0})^2 + \frac{2E_L}{Nm_a}} \tag{17}$$

Velocity v_{total} is the final exhaust velocity after the exhaust gases leave both the combustion chamber and the LKET chamber and after exits via the exhaust nozzle. After the exhaust gases pass through both the combustion chamber and the LKET chamber, the total exhaust velocity v_{ex}(which is a constant) of Eq.1 can be set equal to exhaust plasma velocity v_{total} as shown below.

$$v_{ex} = v_{total} \tag{18}$$

Thus substituting Eq.18 into Eq.1 gives:

$$v - v_0 = (v_{total})\ln\left(\frac{m_0}{m}\right) \tag{19}$$

This can alternatively be expressed such that:

$$v - v_0 = \left[(v_{ex0})^2 + \frac{2E_L}{Nm_a}\right]^{1\backslash 2} \ln\left(\frac{m_0}{m}\right) \tag{20}$$

Observe that velocity v_{total} which is the resultant velocity after the exhaust gases pass through the combustion chamber and the LKET chamber is greater than exhaust velocity v_{ex0} which pertain to a conventional rocket engine possessing a <u>single</u> combustion chamber (excluding an LKET chamber) as shown below.

$$v_{ex0} < v_{total} \tag{21}$$

Or alternatively,

$$v_{ex0} < \left[(v_{ex0})^2 + \frac{2E_L}{Nm_a}\right]^{1\backslash 2} \tag{22}$$

Where m_0 is the initial mass value of the vehicle (e.g. m_0= vehicle mass + propellant mass) and m is the final vehicle mass after propellant mass is lost as exhaust, $\Delta m_{propellant}$ is the rate of propellant mass loss per time interval Δt which can be expressed such that:

$$\Delta m_{propellant} = \frac{m_0 - m}{\Delta t} \tag{23}$$

Both hypothetical vehicles (to be compared) are assumed to have an equal initial mass m_0 , one having the mass of a booster rocket and the other the mass of an LKET chamber power source. The change in velocity will be denoted Δv (i.e. $\Delta v = v - v_0$). If exhaust velocity v_{ex0} is set equal to exhaust velocity v_{ex} ($v_{ex} = v_{ex0}$) of Eq. 1 for <u>a conventional rocket</u> (without an LKET chamber), then the vehicle change in velocity Δv would be expressed such that:

$$\Delta v = v_{ex0} \ln\left(\frac{m_0}{m}\right) \tag{24}$$

Then a rocket possessing an LKET chamber at an initial exhaust velocity v_{ex0} would have a velocity v_{ex} equal to velocity v_{total} ($v_{ex} = v_{total}$), hence, an engine featuring an LKET chamber will have a change in velocity denoted Δv_L ($\Delta v_L = v - v_0$) such that:

$$\Delta v_L = \left[(v_{ex0})^2 + \frac{2E_L}{Nm_a}\right]^{1\backslash 2} \ln\left(\frac{m_0}{m}\right) \tag{25}$$

The change in velocity Δv_Lwould have a greater change in velocity compared to Δv for a rate $\Delta m_{propellant}$ of propellant mass loss per time interval Δt as shown by the inequality below.

$$\Delta v_L \quad > \quad \Delta v \tag{26}$$

This can alternatively be expressed such that:

$$\left[(v_{ex0})^2 + \frac{2E_L}{Nm_a}\right]^{1\backslash 2} \ln\left(\frac{m_0}{m}\right) \quad > \quad v_{ex0} \ln\left(\frac{m_0}{m}\right) \tag{27}$$

Conclusively, for a propellant lost rate per time Δt of $\Delta m_{propellant}$ and an initial combustion chamber exhaust velocity v_{ex0} that is the <u>same for both hypothetical vehicles</u> (i.e. with and without LKET chambers); the rocket engine incorporating the use of an LKET chamber will produce a greater change in velocity Δv_L than the Δv of a conventional engine.

At this juncture, the efficiency of the LKET rocket engine will be expressed in terms of specific impulse. Specific impulse is the a ratio of thrust to weight [6]; the goal of the LKET propulsion concept is to substitute the weight of booster rockets with a power source thus allowing launch-orbit-re-entry to be performed by a single vehicle. Thus, the specific impulse or thrust to weight ratio of a conventional vehicle is compared to one incorporating the LKET propulsion system. The specific impulse equation is given such that [6]:

$$I_{sp} = \frac{F_{th}}{F_g} = \frac{a_v m'}{g m'} \equiv \frac{a_v{}'}{g} \tag{28}$$

Where I_{sp} denotes specific impulse, F_{th} is the force of thrust, F_g is the weight of the vehicle, m' is the arbitrary mass of the vehicle, g is the acceleration due to gravity, and a_v is the vehicle's acceleration. The vehicle acceleration is of the form [9]:

$$a_v = \frac{\Delta v}{\Delta t} \equiv \frac{v - v_0}{\Delta t} \tag{29}$$

The acceleration pertaining to the vehicle utilizing a conventional rocket engine will be denoted a ($a \rightarrow a_v$) as shown below.

$$a = \frac{\Delta v}{\Delta t} = \frac{v_{ex0} \ln\left(\frac{m_0}{m}\right)}{\Delta t} \tag{30}$$

The “delta v”or Δv for the conventional vehicle is that of Eq.24, thus, substituting Eq.24 into Eq. 30 above gives the latter expression in Eq. 30. The “delta v” for the vehicle incorporating the rocket energy utilizing the LKET chamber has an acceleration of:

$$a_L = \frac{\Delta v_L}{\Delta t} = \frac{\left[(v_{ex0})^2 + \frac{2E_L}{Nm_a}\right]^{1\backslash 2} \ln\left(\frac{m_0}{m}\right)}{\Delta t} \tag{31}$$

Therefore, the specific impulse for I_{sp} for a vehicle incorporating a conventional rocket engine and the specific impulse I_{spL} for a vehicle with an engine utilizing an LKET chamber are expressed such that:

$$I_{sp} = \frac{a}{g} = \frac{v_{ex0} \ln\left(\frac{m_0}{m}\right)}{g\Delta t} \tag{32}$$

$$I_{spL} = \frac{a_L}{g} = \frac{\left[(v_{ex0})^2 + \frac{2E_L}{Nm_a}\right]^{1\backslash 2} \ln\left(\frac{m_0}{m}\right)}{g\Delta t} \tag{33}$$

The two values of specific impulse adhere to the inequality of:

$$I_{spL} \quad > \quad I_{sp} \tag{34}$$

This can be alternatively expressed such that:

$$\frac{\left[(v_{ex0})^2 + \frac{2E_L}{Nm_a}\right]^{1\backslash 2} \ln\left(\frac{m_0}{m}\right)}{g\Delta t} \quad > \quad \frac{v_{ex0} \ln\left(\frac{m_0}{m}\right)}{g\Delta t} \tag{35}$$

Conclusively, again assuming that the propellant lost rate per time Δt of $\Delta m_{propellant}$ and the initial exhaust velocity v_{ex0} from the combustion chamber is same for both hypothetical rockets (i.e. with and without LKET chambers); the rocket engine incorporating the use of an LKET chamber will produce a greater value of specific impulse I_{spL} as compared to the conventional rocket engine corresponding to the specific impulse of I_{sp} . Hence, the rocket engine featuring the LKET chamber is comparatively more fuel efficient for mass loss value m.

The definition of the laser kinetic energy E_L transferred by the LKET chamber

This paper’s objective is to introduce and define all aspects of the LKET rocket propulsion concept, therefore, in this section; the energy value E_L which is the energy of the lasers which is emitted and transferred to the kinetic energy of the exhaust gases (or plasma) of the combustion chamber is defined mathematically.

We begin with the function which describes the gas used to generate a laser emission displayed below [9].

$$f(E_i) = Ae^{-E_i/kT} \tag{36}$$

Where E_i is the energy level of the gas within the emitting device, k is Boltzmann's constant, and T denotes absolute temperature[9]. Figure 2 below is an illustration which gives an <u>example</u> of the fluctuations in energy levels and components of a functioning laser emitter [9].

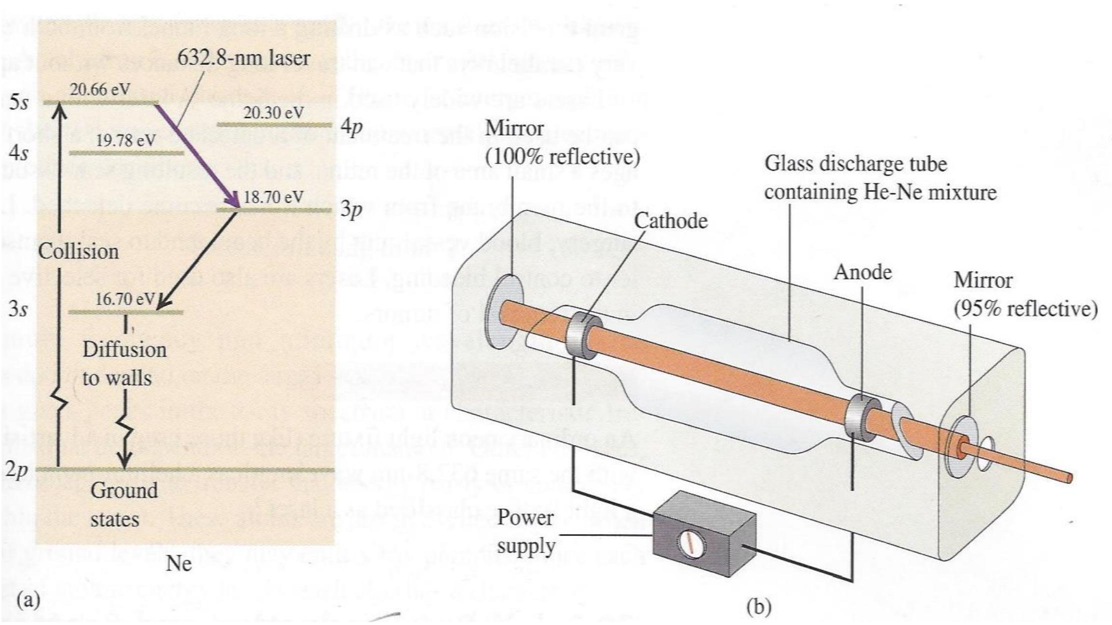

Figure 2

Image credit: Young and Freedman (2004); University physics; Page 1469

The energy levels of E_i assume values of E_g and E_{ex} where energy E_g will denote the ground state of energy and E_{ex} will denote the excited state energy [9]. The number of ground state atoms will be denoted n_g, and the number of excited state atoms will be denoted n_{ex}[9]. The ratio of atom numbers (i.e. n_g and n_{ex}) is expressed as [9]:

$$\frac{n_{ex}}{n_g} = \frac{Ae^{-E_{ex}/kT}}{Ae^{-E_g/kT}} = e^{-(E_{ex}-E_g)/kT} \tag{37}$$

This implies that:

$$ln\left(\frac{n_{ex}}{n_g}\right) = \frac{-(E_{ex}-E_g)}{kT} \tag{38}$$

Eq.30 can be re-arranged such that:

$$E_{ex} - E_g = -kTln\left(\frac{n_{ex}}{n_g}\right) \tag{39}$$

Where laser is an acronym for Light-amplification by stimulated emission of radiation, the radiant energy or packet of photons emitted by the laser is the difference between energy levels E_g and E_{ex}, thus, the combined energy of the laser or lasers within the LKET chamber is equal to the difference in energy levels $E_{ex} - E_g$[9]. Resultantly, the LKET energy E_L is set equal to the difference in energy levels $E_{ex} - E_g$, such that [9]:

$$E_L = E_{ex} - E_g \tag{40}$$

Eq.32 implies the expression of:

$$E_L = -kTln\left(\frac{n_{ex}}{n_g}\right) \tag{41}$$

Eq. 33 must satisfy the condition of <u>population inversion</u> which is the condition required for laser emission from the gases [9]. Population inversion occurs when the number of <u>higher energy state</u> atoms is greater than the number <u>of lower energy state atoms</u> [9]. Energy E_L is the combined energy of the laser hence all of the photons emitted have the same frequency, phase, polarization, and direction of propagation [9]. Thus, energy E_L can be expressed in terms of wavelength λ, Planck's constant h, and the velocity of light c such that [9]:

$$E_L = \frac{hc}{\lambda} \tag{42}$$

This implies that:

$$\frac{hc}{\lambda} = -kTln\left(\frac{n_{ex}}{n_g}\right) \tag{43}$$

Hence, the absolute value of the radiant energy entering the LKET chamber as a laser beam can be expressed such that:

$$|E_L| = \frac{hc}{\lambda} = kTln\left(\frac{n_{ex}}{n_g}\right) \tag{44}$$

Eq. 44 concludes the mathematical description of the process to which the lasers generate energy E_L which is transferred to the exhaust gases egressing through the LKET chamber.

Conclusion

As previously communicated, the inclusion of the LKET chamber to a conventional rocket engine will potentially increase a rocket's fuel efficiency to a level where a spacecraft can carry-out an entire orbital flight while replacing the weight of a booster rocket with slightly less heavy electrical power source (e.g. battery, fuel cell, reactor, etc.) and corresponding LKET chamber. Thus, the goal of the LKET system is to allow the construction of a single vehicle that will launch into orbit and to re-entry without the use of booster rockets. This will be particularly beneficial to vehicle designs for private space flight industry and eventually beyond.

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