Power and Energy Characteristics of Continuous Waves / Pulsed CO_2 Laser Application in CNG-DI Ignition

N. Mariun, N. Md. Saad, M. F. Abas, N. Khan and S. Abdullah

Abstract**—**This work was arranged to develop the scientific database and integrate the application of lasers in high voltage engineering. The design and experimental studies on continuous wave (CW) / repetitively pulsed CO_2 laser was carried out in detail to determine the laser characteristics between various design parameters and the effect of varying one parameters on others. The thresholds and steady state input voltage and power across the laser tube are determined. The maximum and minimum output energy and power of the laser system are also presented as function of the pulse repetition rate and discharge current. The CO_2 laser system was operated at 10.6 µm wavelengths range of infrared electromagnetic spectrum. This study is presented due to the wide applications of CO_2 lasers in industry and for this project for compressed natural gases-direct injection (CNG-DI) ignition.

Keywords**—CO_2 laser, continuous wave, repetitively pulsed wave.**

I. Introduction

THIS paper presents an explanation of the lasing processes involved for continuous wave and repetitively pulsed CO_2 laser at 10.6µm in terms of laser energy and power characteristics. The CO_2 molecule is symmetric and it consists of two oxygen atom tied to a central carbon atom by elastic forces. These molecules can vibrate and rotate at their equilibrium position. The total energy of the molecules is due to the contributions of both vibrational and rotational motions. These motions are characterized by corresponding quantum numbers [1].

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Three types of non-degenerate modes of vibration are symmetric stretching, bending and asymmetric stretching [1]. The most commonly observed laser transitions in the CO_2 molecule are from the CO_2 asymmetric stretch mode 001 to the symmetric stretch mode 100 (10.6µm) and to bending mode 020 (9.6 µm). The energy states of all of these vibrations are quantized and are represented by three quantum numbers, v_1, v_2, v_3 where v_1 refers to the symmetric stretch quantum number, v_2 refers to the bending quantum number and v_3 refers to the asymmetric stretch quantum number [2-4]. The energy levels diagram of CO_2 molecules involved in the lasing process are illustrated in Fig.1 [3]-[5].

Depends on the output power, CO_2 lasers have wide applications such as in communication, national defense and as tools in many area of scientific research. The high power of CO_2 lasers are widely used in industry for various purposes such as laser marking, laser cutting, welding, drilling and material processing. In medical instruments, CO_2 lasers are used for laser surgery, laser therapy, reduction of bleeding and neurosurgery [5]. In the area of scientific research, the CO_2 lasers at 10.6 µm are the most suitable for earth atmosphere ionization experiment and high voltage laser triggered lightning discharge [6]. Besides that, the most important research area to be explored is the infrared laser spectroscopy study in combustion research.

The purpose of this project is to build a CO_2 laser system for application in CNG-DI ignition.

All works were performed at the High Voltage Laboratory in Electrical Engineering Department, Universiti Putra Malaysia (UPM), Serdang.

II. Laser Energy and Power

If the power distribution of the laser beam is assumed Gaussian, as shown in Fig.2, then the laser pulse energy for appropriate pulse duration is calculated below [7]-[11],

$$E(\tau) = E_{\max} \exp(-\tau^2 / \tau_\circ^2) \tag{1}$$

Where E is the pulse energy (J), Emax is the maximum laser energy, τ is the time, and τo is the time at which E (τo) = Emax/e, (e = 2.7183).

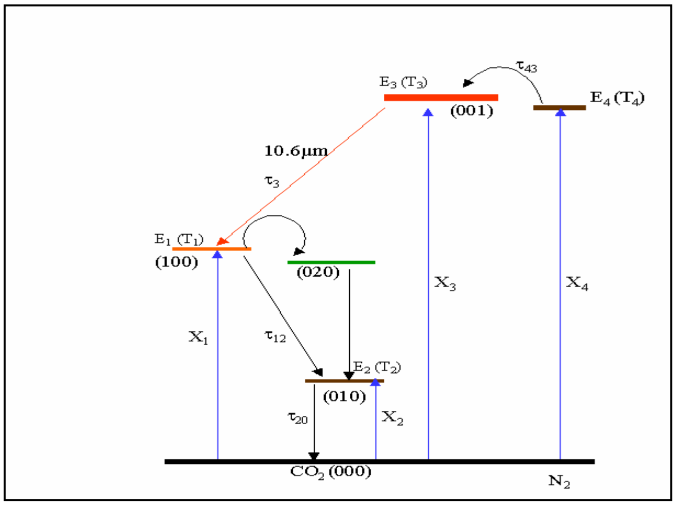

Fig.1 energy level diagram of lasing mechanism in CO_2 laser [5-7]

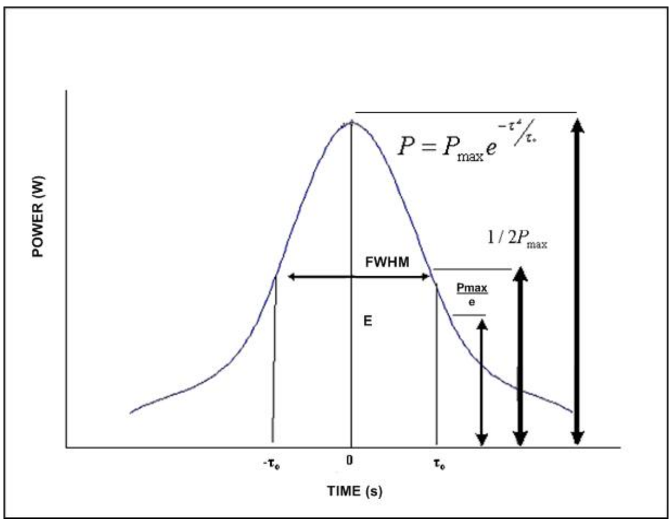

Fig.2 Gaussian distribution from a single pulse of laser power [10]

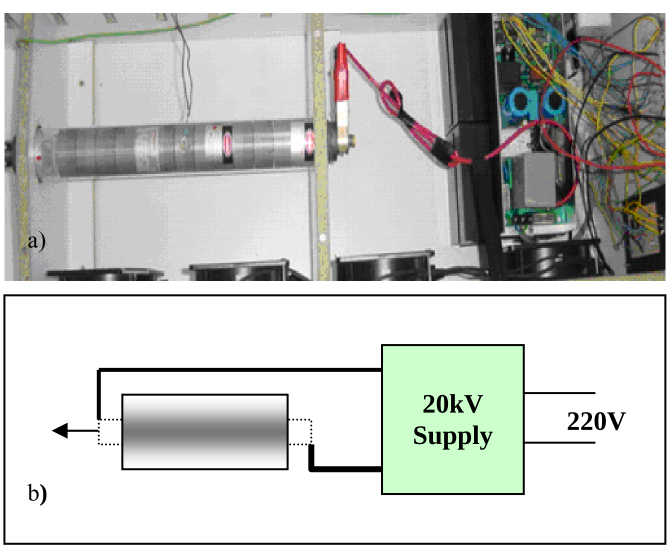

Fig. 3 (a) Top view of the laser system (b) 20 kV power supply connected to CO_2 laser tube terminal

Let τ_{FWHM} is the pulse duration (full width at half maximum). Then τ_o is calculated from the following relation,

$$\tau_\circ = \frac{\tau_{FWHM}}{2\sqrt{\ln 2}} \tag{2}$$

The average laser energy, E_o over τ_o is given as,

$$E_\circ = \int_{-\infty}^{\infty} P(t)dt \tag{3}$$

From Figure 2,

$$P(t) = P_{\max} \exp\left(-\tau^2 / {\tau_o}^2\right) \tag{4}$$

Where P_{max} is the maximum laser power (Watts). Using (4) into (3) gives,

$$E_\circ = \int_{-\infty}^{\infty} P_{\max} \exp(-\tau^2 / {\tau_\circ}^2) dt \tag{5}$$

Maximum power, P_{max} relates to initial laser energy, E_o by the following relation,

$$P_{\max} = \frac{E_\circ}{\tau_\circ \sqrt{\pi}} \tag{6}$$

III. Design and Experimental Procedures

The CO_2 laser system which is used in this work is shown in Fig.3. A 20 kV power supply was used to excite the laser tube. The mirrors constituting a resonator are attached to the laser tube windows after alignment. Four fans are used for cooling of the laser system.

The laser system control unit is designed to control the CO_2 laser operation. The CO_2 laser was operated in continuous wave (cw) mode and in repetitively pulsed mode.

The experimental setup consists of CO_2 laser system with the control unit, R-752 Universal Laser Radiometer unit (DigiRad Division of TeraHertz Tech. Inc.) and the digital oscilloscope (Textronix). The R-752 Universal Laser Radiometer unit consists of P-444 pyroelectric energy meter probe and PH-30 power head in order to obtain the profile of the energy in a short pulse of light and power of a continuous wave of light for comparison with the output profile from the oscilloscope. The schematic diagram of the studies can be seen in Fig.4 below.

The measurements were obtained by varying the discharge current, pulse repetition rate (PRR), pulse repetition time (PRT), pulse duration and duty cycle of the laser system. These can be simply done through the control unit which has been designed for driving the CO_2 laser system in order to get the output profiles in continuous waves or in pulsed mode.

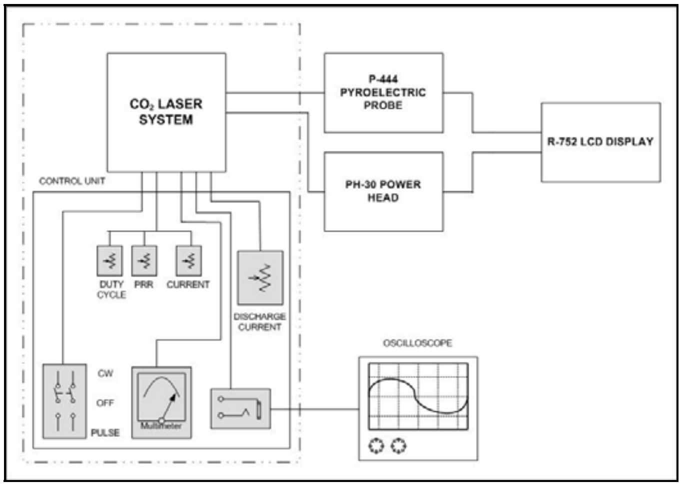

Fig.4 Block Diagram for Measurement of Output Parameters of CO_2 Laser.

IV. Results and Discussion

The results and discussions are presented in detail for the measurement of threshold and steady state voltage across the laser tube and the output energy and power of the laser system. These works were carried out subject to pulse repetition rate and the discharge current of the laser system.

A. Thresholds and Steady State Voltage

The measurements of the thresholds and steady state voltage across the laser tube were done when the laser system is operated in continuous wave (cw) mode.

The threshold and steady state voltage across the laser tube was measured to be 15.64 kV and 8.16 kV, respectively. The thresholds voltage electric discharge starts between the electrodes through the gas mixture. As the discharge starts, the threshold voltage drops to steady state voltage. The steady state voltage remains unchanged as discharge current increased as shown in Fig.5. However, the input power increased linearly as the discharge current increased as shown in Fig.6.

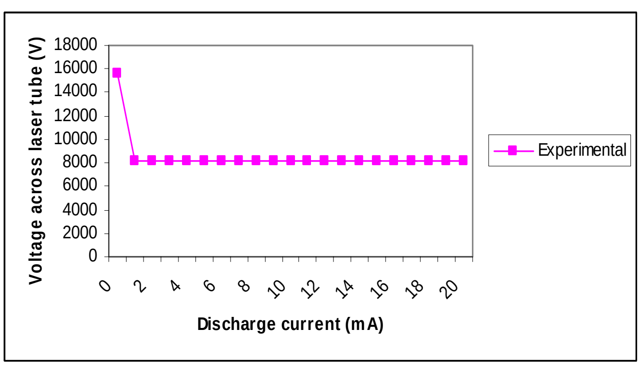

Fig.5 Voltage across laser tube as function of Discharge current

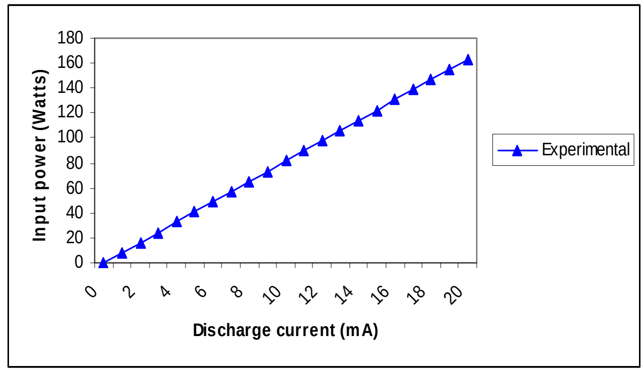

Fig.6. Input power as function of Discharge current

B. Output Energy

The output pulse energy has been measured experimentally as function of pulse repetition rate and discharge current. The energy measurements are performed using P-444 Pyroelectric energy meter probe which placed in front of the laser beam. The power supply to P-444 was switched on. The meter will automatically scale to pulse energy measurement and will display the reading in joule on the LCD display. The energy meter is averaged to 100 samples. The pulse repetition rate was increased in steps starting from 25 Hz up to 1500 Hz at fix discharge current and the energy of the pulse is calculated. The processes were then repeated for different values of discharge current.

The pulse energy is found to increase with the increase in pulse repetition rate. The maximum pulse energy was found at 50 Hz at the discharge current of 10mA which is about 32mJ. A decrease in the pulse energy was noted with further increase in pulse repetition rate. This is due to the decrease in the on time of the input electric discharge through the lasing media which will cause the probability of all the molecules in the upper level decreases.

For the measurement of the energy as function of discharge current, the discharge current was increased in steps up to 20mA at fix pulse repetition rate. Then, the processes were repeated for different values of pulse repetition rate and the energy of the pulse is calculated. Again, it yielded the same results in which the maximum output energy was found at 32mJ with 50 Hz pulse repetition rate and 10mA discharge current. The results were illustrated in Fig.7 and Fig.8 respectively.

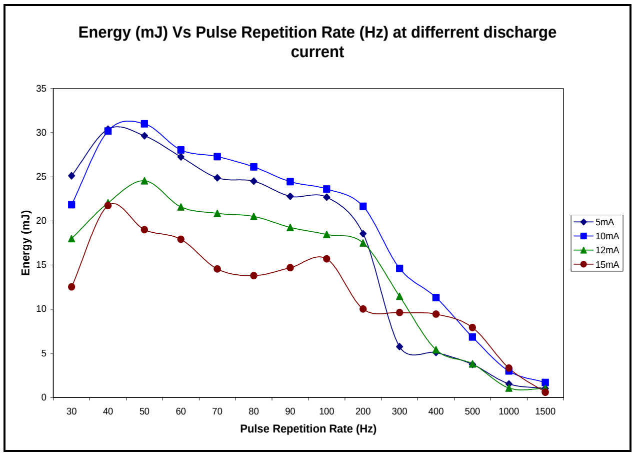

Fig.7 Output pulse energy as a function of pulse repetition rate at different discharge current

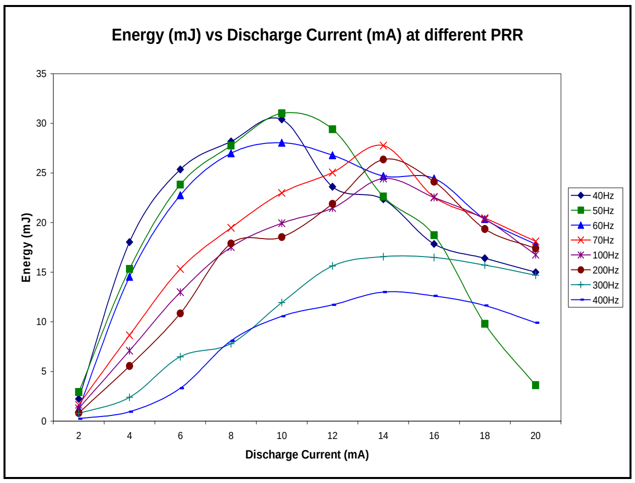

Fig.8 Output pulse energy as a function of discharge current at different pulse repetition rate

C. *Output Power*

For the measurements of the output power, the laser system was operated in both, continuous wave and pulsed mode. The output power measurements were performed using P-444 Pyroelectric energy meter with PH-30 power head which is placed in front of the laser beam. The meter will automatically scale to power measurement and display the reading in watts on the LCD display.

The results for measurements of output power in pulsed mode as function of pulse repetition rate at different discharge current can be seen in Fig.9.

An increase in maximum power has been found with increase in pulse repetition rate. The highest output power is achieved at 10mA discharge current with the pulse repetition rate of 400 Hz, which is 11.02 watts. The further increase in pulse repetition rate and discharge currents results in decrease of maximum power. This is due to the increase in the energy which will increase the rate of collision between the molecules and electrons. The increase in the rate of collision causes the population density of the lower levels to increase, which hinder the transition from upper level to lower level. This blocking in the transition path causes the reduction in output power of the laser system. In the continuous wave operation, the output power is maximum when the population density of upper levels becomes equal the population density of lower levels in the ground state.

The results for measurements of output power in continuous wave as function of discharge current can be seen in Fig.10. It was found that the laser power increases with increase in the current. This increase in power continues until the discharge current reaches to a value of 14mA. The further increase in currents results in decrease of output power. The maximum power was found at 12.12 watts at 14mA discharge current. The relationship between the output power and discharge current is given by [2],

$$P = -0.065I^2 + 1.796I + 0.294 \qquad (7)$$

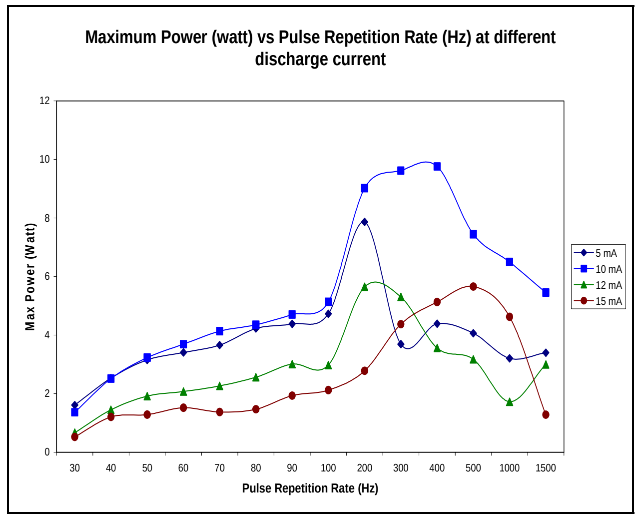

Fig.9. Maximum power as function of pulse repetition rate at different discharge current

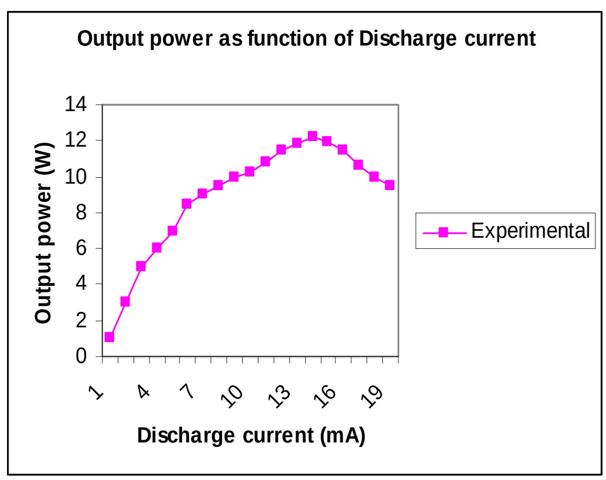

Fig.10. Output power as function of discharge current

Fig.11 shows the results for measurement of average power as function of pulse repetition rate at different discharge current. The relationship between the maximum output power and the average power is given by,

$$P_{avg} = \frac{E}{PRT} = E \times PRR \tag{8}$$

Again, the average power continues increase until it reaches a maximum value and then starts decreasing with further increase in discharge current and pulse repetition rate. The highest power average is achieved at 10mA of discharge current with pulse repetition rate of 400Hz, which is about 4.7 watts. The further increase in pulse repetition rate results in the decrease of output power average.

The calculation for maximum power was done to compare the theoretical and experimental results of CO_2 laser in term of maximum power characteristics. The results were tabulated in Fig.12. The results of experimental findings are acceptable with percentage of total power loss less than 10%. Equation (9) gives the total power loss for experimental finding as function of discharge current [1].

$$P_{loss} = \left(-0.0657I^2 + 1.796I + 0.294\right) \tag{9}$$

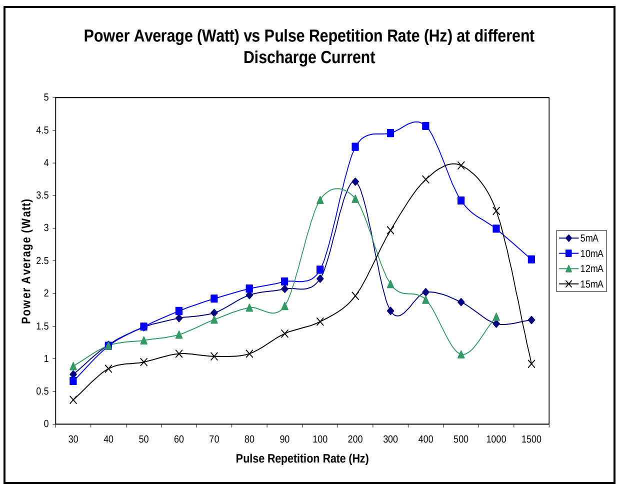

Fig.11 Average power as function of pulse repetition rate

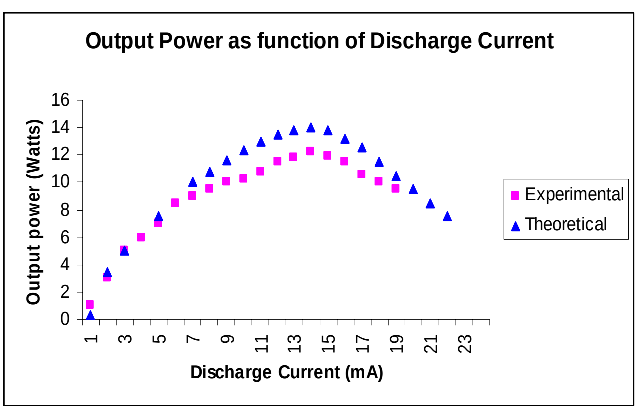

Fig.12 Calculated and Measured Output Power as Function of Discharge Current

D. Application in CNG-DI Ignition

The absorption characteristics of leaner air/ compressed natural gases (CNG) mixtures have been experimentally investigated using continuous wave (cw)/pulsed CO_2 laser at 10.6µm at variable laser energy and pressures operated at 295K temperature. The measurements were done using optical transmission loss techniques with 19% transmission loss due to optical window and lens.

The purpose of this experiment is to investigate the application of continuous wave (cw)/repetitively pulsed CO_2 laser system for compressed natural gases-direct injection (CNG-DI) laser ignition system.

The results for absorption coefficients, k_v are shown in Fig.13 and Fig.14 respectively. As E_o or pressure increased, the absorption coefficient, k_v of CO_2 laser in CNG, air and CNG/air mixtures increased drastically in the region of E_o less than 25mJ or pressure less than about 2 to 3 bar. Depending on E_o or pressures, the absorption coefficients are in the range from $2cm^{-1}$ to about $51cm^{-1}$ for CNG, $0.85cm^{-1}$ to $48cm^{-1}$ for air and $1cm^{-1}$ to $50cm^{-1}$ for CNG/air mixtures. The curves for absorption coefficient, k_v of all the test gases were found in agreement with the exponential law of absorption that is call as Beer-Lambert Law.

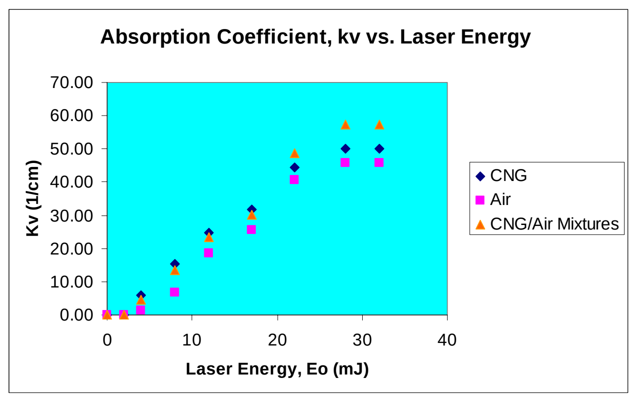

Fig.13 Absorption coefficient, k_v of CO_2 laser in CNG, air and CNG/Air mixtures on the initial laser energy, E_o

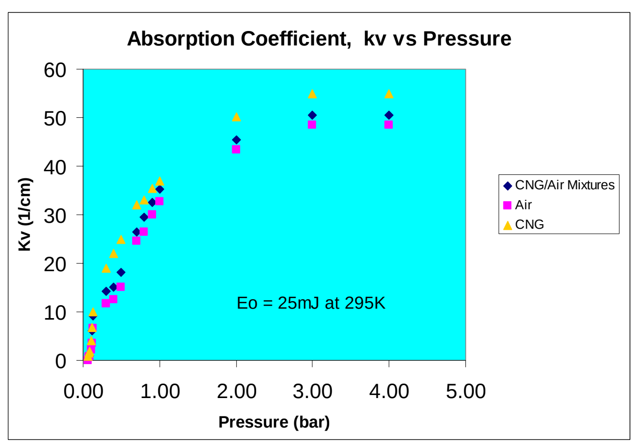

Fig.14 Absorption coefficient, k_v of CO_2 laser in CNG, air and CNG/Air mixtures on gases pressure

V. CONCLUSIONS

The CO_2 laser system was successfully operated in continuous wave mode as well as in pulse mode to experimentally study the power and energy characteristics of CO_2 laser system at 10.6μm wavelengths. The variation in power and energy parameters of CO_2 laser have been analyzed experimentally as function of pulse time period and discharge current. The results of experimental findings were found acceptable with low power loss. These losses might be due to the rise of laser tube temperature which will cause output power to drop. Overall, the operation of CO_2 laser system in both, continuous wave and pulse mode was found stable optically and thermodynamically.

The study has shown that absorption coefficient significantly varies with change in pressures and the ratio of fuel/air mixtures over a wide range of laser energy. Absorption data showed a strong dependence on both laser energy and pressure. Laser wavelength has a strong effect on the absorption coefficient as function of total laser energy. The results were found to follow the exponential law of absorption that is called as Beer-Lambert Law.

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