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Research Article

Mode-Locked CO Laser for Isotope Separation of Uranium Employing Condensation Repression

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In the present work, we have suggested a technical solution of a CO laser facility for industrial separation of uranium used in the production of fuel for nuclear power plants. There has been used a method of laser isotope separation of uranium, employing condensation repression in a free jet. The laser operation with nanosecond pulse irradiation can provide acceptable efficiency in the separating unit and the high effective coefficient of the laser with the wavelength of 5.3 μm. Receiving a uniform RF discharge under medium pressure and high Mach numbers in the gas stream solves the problem of an electron beam and cryogenic cooler of CO lasers. The laser active medium is being cooled while it is expanding in the nozzle; a low-current RF discharge is similar to a non-self-sustained discharge. In the present work, we have developed a calculation model of optimization and have defined the parameters of a mode-locked CO laser with an RF discharge in the supersonic stream. The CO laser average power of 3 kW is sufficient for efficient industrial isotope separation of uranium at one facility.

1. Introduction

Researches that have been done recently have resulted in a breakthrough method of isotope laser separation of uranium employing condensation repression in a free jet [1, 2]. The cost of uranium enrichment for nuclear power plants fuel realized by this method can be twice lower than by ultracentrifuges [2].

Under low temperatures and low pressures in the free supersonic jet, dimers are being effectively produced, which consist of isotopes ${}^{i}UF_6$ and the carrier gas G. Irradiation of the 5.3 μm wavelength is employed for the selective excitation of ${}^{235}UF_6$ due to a shift in the absorption bands of ${}^{235}UF_6$ and ${}^{238}UF_6$. The dimers ${}^{238}UF_6$:G formed in the supersonic jet and tend to stay in the jet core. The dimers with the excited molecule ${}^{235}UF_6{}^{*}$ break down quickly due to the vibrational energy transiting to the fragment kinetic energy. As a result, molecules ${}^{235}UF_6$ escape from the core to the jet rim [2]. The energy consumption per one dimer is only 0.23 eV.

Small absorption cross section of ${}^{235}UF_6$ requires a separating unit with a long length and the nanosecond pulse irradiation with a high power peak. This results in high productivity in the separating block and high efficiency of the mode-locked CO laser with the wavelength of 5.3 μm. The average power of several kilowatts and the pulse repetition rate of 10 MHz are sufficient for efficient industrial isotope separation of uranium at one facility. When the laser having the power of several kilowatts operates in a continuous-wave mode, the photon absorption in the separating block in a pass is small even in case of a long length of the block. It is required that the laser beam passes multiply through the general cavity with a diffraction grating and a mirror. In this case, nearly all power is spent on mirror losses.

Employing an RF discharge in the supersonic stream instead of a non-self-sustained discharge and the gas cooling by its expansion in the nozzle allow to simplify considerably the CO laser design. We have received the lasing on the experimental small-scale facility with an RF discharge in the supersonic stream [3]. In the present work, the parameters of a mode-locked CO laser with a continuous RF discharge in the supersonic stream have been calculated. The conditions that provide high efficiency of the laser at the wavelength of 5.3 μm and acceptable effective photon employing in the separating block have been determined. The technical solution of a mode-locked CO laser and of a facility for industrial isotope separation of uranium employing condensation repression in a free jet has been developed.

2. CO Laser

To operate effectively, CO lasers power of several kilowatts requires the cryogenic temperature in the active medium with the gas streaming through the discharge and the preliminary e-beam ionization. There is the electron accelerator voltage of 2×10^5 V, the compulsory radioactive protection, and cryogenic cooler. Receiving a homogeneous RF discharge under the moderate pressure and high Mach numbers in the gas stream [3] solves the problem related to an e-beam and cryogenic cooler for CO lasers. The active medium is being cooled while it is expanding in the nozzle; a low-current RF discharge is similar to a non-self-sustained discharge [4].

It was acquired lasing with an RF discharge under excitation in the discharge before the nozzle as well as after it [3, 5–10]. Though only in case of a discharge exciting after the nozzle, the supersonic stream parameters allow to restore the pressure in the diffuser to the level of the atmospheric pressure and to apply a commercial compressor for gas streaming and piping. The stream supersonic speed and medium pressures provide the required great active medium consumption in the discharge chamber of small dimensions. Small dimensions of the laser head (nozzle, discharge chamber, diffuser) and employing pipes allow to install it near the irradiated object.

The nanosecond pulses with the wavelength of near $5.3\,\mu$m are acquired on the experimental mode-locked CO laser facilities [11, 12]. In the work, [11] described the experiments carried out on a facility operating at the room temperature of an active medium and pumped by a pulsed self-sustained TEA discharge. In the experiment, [12] used a facility with a cryogenic cooler and an e-beam. In the present paper, the parameters of an active mode-locked and continuous RF discharge in the supersonic stream CO laser have been evaluated. There is neither e-beam nor cryogenic cooler in the laser.

3. Calculation Model

The model includes the calculations of the following: an RF discharge parameters; the vibrational kinetics of CO molecules; a supersonic RF discharge stream; pressure restoring in the diffuser; an optical cavity; the intracavity losses for absorption of photons in a separating unit.

3.1. Low-Current RF Discharge. A low-current mode of an RF discharge is not carried away with the gas stream, and it has a low field in the discharge column, and so it is optimal for the CO laser with supersonic gas streaming through the discharge. The conditions to provide a low-current RF discharge are determined in the work [4], and the evaluation model considering all its peculiarities is designed.

In a low-current RF discharge, two sheaths of variable thickness simultaneously exist near an electrode throughout the field period. An electron cloud forms at the sheath boundary; it fills the sheath or leaves it depending on the phase of the applied RF voltage. The sheath electrons produce metastable particles, interacting with the cloud electrons in the subsequent field periods. The cloud electrons transfer the metastable particles to the emitting levels at the maximum field moment. The resulting flux of photons triggers the avalanches in the sheath and irradiates intense photoemission from the electrode surface. The sheath of the discharge forms when the secondary avalanches, initiated by the photoelectrons, overlap. A low-current mode of an RF discharge forms as long as the avalanches from the electrode surface depend on the cloud irradiation. The main current in the sheath is the displacement current.

A small part of the cloud electrons undergo only elastic collisions for half the period of RF field. These electrons exit from the cloud to the positive column due to the directed velocity, that electrons acquire since the phase of the cloud electrons moving coincides with phase of the field. In case in elastic collisions electrons lose their directed velocity in the positive column for a longer time than the period, the electrons execute translational oscillatory motion until they lose the phase at which they began moving. During every period of the field, a part of electrons escape to the positive column. Accumulation of the electrons results in weakening the field. This makes a low-current RF discharge similar to a non-self-sustained discharge [4].

Solving the equation where the ions lost are equal to the ions produced in the sheath over the field period along with Poisson's equation determine the root-mean-square parameters of the sheath. The temperature of the cloud electrons is determined, on the one hand, by the energy they obtain in the field and in superelastic collisions and, on the other hand, by the energy they lose in exciting and ionizing. The number of electrons in the column is determined by the equation between the electrons coming from the sheath and the losses on recombination. The root-mean-square field of the column is found from the equation of the current in the sheath and in the column. Choosing the discharge gap, the frequency of the RF field, the pressure, the temperature, and the composition of the active medium makes it possible to provide effective exciting CO molecules in the discharge up to 90%. The calculation model of a low-current RF discharge is verified in the work [4].

3.2. Vibrational Kinetics. Exciting CO molecules by the electrons of the RF discharge plasma, VV-exchange and VT-exchange lead to energy distributions over the vibrational levels, the Treanor distribution on the lower levels and the "plateau" area on the upper levels. The "plateau" area is formed due to VV-exchange and filling the upper vibrational levels at different time. Different time allows filling of the upper laser level by means of VV-exchange without great energy losses at the overlying levels. It requires an alternating energy pickup in the radiation and employing a frequency-selective cavity. The time of repetition pulses should be sufficient only for the upper laser level filling that corresponds with the wavelength of $5.3\,\mu$m. The speed of

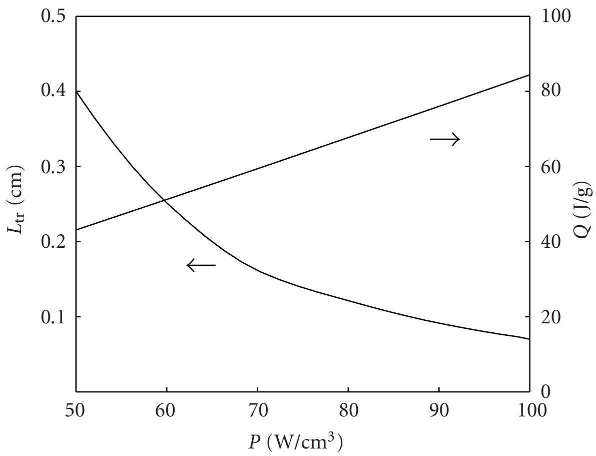

FIGURE 1: The dependences of a Treanor distribution formation length and a specific input energy on the input power for the laser medium CO : Ne (1 : 10). The discharge gap is equal to 0.5 cm; mass flow is equal to 0.4 kg/s.

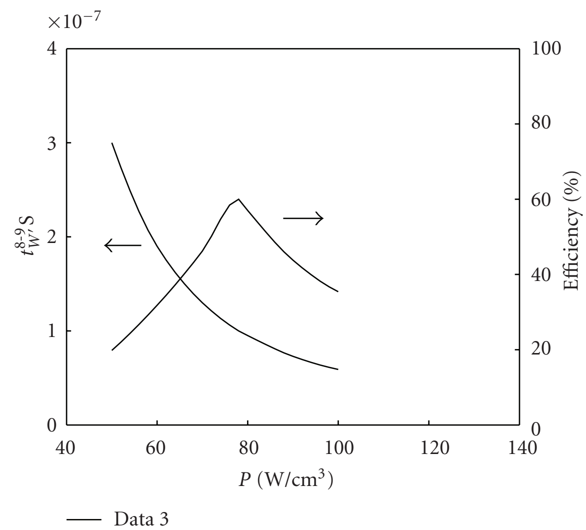

FIGURE 2: The dependences of the time of VV-exchange for the upper laser level (from V = 8 up to V = 9) and the efficiency of filling on the input power for the laser medium CO : Ne (1 : 10).

power supply in the discharge should be equal to the speed of power escape to the laser level due to VV-exchange. The pulse duration should be much shorter than the time of VV-exchange for the upper laser level, but longer than the time for the energy exchange between the rotational levels.

The evaluation of filling of CO molecules vibrational levels is done according to the Treanor distribution and the "plateau" [13]. Figure 1 displays the dependences of a Treanor distribution formation length and a specific input energy on an input power for the laser medium CO : Ne (1 : 10).

Figure 2 displays the dependences of the time of VV-exchange for the upper laser level (from V = 8 up to V = 9) and the efficiency of filling on the input power.

The power losses at the overlying no-radiation levels will be small if the time of VV-exchange from V = 8 up to V = 9 level is equal to the time of repetition pulses. Consequently, the effective coefficient of the mode-locked single-line CO laser operated on vibrational-rotational transition 9-8 P(15) with wavelength 5.3 μm will be high. If the input power is equal to 80 W/cm^3, the time of VV-exchange for the upper laser level is 10^{-7} s (Figure 2). It requires pulse repetition rate of 10 MHz and the general cavity with optical length 15 m. The scheme of the general cavity with optical length 15 m is presented in Figure 3.

The general cavity consists of the active medium of laser 0.4 m and the separating unit 14 m. The pulse duration is about 3 ns for the mode-locked single-line 5.3 μm. The time for the energy exchange between the rotational levels is less than 1 ns. The active medium gain of a CO laser is calculated from the formula of work [14]. Figure 4 shows the gain distribution through the cavity length under the input power 80 W/cm^3 for the laser medium CO : Ne (1 : 10).

3.3. Gas Dynamics. To define the active medium parameters in the discharge, a one-dimensional supersonic stream in environment of heat sources has been investigated [15]. The heat release is related to the anharmonicity of the vibrational levels and the electron energy losses occurred in collisions with neutral gas particles and with rotational excitation of molecules. Figure 5 displays the dependences of pressure, temperature, Mach number, stream speed, and gas density through the cavity under the input power 80 W/cm^3 for the laser medium CO : Ne (1 : 10).

In the supersonic flow with the low-current RF discharge with length downstream 15 cm, a boundary layer is about 0.05 cm. It is not included in the modeling because a boundary layer is much less than discharge gap 0.5 cm, and the main current in the sheath of low-current RF discharge is the displacement current. The estimation of the pressure restoring in the diffuser is done correspondingly for a normal shock.

3.4. Intracavity losses for Absorption. To define the parameters of the irradiated gas in the separating unit, the dependence of a one-dimensional free jet streaming in the strongly rare medium is applied [16]. The coefficient of the intracavity losses for absorption depends on the density of molecules $^{235}UF_6$ in the irradiation area, the separating unit length, the absorption cross section, and the number of photons in the pulse. The generation mode is stable if the condition for the gain of the active medium is observed

$$g > \frac{(a+r)}{L}, \quad (1)$$

where L: active medium width, a: intracavity losses, r: mirror losses.

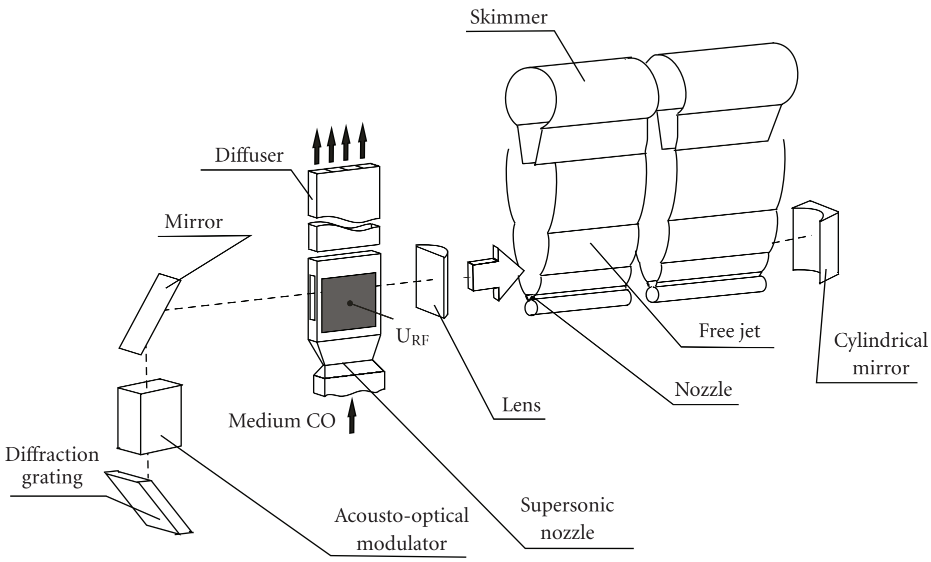

Figure 3: The scheme of the general cavity with optical length 15 m.

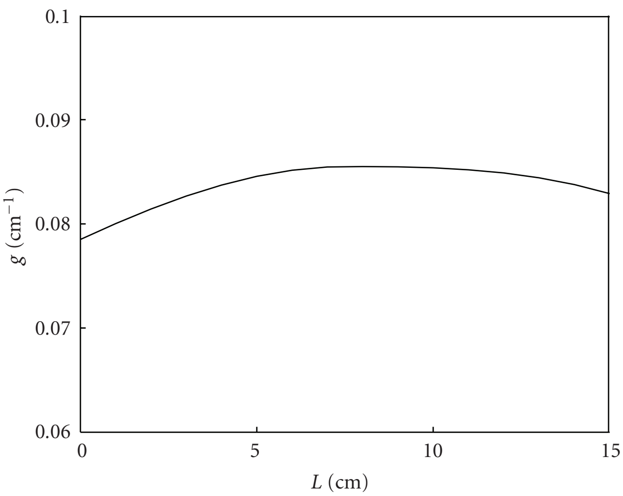

Figure 4: The gain distribution through the cavity length under the input power 80 W/cm^3 for the laser medium CO : Ne (1 : 10). Mass flow is equal to 0.4 kg/s, cavity length downstream is equal to 15 cm.

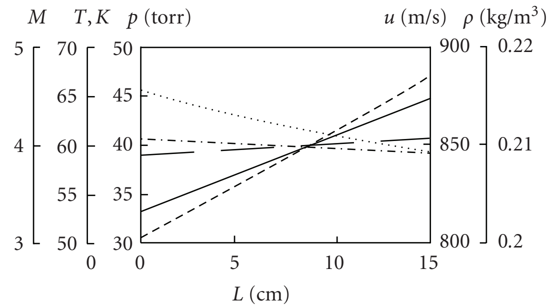

Figure 5: The dependences of pressure (solid line), temperature (short-dashed line), Mach number (dotted line), stream speed (dash-dotted line), and gas density (long-dashed line) through the cavity under the input power 80 W/cm^3 for the laser medium CO : Ne (1 : 10). Mass flow is equal to 0.4 kg/s, cavity length downstream is equal to 15 cm.

4. Technical Solution

The technical solution of a facility for industrial isotope separation of uranium by a mode-locked CO laser is presented in Figure 6.

There is applied a method of a laser isotope separation of uranium employing condensation repression in a free jet and a general cavity with an active mode locking and a diffraction grating (Figure 3). The laser pumping is realized by a continuous RF discharge, and a mode locking is achieved by means of an acousto-optical modulator. The wavelength is 5.3 μm, the pulse duration is about 3 ns, the pulse repetition rate is 10 MHz, the active medium of laser is 0.4 m, and the separating unit is 14 m. The pressure before the nozzle of the separating unit is 5 torr at temperature 290 K, the dimension of nozzle is 0.004 × 14 m. The pressure and temperature in the irradiated zone of a free jet at the nozzle exit are 1 torr and 150 K, respectively. The gas mixture of isotopes $^{i}UF_6$ and the carrier gas Ar (5 : 95) enters the separating unit where it expands further to pressure 0.01 torr and temperature 30 K.

The average CO laser power is 3 kW; the optimized effective coefficient of the laser is about 20%. The dependence of the effective coefficient of a mode-locked single-line 5.3 μm CO laser on the input power for the laser medium CO : Ne (1 : 10) is presented in Figure 7.

The dependences of the ratio of the quantity excited molecules $^{235}UF_6$to the full quantity of molecules $^{235}UF_6$ in the free supersonic jet of the separating unit n^*_{235}/n_{235} and the estimated productivity of the facility of nuclear fuel per year on the average CO laser power are presented in Figures 8 and 9, respectively.

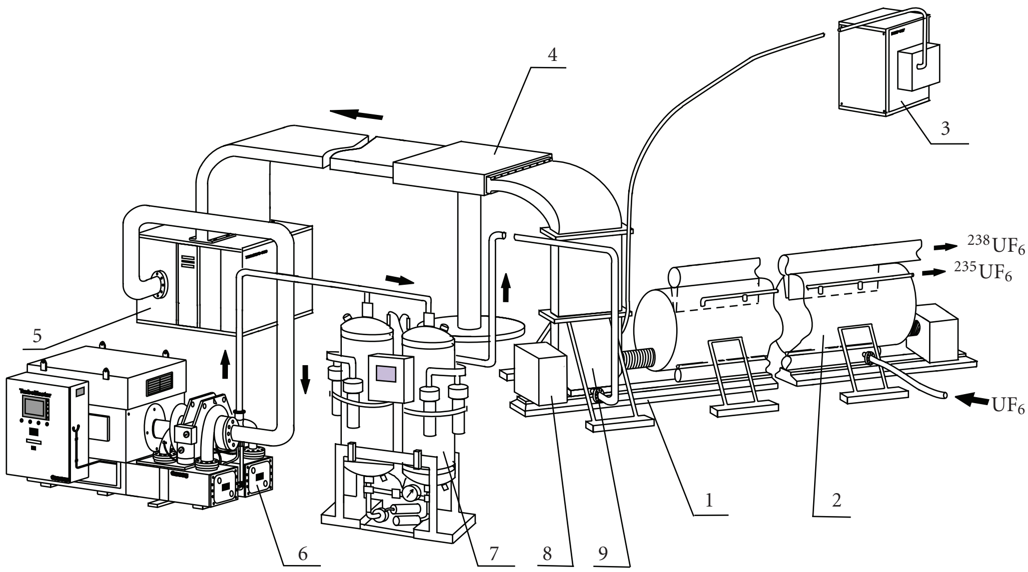

Figure 6: The technical solution of a facility for industrial isotope separation of uranium by a mode-locked CO laser. (1) Optical bench, (2) separating unit, (3) RF generator, (4) cooling jacket, (5) low-pressure compressor, (6) high-pressure compressor, (7) receiver and regenerator of the laser medium, (8) optical cavity, (9) CO laser head.

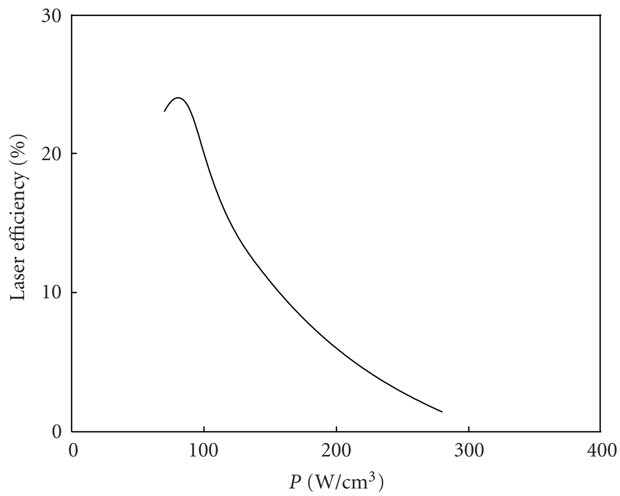

Figure 7: The dependence of the effective coefficient of a mode-locked single-line 5.3 μm CO laser on the input power for the laser medium CO : Ne (1 : 10). The pulse repetition rate is 10 MHz.

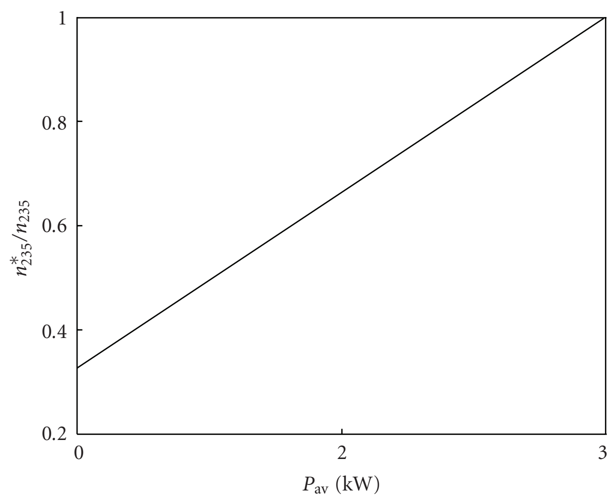

Figure 8: The dependence of the ratio n^*_{235}/n_{235} on the average CO laser power. Mass flow in the free supersonic jet is equal to 0.12 kg/s.

The low cost of the laser is related to the average power only of 3 kW, the simple construction, using piping, a commercial compressor, and a small laser head. The uranium enrichment realized on this facility might be several times cheaper than by centrifuges. More efficient usage of the feedstock makes it possible to consume less natural uranium in the fuel production.

5. Conclusion

The value of average power of the CO laser required to separate uranium isotopes on a scale of the industrial production of the fuel is 3 kW. Though $^{235}UF_6$ absorption cross-section for 5.3 μm photons is low, the photons employing to separate can be efficient if they apply a general cavity, a mode-locked CO laser, and a separating unit of 14 m long. Employing an RF discharge in the supersonic stream allows to simplify significantly the CO laser design. We have developed a calculation model for the optimization of a CO laser with an RF discharge in the supersonic stream. The parameters of a mode-locked single-line 5.3 μm CO laser that has the high effective coefficient and the low cost are determined. The technical solution of a facility for industrial isotope separation of uranium by a laser with high efficiency is suggested.

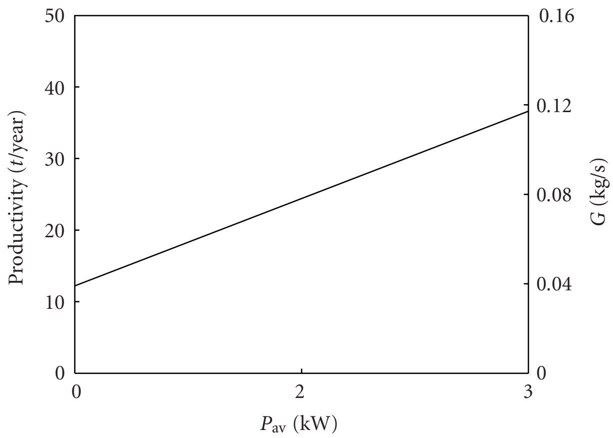

Figure 9: The dependences of the estimated productivity of the facility of nuclear fuel per year and corresponding mass flow in the free supersonic jet on the average CO laser power. The ratio n^*_{235}/n_{235} is equal to 1.

References

[1] J. W. Eerkens, J. F. Kunze, and L. J. Bond, "Laser isotope enrichment for medical and industrial applications," in *Proceedings of the 14th International Conference on Nuclear Engineering (ICONE '06)*, July 2006, ICONE- 89767.

[2] J. W. Eerkens and W. H. Miller, "Laser Isotope Separation Employing Condensation Repression," SPLG2003, October, OSTI, ID:912774, 2003, http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=912774.

[3] G. A. Baranov, I. Ya. Baranov, A. S. Boreisho, and I. V. Timoshchuk, "A combustion-driven supersonic RF-excited CO-laser," *Kvantovaya Elektronika*, vol. 20, pp. 222–226, 1993, in: *Quantum Electronics*, vol. 23, p. 189, 1993.

[4] I. Ya. Baranov and A. V. Koptev, "Low-current medium-pressure RF discharge with electron photoemission in the electrode sheath and penetration of the sheath electrons into the discharge column," *Plasma Physics Reports*, vol. 33, no. 12, pp. 1038–1056, 2007.

[5] J. A. Shirley, R. J. Hall, and B. R. Bronfin, "Stimulated emission from carbon monoxide transitions below 5 μm excited in supersonic electric discharge," *Journal of Applied Physics*, vol. 45, no. 9, pp. 3934–3936, 1974.

[6] W. Bohn, H. Von Bülow, S. Dass et al., "High-power supersonic CO laser on fundamental and overtone transitions," *Kvantovaya Elektronika*, vol. 35, no. 12, pp. 1126–1130, 2005.

[7] H. Von Bülow and E. Zeyfang, "Supersonic CO laser with rf excitation," *Review of Scientific Instruments*, vol. 64, no. 7, pp. 1764–1769, 1993.

[8] H. V. Bulow and M. Schellhorn, "High power gasdynamically cooled carbon monoxide laser," *Applied Physics Letters*, vol. 63, no. 3, pp. 287–289, 1993.

[9] M. Shellhorn and H. von Büllow, "Improvement of the beam quality of a gasdynamically cooled CO laser with an unstable resonator by use of a cylindrical mirror," *Optics Letters*, vol. 20, pp. 1380–1382, 1995.

[10] J. E. McCord, R. Tate, G. D. Hager et al., "Multi-line and single-line spectral characteristics of RF discharge supersonic CO laser," in *Proceedings of the International Conference on LASERS*, STS Press, McLean, Va, USA, 2001.

[11] A. V. Nurmikko, "Forced mode locking of a single-line high-pressure CO laser," *Journal of Applied Physics*, vol. 46, no. 5, pp. 2153–2154, 1975.

[12] A. A. Ionin, Y. M. Klimachev, A. A. Kotkov et al., "Influence of nitrogen oxides on singlet delta oxygen production in pulsed electric discharge for oxygen-iodine laser," in *XVII International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers*, vol. 7131 of *Proceedings of SPIE*, 2008.

[13] I. Ya. Baranov, V. D. Goncharov, and I. V. Timoshchuk, "Calculation model of a CO laser with a high-frequency discharge in a supersonic stream of combustion products," *Kvantovaya Elektronika*, vol. 21, p. 111, 1994, in: *Quantum Electronics*, vol. 24, p. 102, 1994.

[14] C. K. N. Patel, "Vibrational-rotational laser action in carbon monoxide," *Physical Review*, vol. 141, pp. 71–83, 1966.

[15] V. N. Karnyushin and R. I. Solouhin, *Macroscopic and Molecular Processes in Gas Lasers*, Atomizdat, Moscow, Russia, 1981.

[16] J. W. Eerkens, "Laser-induced migration and isotope separation of epi-thermal monomers and dimers in supercooled free jets," *Laser and Particle Beams*, vol. 23, no. 2, pp. 225–253, 2005.