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I hereby declare that I have checked this thesis/project and in my opinion, this thesis/project is adequate in terms of scope and quality for the award of the degree of Bachelor of Chemical Engineering (Gas Technology)

Signature:
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I hereby declare that the work in this thesis/project is my own except for quotations and summaries which have been duly acknowledged. The thesis/project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my parents, Mohd Jaafar & Solihah; my brother, Zaidi and my dear friend, Abraham for their unconditional love and continuous support.

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My sincere thank to all my roommates that physically and mentally supporting me to go through a rough and tough, the beautiful and memorable journey.

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ABSTRACT

An experimental study on the effect of carbon dioxide (CO_2) dilution on flammability limit of acetylene (C_2H_2) was performed, for system with various concentration of fuel. The objectives of this experiment were to determine the lower flammability limit (LFL) and upper flammability limit (UFL) of C_2H_2 and to determine the effect of CO_2 on flammability limits of C_2H_2. The explosion pressure and explosion time were measured using an apparatus called 20 L explosion vessel at operating condition 20 ^{o}C and 1 bar. The first part of this experiment was conducted with different percentages of C_2H_2 without the presence of CO_2 to determine the LFL and UFL of pure acetylene at temperature 20 ^{o}C and pressure 1 bar. The second part was conducted with different percentage of C_2H_2 with the presence of 15% of CO_2. From the theory, when there is dilution of inert gases in fuel happen, the LFL of the fuel will increase while the UFL of the fuel will decreases, thus the flammability range of those fuel will be smaller. The explosion pressure data was collected to determine the flammability limit of acetylene and also acetylene with the presence of CO_2.

ABSTRAK

Satu kajian eksperimen tentang kesan pencairan karbon dioksida (CO_2) pada had kemudahbakaran asetilena (C_2H_2) dilakukan, untuk satu sistem dengan pelbagai kepekatan bahan api. Objektif eksperimen ini adalah untuk menentukan kemudahbakaran had yang lebih rendah (LFL) dan had kemudahbakaran atas (UFL) C_2H_2 dan untuk menentukan kesan CO_2 terhadap kemudahbakaran C_2H_2. Tekanan letupan dan masa letupan diukur menggunakan radas yang dipanggil 20 L bekas letupan pada keadaan operasi 20 °C dan 1 bar. Bahagian pertama daripada eksperimen dijalankan dengan peratusan C_2H_2 yang berbeza tanpa kehadiran CO_2 untuk menentukan LFL dan UFL asetilena tulen pada suhu 20 °C dan tekanan 1 bar. Bahagian kedua dijalankan dengan peratusan C_2H_2 yang berbeza dengan kehadiran 15 % CO_2. Berdasarkan teori, apabila terdapat pencairan gas lengai dalam bahan api berlaku, LFL bahan api akan meningkat manakala UFL bahan api akan berkurangan, dengan itu had terbakar bahan api akan menjadi lebih kecil. Tekanan letupan data dikumpul untuk menentukan had kemudahbakaran asetilena dan juga asetilena dengan kehadiran CO_2.

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LIST OF SYMBOLS

°C	Celcius
J	Joule
K	Kelvin
O_2	Oxygen
Vol. %	Percentage by volume

LIST OF ABBREVIATIONS

C_2H_2	Acetylene
CO_2	Carbon Dioxide
LFL	Lower Flammability Limit
UFL	Upper Flammability Limit
LOC	Limiting Oxygen Concentration
IE	Ignition energy
P_{exp}	Explosion overpressure: the difference between the pressure at ignition time (normal pressure) and the pressure at the culmination point is the maximum explosion overpressure P_{ex} measured in the 20-L-apparatus at nominal fuel concentration.
P_{max}	Maximum explosion overpressure: Maximum value of P_m determined by test over a wide range of fuel concentrations
t1	Duration of combustion: time differences between the activation of the ignition and the culmination point
tv	Ignition time delay: tv influences the degree of turbulence. This is the most important control parameter
P_m	Corrected explosion overpressure: Due to cooling and pressure effects caused by the chemical igniters in the 20-L-apparatus, the measured explosion overpressure P_{ex} has to be corrected

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Knowing the flammability limits of flammable substances are crucial knowledge as it is related to safety of the substances. Flammability limits is one of important features in development of safe practices for handling a flammable vapor or gas. It is a crucial issue in research on processing and storing organic matter safely (Chen et al., 2008). Flammability limits studies also are important for assessment of fire safety in many environments and determining the operation limits of combustion devices (Ju, Masuya and Rooney, 1998).

Different methods have been proposed to predict the flammability limits, especially the lower flammability limit for pure flammable gases. Complex gaseous mixtures, for which the Le Chatelier equation is regularly used to estimate the flammability limits, are also consumed or formed in normal and emergency situation in process industries (Chen et al., 2008). Thus, to know the effect of carbon dioxide (CO_2) on the explosion characteristics of acetylene (C_2H_2) is a need for a better handling, storage and processing of the substances.

There are way to predict the upper and lower flammability limits of mixture composed of hydrocarbon and inert CO_2 (Chen et al., 2008). The experiment that has been carried out studies on the CO_2 effects on lower flammability limit (LFL) and upper flammability limit (UFL) of C_2H_2. There are linear relations between reciprocal of upper or lower flammability limits and reciprocal of molar fraction of hydrocarbons in hydrocarbons/inert gas mixture (Chen et al., 2008).

C_2H_2 which has been used as fuel in this experiment is a colorless and odorless substance which has the flammability range of 2.50 vol. % to 81 vol. % (Coward and Jones, 1952). C_2H_2 when liquefied, compressed, heated or mixed with air will become highly explosive especially in the presence of open flames, sparks or heat (Stacey, 2002; Foxall, 2009).

1.2 Problem statement

Today industries are now more concern about the safety handling of chemical substances. Flammable substances were given more attention in order to keep a healthy and safe working place. There are incidents of fire disasters in chemical and petrochemical plants caused by the leak of materials at or above their auto ignition temperature or flash point or within their flammability limit (Tareq, 2003). The operation of tank filling and emptying or more generally speaking, of process or transportation equipment, involving flammable substances, have traditionally been quoted as very dangerous, as they involve very serious fire and explosion risks (Planas-Cuchi et al., 1999).

C_2H_2 is an extremely flammable substance in the presence of open flames, sparks and heat. It is widely used in industry as a raw material in production of other chemical (Foxall, 2009). The flammability limits characteristic of chemical substances is a crucial knowledge for safety handling, storage and also processing activities.

Due to this problem, dilution with nitrogen and carbon dioxide is a typical way of ensuring safety in the use of flammable gases (Kondo et al., 2006). Therefore, to know the effects of inert gas, in this case CO_2, on flammability limits of C_2H_2 is a need.

1.3 Objectives

There are two objectives in this study to be achieved. The two objectives are as follows:

(a) To determine the LFL and UFL of acetylene
(b) To determine the effect of CO_2 on flammability limits of C_2H_2

1.4 Scope of Study

The scopes of the study of this project are as follows:

1) The fixed variables were pressure and temperature which fixed at 1 bar absolute and 20 ^{o}C respectively. The pressure and temperature was maintained to avoid disturbance in the results obtained.
2) The manipulated variable in this experiment was volume percentage of CO_2 (0 vol. % and 15 vol. %) use in explosion. The percentage of CO_2 was varied to study the effects of CO_2 on the flammability limits of C_2H_2.
3) The controlled variables are LFL and UFL of C_2H_2. The LFL and UFL were observed and discuss to evaluate the effects of manipulated variables.

1.4 Significance of the Study

This study is related mostly about the safety handling, storage and processing of C_2H_2. As C_2H_2 is widely used in process industries, in oxy-acetylene welding and metal cutting, safety matter of the C_2H_2 must be taken into consideration. Hristova and Tchaoushev (2006) stated that flash point and flammability limits are important factors in the development of safe practices for handling and storage of pure substances and mixtures. Regulatory authorities use data for flash point in order to classify flammable and combustible substances (Hristova and Tchaoushev, 2006).

Mixtures at different temperatures and pressures are used in industrial activities. The flash point can be used to determine the level of risk in different stages of the process. Knowledge of flammability limits at elevated temperatures and pressures is needed in order to ensure safe and economically acceptable operation of chemical processes (Hristova and Tchaoushev, 2006).

By finding the effect of CO_2 on C_2H_2 and percentage of CO_2 that can reduce the possibility of explosion of acetylene, the safety precautions can be taken into consideration.

CHAPTER 2

LITERATURE REVIEW

2.1 Acetylene (C_2H_2)

Acetylene (C_2H_2) is a colorless, odorless and flammable gas. The other names of C_2H_2 are ethine and ethyne (Foxall, 2009). Table 2.1 shows some of the properties of C_2H_2.

Table 2.1: Properties of acetylene

Property	Value
Molecular weight (g/mol)	26.04
Specific gravity	920
Flammable limits (vol. %)	2.5 – 81
Density (kg/m^3)	1.097

Source: Engineering Toolbox Data (2011)

C_2H_2 is use in industry as a raw material in other chemicals production such as acetaldehyde and vinyl chloride. Most common use of C_2H_2 is as raw material for the production of various organic chemical, including 1,4-butanediol, which is widely used in the preparation of polyurethane and polyester plastics (Stacey, 2002). C_2H_2 also used as a fuel in oxy-acetylene welding and metal cutting (Foxall, 2009; Stacey, 2002).

C_2H_2 has the highest flame temperature of any common hydrocarbon because of its triple-bond structure H-C=C-H. Combustion with oxygen achieves a flame temperature of 5580 °F (3087 °C), releasing 1470 BTUs per cubic foot. Its high flame temperature allows it to be used in a variety of metal working applications like cutting, welding, brazing, and soldering (Airgas Data, 2012).

Acetylene's chemical and physical properties account for many of its uses. Its flame is highly luminous, thus it was used in miners, bicycle, automobile and streets lamps (O'Hara, 1997).

Combustion of C_2H_2 in pure oxygen produces the highest achievable flame temperature, over 3300 °C, releasing 11,800 J/g, allowing it to weld, cut, braze and solder metals in various environments. The oxy-acetylene torch is used to repair ships underwater, to construct bridges, pipelines, dams, tunnels, buildings and to reinforce concrete (O'Hara, 1997).

Exposure to C_2H_2 is most likely to occur in an occupational setting where it is produced and used. Exposure of C_2H_2 in the home is very unlikely as it is not used domestically (Foxall, 2009).

Storing and handling of C_2H_2 must with great care. When it is transported through pipelines, the pressure is kept very low and the length of the pipeline is very short. When acetylene must be pressurized and stored for use in oxy-acetylene welding and metal cutting operations, special storage cylinders are used. The cylinders are filled with an absorbent material, like diatomaceous earth, and a small amount of acetone (Stacey, 2002). Table 2.2 listed the flammability limits of some common gases used as fuel in combustion process.

Table 2.2: Flammability limits for some common gases

Gas or Vapor	Limits in air, %		Limits in Oxygen, %	
	Lower	**Higher**	**Lower**	**Higher**
Methane	5.3	15.0	5.1	61
Ethane	3.0	15.0	3.0	66
Propane	2.2	9.5	2.3	55
Butane	1.9	8.5	1.8	49

Table 2.2: Continued

Gas or Vapor	Limits in air, %		Limits in Oxygen, %	
	Lower	**Higher**	**Lower**	**Higher**
Isobutane	1.8	8.4	1.8	48
Pentane	1.5	7.8	-	-
Isopentane	1.4	7.6	-	-
Acetylene	2.5	81	-	-
Hydrogen	4.0	75	4.0	9.4
Toluene	1.4	6.7	-	-
Gasoline	1.4	7.6	-	-
Kerosene	0.7	5	-	-

Source: Coward and Jones (1952)

In this experiment, C_2H_2 was used concerning that acetylene has wide range of flammability limits which make it highly flammable especially with the presence of sparks, heat or open flames (Foxall, 2009). There are hazardous situations that can occur during filling or emptying operations which associates with the release and evaporation of flammable gases due to the rupture of a flexible hose or pipe through which the filling or emptying is being performed. The hazards of this situation are pool-fire, or if there is a delay in ignition, the formation of a flammable cloud will occur. Fire and explosion, together with release, are the most common accidents in filling or emptying operations (Planas-Cuchi, 1999). Thus, this make the selection of acetylene in this study is reasonable as it is highly flammable may caused undesired explosion if not properly handled and stored.

2.2 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is a molecule with the molecular formula CO_2 (Black, 1750). CO_2 is an odourless and colourless gas (Sickler, 1995). Although CO_2 mainly consists in the gaseous form, it also has a solid and a liquid form. It can only be solid when temperatures are below -78 ^{o}C. Liquid CO_2 mainly exists when CO_2 is dissolved in water. CO_2 is only water-soluble, when pressure is maintained. After pressure drops, the CO_2 gas will try to escape to air. This event is characterized by the CO_2 bubbles forming into water (Black, 1750). Table 2.3 shows the properties of CO_2.

Table 2.3: Properties of Carbon Dioxide

Property	**Value**
Molecular weight	44.01
Specific gravity	1.53 at 21 ^oC
Critical density	468 kg/m^3
Concentration in air	370,3 * 10^7 ppm
Stability	High
Liquid	Pressure < 415.8 kPa
Solid	Temperature < -78 ^oC
Henry constant for solubility	298.15 mol/ kg * bar
Water solubility	0.9 vol/vol at 20 ^oC

Source: Black (1750)

CO_2 has important uses in the home and in industry. For example, CO_2 released by baking powder or yeast makes cake batter rise. CO_2 in soft drinks, beer, and sparkling wines gives the beverages their fizz. Some fire extinguishers use CO_2 because it does not bum and because pure carbon dioxide is denser than air. CO_2's heaviness enables it to blanket a fire and prevent oxygen from getting to the fire (Sickler, 1995).

Dry ice is solid CO_2. CO_2 becomes a solid at -78.5 ^0C. The name dry ice refers to the fact that the substance changes from a solid to a gas without first becoming a liquid. Because of this property, dry ice is widely used in industry to refrigerate food, medicine, and other materials that would be damaged by the melting of ordinary ice (Sickler, 1995).

In this research, CO_2 is an inert gas that acts as diluents in the reaction of C_2H_2 with igniter. The CO_2 will be used in inerting process, where it will reduce percentage of oxygen (Planas-Cuchi et al., 1999; Crowl and Louvar, 2002). Alteration of upper flammability limit due to CO_2 dilution is larger than the ones for nitrogen dilution (Kondo, 2006). The addition of CO_2 in flammable gas (for this case is C_2H_2) will alter the flammability limit of C_2H_2.

2.3 Flammability limits

Flammability limits can be defined as concentration range in which a flammable substance can produce a fire or explosion when an ignition sources (such as a spark or open flame) is present (Toreki, Restivo and Gil, 2010). Flammability limits also can be defined as a range of fuel and air proportion in which combustion can be self-sustaining (Md Noor, 2011). Zlochower and Green (2006) defined flammability limits as the limiting fuel concentrations in air that can support flame propagation and lead to an explosion. Fuel concentrations outside those limits are non-flammable. In other word, flammability limit can be defined as the range of those flammable substances can produce fire or explosion if an ignition sources is present.

For an explosion to occur, there are three things needed called fire triangle. There are source of fuel (e.g., flammable gas or vapor), air (oxygen) and a source of ignition (e.g., spark, open flame, or high-temperature surface). Figure 2.1 shows the three components needed for an explosion to occur.

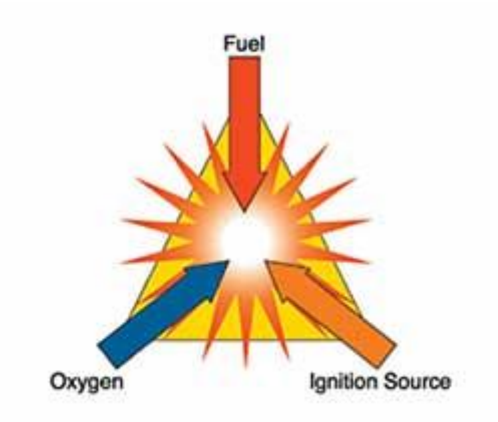

Figure 2.1: Fire triangle

Source: Holcom (2005)

The three components shown in Figure 2.1 which are fuel, oxygen and ignition source must present for an explosion to occur. Correct amount of fuel and oxygen, molecularly mixed fuel and oxygen, and minimum ignition energy are the requirements for successful combustion or explosion (Md Noor, 2011).

Flammability limits has two types which are lower flammability limit (LFL) and upper flammability limit (UFL). Lower explosive limit (LEL) and upper explosive limit (UEL) are used interchangeably with LFL and UFL (Crowl and Louvar, 2002). When the combustion of the fuel is not controlled within the confines of the burner system, the limits of flammability can be called the explosive limits (Md Noor, 2011). Figure 2.2 shows the flammable range of flammable substances.

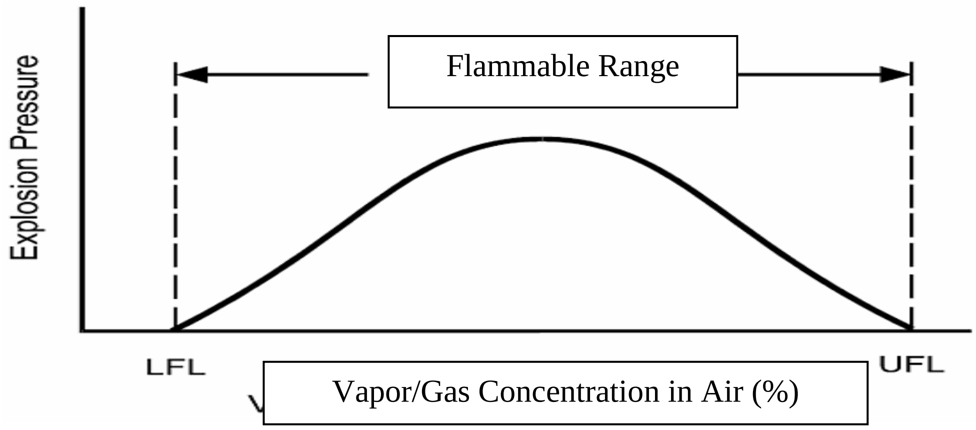

Figure 2.2: Flammable range

Source: Michaels et al. (2012)

LFL means the mixture with the smallest fraction of combustible gas and still can explode. The UFL means the mixture with the richest fraction of combustible gas and can still explode. When the mixture is below LFL, that mixture is too lean to burn. In this state, there is not enough fuel to continue an explosion and explosion cannot occur even if a source of ignition is present. Above the UFL, that mixture is too rich to burn (Chen et el., 2008). Figure 2.3 shows LEL versus UEL.

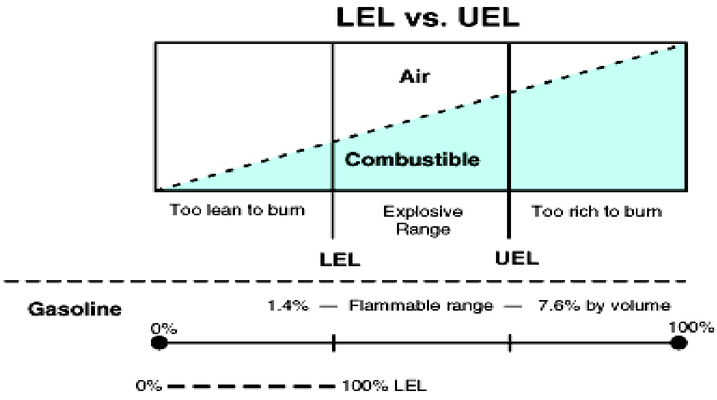

Figure 2.3: Example of LEL and UEL of Gasoline

Source: Wallace (2009)

Figure 2.3 illustrated the explosive range for gasoline. Below LEL, the mixture is too lean to burn and above the UEL, the mixture is too rich to burn. The explosion only occurs in between LEL and UEL (Wallace, 2009).

Flammability limits are one of the important features in the development of safe practices for handling a flammable vapor or gas. For this reason, they constitute a crucial research on processing and storing organic matter safely. Different methods have been proposed to predict the flammability limits, especially the LFL, for pure flammable gases. However, it is known that values of flammability limits are dependent upon the experimental apparatus and condition used for the measurement (Chen et al., 2008).

Le Chatelier's formula is commonly used to predict the flammability limits of blended gases of various fuels. Le Chatelier's formula can very well predict the values of lower flammability limits and can reasonably well predict the upper flammability limits (Kondo, 2006). Le Chatelier's formula is expressed in Eq. (2.1)

$$\frac{1}{L} = \frac{c1}{l1} + \frac{c2}{l2} + \frac{c3}{l3} + \dots + \frac{Cn}{Ln} \tag{2.1}$$

L : Flammability limits of mixtures by volume % (LFL & UFL)

C : Concentration of component, i in the gas mixture

l : Flammability limits of component, i by volume % (LFL & UFL)

The traditional criterion used in the US, which was the basis of an extensive database of flammability limits, required that flame and explosion propagation be distinguished from ignition phenomena (Coward and Jones, 1952; Kuchta, 1985). The flammability limit is a widely used index for representing flammability of gases and vapors. LFL is important for risk evaluation in the chemical industry (Cesana and Siwek, 2011).

2.4 Inerting Process

Inerting process is the process of adding an inert gas to a combustible mixture to reduce the concentration of oxygen below the limiting oxygen concentration (LOC) for the purpose of lowering the likelihood of explosion. The inert gases that usually have been used are nitrogen, carbon dioxide and sometimes steam. This inert gas does not take part in the reaction mechanism (Chen et al., 2008).

Inerting process is to alter the flammability limit and in turn to reduce the possibility of explosion or catching fire (Crowl and Louvar, 2002; Planas-Cuchi et al., 1999). The progressive addition of an inert gas to a fuel-air mixture causes the narrowing of the flammability range to the point where two limits coincide (Zlochower and Green, 2009). Inerting process commonly used to bring the oxygen concentration below 4 % (Crowl and Louvar, 2002).

Procedure of diluting a combustible gas with inert gas could be also taken as a mixing process of fuel and inert gas. Inert gas does not take part in the combustion kinetics; it seems possible that we could explain the inert gas dilution effects on the flammability limits from the viewpoint of physical principles only. In this study, the carbon dioxide dilution effects on the flammability limits for pure hydrocarbons are explored (Chen et al., 2008).

If the percentage of oxygen in the reaction of flammable gas is low, the possibility of explosion will be reduced. This is due to concentration of oxygen which is below stoichiometric.

2.5 Diluents effect

Diluents have been significantly used in industries today. The presence of diluents in methane, which is often encountered in practice, brings about significant changes in the combustion process in engines and undermines performance. The presence of diluents with methane reduces the effective heating value of the fuel mixture when the energy releases by the oxidation reactions of the fuel component is shared with diluents (Shrestha and Karim, 2000).

Dilution with nitrogen is a typical way of ensuring safety in the use of flammable gases. CO_2 is another typical gas to be used for the same purposes (Kondo et al., 2006). The alterations of UFL due to CO_2 dilution are larger than the ones for nitrogen dilution as well (Kondo et al., 2006). CO_2 is more effective than nitrogen as diluents due to its higher molar heat capacity.

2.6 Limiting Oxygen Concentration (LOC)

The maximum oxygen amount of a non-flammable fuel–air–inert mixture is the LOC (limiting oxygen concentration), an important safety characteristics. LOC which stands for limiting oxygen concentration is same as the minimum oxygen concentration. It is the limiting concentration of CO_2 below which combustion is not possible, independent of the concentration of fuel. The unit for limiting oxygen concentration is volume percent of oxygen. It varies with temperature and pressure and dependent on type of inert (non-flammable) gas (Razus et al., 2005).

Zlochower and Green (2009) stated that the limiting oxygen concentration (LOC) is the minimum oxygen concentration in a mixture of fuel, air, and an inert gas that will propagate flame. In practice, the limits (LFL, UFL, and LOC) represent an average between the neighboring concentrations inside and outside the experimental flammability limits.

When concentration of inert gas increased, the oxygen concentration decreases. When oxygen concentration below limiting oxygen concentration (LOC), flammable gas can be safely admitted to the vessel because the possibility of internal explosion has been eliminated.

2.7 Previous Work/Research

2.7.1 The Limiting Oxygen Concentration and Flammability Limits of Gases and Gas Mixtures

Zlochower and Green (2009) study on the limiting (minimum) oxygen concentration (LOC), in the presence of added nitrogen of methane (CH_4), propane (C_3H_8), ethylene (C_2H_4), carbon monoxide (CO), and hydrogen (H_2). This study also addresses the issue of the flammable concentration (flammability) limits of these pure gases in air. The study was conducted based on spark ignited explosion in large, spherical laboratory vessels (120-L and 20-L). The results obtained are compared with the older values which used long flammability tubes with a diameter more or equal to 5 cm. the results also compared with the results from 12-L spherical flask with a visual flame propagation criterion.

From the obtained results and comparison, 120-L and 12-L results show excellent agreement with 20-L results and also with earlier flammability tube values for lower flammability limits.

Table 2.4 and 2.5 summaries the comparison between 120-L, 20-L, 12-L, and flammability tubes results.

Table 2.4: Flammability/LOC: 120-L and 20-L closed vessel results vs. 12-L glass sphere and flammability tube

Fuel (F)	**Vessel**	**Stoichiometric eq.**	**Mole ratio (O_2/F)**	**LFL (mol %)**	**UFL (mol %)**	**LOC (N_2) (mol)%**
Hydrogen (H_2)	120-L	$2H_2 + O_2 \rightarrow 2H_2O$	0.5	7	75.9	4.6
	20-L			6		4.7
	Flam. tube			4	75.0	5.0
Carbon monoxide (CO)	120-L	$2CO + O_2 \rightarrow$ 2CO2	0.5	12.2	72.0	5.1
	12-L			12.2	72.5	
	Flam. tube			12.5	74.0	5.5
Methane (CH_4)	120-L	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	2	5.0	15.8	11.1
	20-L			4.9	15.9	10.7
	12-L			4.9	15.8	11.3
	Flam. tube			5.0	15.0	12.0
Ethylene (C_2H_4)	120-L	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$	3	2.7	31.4	8.5
	12-L			2.7	31.5	8.6
	Flam. tube			2.7	36.0	10.0
Propane (C_3H_8)	120-L	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	5	2.0	9.8	10.7
	12-L			2.0	10.0	10.5
	Flam. tube			2.1	9.5	11.5

Source: Zlochower and Green (2009)

Table 2.5: LOC:fuel mixtures containing methane: $CH_4 - H_2$; $CH_4 - CO$; $CH_4 - C_2H_4$; CH_4-1:1 $CO:H_2$; experimental vs. calculated

Fuel:	CH_4-H_2		CH_4-CO		CH_4-Ethylene		CH_4-1:1 CO:H_2	
% CH_4	$(LOC)_{exp}$	$(LOC)_{calc}$	$(LOC)_{exp}$	$(LOC)_{calc}$	$(LOC)_{exp}$	$(LOC)_{calc}$	$(LOC)_{exp}$	$(LOC)_{calc}$
0	4.6	4.6	5.1	5.1	8.6	8.6	4.8	4.8
10	6.5	5.6	6.1	6.1	8.6	8.7	-	-
20	-	-	-	-	-	-	7.3	6.7
25	7.7	6.9	7.8	7.4	8.9	9.0	-	-
35	8.3	7.65	-	-	-	-	-	-
40	-	-	-	-	-	-	8.7	8.2
50	9.1	8.64	9.5	9.0	9.3	9.45	-	-
60	-	-	-	-	-	-	9.7	9.4
75	10.3	10	10.9	10.2	10.05	10.1	-	-
80	-	-	-	-	-	-	10.5	10.3
90	10.9	10.7	11	10.8	-	-	-	-
100	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1

Source: Zlochower and Green (2009)

2.7.2 Extended Le Chatelier's Formula for Carbon Dioxide Dilution Effect on Flammability Limits

Kondo et al. (2006) conducted a study to measure CO_2 dilution effect on the flammability limit for various flammable gases. The Le Chatelier's formula as shown in eq. (2.2) is commonly used to predict the flammability limits of blended gases of various fuels.

$$\frac{1}{L} = \frac{c1}{l1} + \frac{c2}{l2} + \frac{c3}{l3} + \ldots + \frac{Cn}{Ln} \quad (2.2)$$

The famous Le Chatelier's formula is modified to be used for calculation of flammability limits with the presence of diluents. Dilution with CO_2 is a typical way of ensuring safety in the use of flammable gases.

The flammability limits of methane, propane, propylene, methyl formate, and 1,1-difluoroethane are adequately explained by the extended Le Chatelier's formula using a common set of parameter values. Table 2.6 shows the results obtained.

Table 2.6: Observed values of flammability limits for fuel-carbon dioxide mixtures of eight kinds of fuels.

Fuel	C_{in}[a]	L_{fuel}[b] **(vol. %)**	U_{fuel}[b] **(vol. %)**
Methane	0.000	4.90	15.8
	0.200	5.05 (0.10)	14.06 (0.15)
	0.400	5.15 (0.10)	12.2 (0.1)
	0.600	5.35 (0.10)	10.08 (0.10)
	0.700	5.65 (0.10)	8.7 (0.1)
Propane	0.000	2.03	10.0
	0.200	2.02 (0.02)	9.2 (0.3)
	0.250	2.02 (0.02)	8.9 (0.3)
	0.400	2.03 (0.03)	8.3 (0.2)
	0.600	2.07 (0.02)	7.15 (0.15)
	0.750	2.14 (0.02)	5.8 (0.1)
	0.850	2.24 (0.02)	4.53 (0.06)
Ethylene	0.000	2.74	31.5
	0.200	2.735 (0.04)	24.1 (1.0)
	0.400	2.77 (0.04)	18.5 (1.0)
	0.600	2.83 (0.04)	12.75 (0.50)
	0.750	2.92 (0.03)	8.8 (0.2)
	0.850	3.08 (0.03)	6.03 (0.15)
Propylene	0.000	2.16	11.0
	0.200	2.18 (0.03)	9.7 (0.5)
	0.400	2.17 (0.02)	8.8 (0.3)
	0.600	2.22 (0.02)	7.35 (0.15)
	0.750	2.30 (0.02)	6.13 (0.15)
	0.850	2.45 (0.02)	4.75 (0.15)
Methyl ether	0.000	3.30	26.2
	0.200	3.33 (0.04)	18.0 (0.7)
	0.400	3.35 (0.03)	14.0 (0.7)
	0.600	3.42 (0.04)	10.74 (0.25)
	0.700	3.51 (0.03)	9.1 (0.2)
	0.800	3.68 (0.03)	7.15 (0.15)
Methyl formate	0.000	5.25	22.6
	0.200	5.31 (0.05)	20.0 (0.7)
	0.400	5.33 (0.04)	17.1 (0.5)
	0.600	5.48 (0.05)	13.5 (0.5)
	0.725	5.75 (0.05)	10.75 (0.20)

Table 2.6: Continued

Fuel	**C_{in}[a]**	**L_{fuel}[b] (vol. %)**	**U_{fuel}[b] (vol. %)**
1,1-difluoroethane	0.000	4.32	17.35
	0.200	4.37 (0.04)	15.6 (0.5)
	0.400	4.41 (0.03)	13.5 (0.5)
	0.600	4.58 (0.04)	11.1 (0.5)
	0.700	4.73 (0.03)	9.35 (0.20)
	0.775	5.00 (0.03)	7.9 (0.2)
Ammonia	0.000	15.2	30.0
	0.100	16.5 (0.5)	26.3 (0.3)
	0.200	18.0 (0.5)	23.3 (0.3)

Source: Kondo et al. (2006)

2.7.3 Effects of Carbon Dioxide on Explosion Limits of Flammable Gases in Goafs

The study was done by Li et al. (2010) to reduce number of accidents due to explosions of flammable gases in the goaf of coalmines. Conditions for explosion of flammable gases and their explosion limits, affected to a considerable extent by CO_2 were explored. The experimental study was done using CH_4/H_2 and CH_4/C_2H_4 mixed with CO_2. After adding CO_2, explosion limits of gas mixtures decreased markedly with increasing amounts of CO_2. When amount of CO_2 exceeded 25 %, flammable gas mixture did not lead to explosion. When amounts of CO_2 increased, the area of explosion limits of gas mixtures decreased.

Flammability limits for CH_4/H_2 without CO_2 was 5.38 – 14.9 %. With the presence of CO_2, upper limit visibly affected while lower limit was barely affected. The limits were reduced with the increased in amount of CO_2.

2.7.4 Additive Effects on Explosion Pressure and Flame Temperature of Stoichiometric Ethylene-air Mixture in Cloud Vessels.

The study done by Movileanu et al. (2009), investigate pressure-time evolution in presence of various inert additives. The study used spherical and two cylindrical vessels with central ignition. The gaseous mixture used was ethylene-air mixture. The peak explosion pressure was measured. The influence of inert or inhibitor additives on gaseous explosion was studied.

From the studied, there were linear correlations between measured explosion pressures and inert concentration. When inert concentration increased, maximum explosion pressure decreased.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Flammability limits provide the range of fuel concentration (normally in percentage volume), within which a gaseous mixture can ignite and burn. Below the flammability limit, there is not enough fuel to cause ignition. Similarly, with fuel concentrations greater than the UFL, there is insufficient oxygen for the reaction to propagate away from the source of ignition. Thus, a precise determination of the flammability limits requires the use of a standard apparatus and conditions. The flammability limits was determined by igniting a uniform mixture of a gas or vapor with air in a closed vessel. The concentration of the flammable components is varied between trials (Tareq, 2003). As for the experiment that has been carried out, a 20-L-fire explosion vessel has been used.

3.2 Experimental apparatus

The experimental apparatus used in this experiment was a 20-L-fire explosion vessel which connected to control system KSEP 332. The 20-L-apparatus was suitable for the explosion testing of gases and vapors because the minimum volume for the explosion testing of gas solvent vapor/air mixtures is 1 L (Cesana and Siwek, 2011).

3.2.1 A 20-L-Fire Explosion Vessel

The 20-L-fire explosion test chamber was a hollow sphere made of stainless steel. There was a water jacket serves to dissipate the heat of explosion or to maintain thermostatically controlled test temperatures. The ignition source was located in the center of the sphere. This equipment was connected to PC interface.

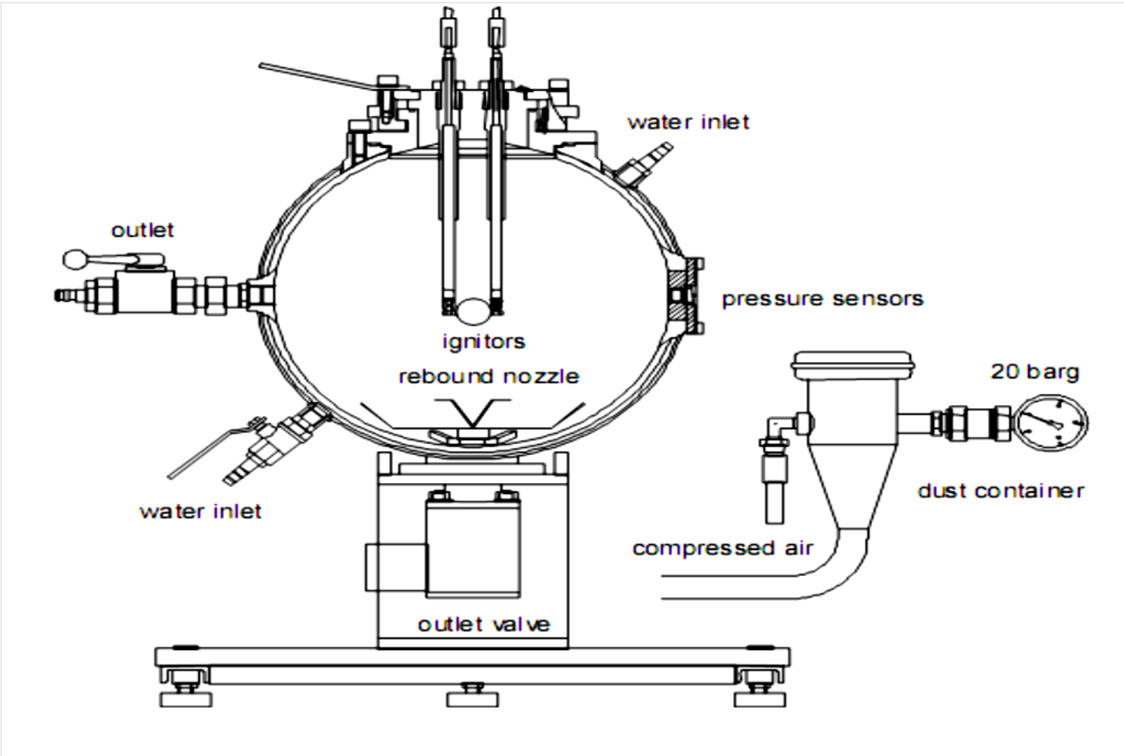

Figure 3.1: Schematic Diagram of 20-L-Fire Explosion Vessel

Source: Cesana and Siwek (2011)

3.2.2 Measurement and Control System KSEP 332

The KSEP 332 unit attached with piezoelectric pressure sensor's was used to measure the pressure as a function of time and controls the valves as well as the ignition system of the 20-L-fire explosion vessel. The measured values were processed by a personal computer. The use of two completely independent measuring channels gives good security against erroneous measurements and follows for self checking.

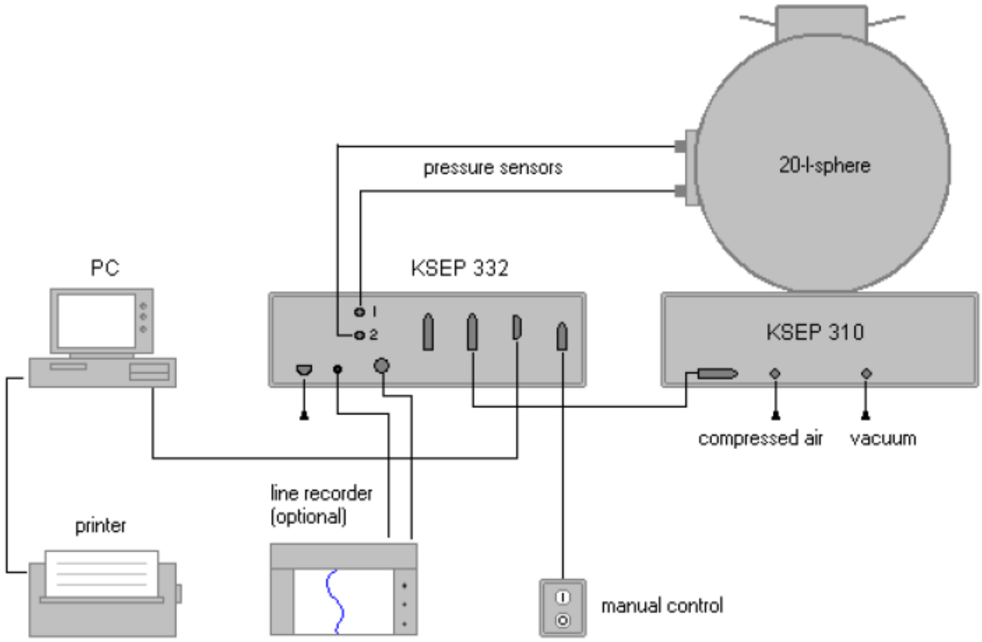

Figure 3.2: The KSEP 332

Source: Cesana and Siwek (2011)

3.3 Raw materials and setting condition

This experiment was conducted using acetylene, carbon dioxide, air (from surrounding) and also fire igniter. The purity of acetylene used was 99.6 %. The purity of carbon dioxide was 99.9 %. The fire igniter was use as source of spark to start the ignition. The fire igniter was provided 10 Joule of energy.

Table 3.1: Setting condition

Parameter	Setting
Pressure (bar absolute)	1
Temperature (^oC)	20
Mixture state	Quiescent state
Ignition energy (J)	10
Ignition delay time (s)	0

Source: Cesana and Siwek (2011)

3.3 Experimental Procedure

Figure 3.3 shows part of the 20-L-fire explosion vessel:

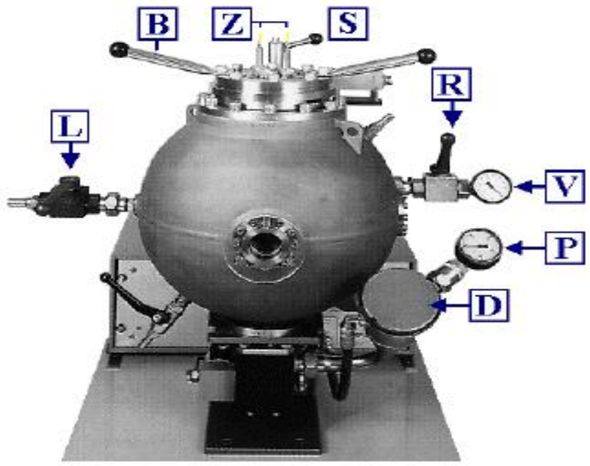

Figure 3.3: 20-L-Fire Explosion Vessel

Source: Cesana and Siwek (2011)

L = Ball valve (Venting)
B = Bayonet-ring
Z = Ignition lines
S = Safety switch
R = Ball valve (Vacuum)
V = Indication
P = Pressure Meter

Table 3.2: Guidance for symbols

Source: Cesana and Siwek (2011)

The experiment was started with switching on the apparatus and computer. The safety switch (S) was opened and the bayonet-ring (B) was turned over anti-clock vise to open the cover of the explosion vessel. The cover vessel was lifted off in order to place the igniter at the centre of the vessel by fitting the igniter in parallel to the electrode rods that connected to the cover of the vessel. Figure 3.4 shows how the igniter was placed in between two electrodes.

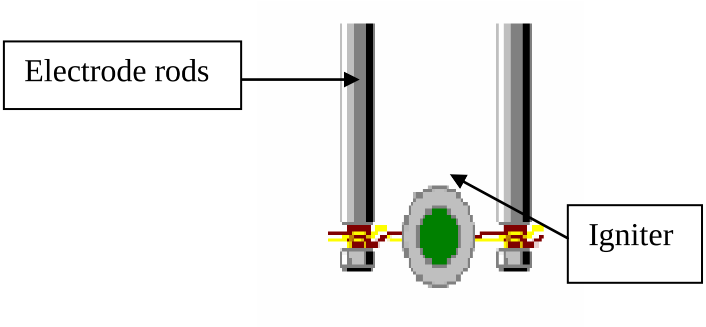

Figure 3.4: Diagram of Igniter between the Electrode Rods

The cover was placed back to vessel and the ignition lines (Z) was connected. The ball valve (L) and ball valve (R) were opened. The vacuum pump was started. The vessel was evacuated to 0.1 bar absolute. The ball valve (R) was closed. Software KSEPT 6.0 was opened in the computer. The test conditions were entered into the computer as shown in Figure 3.5.

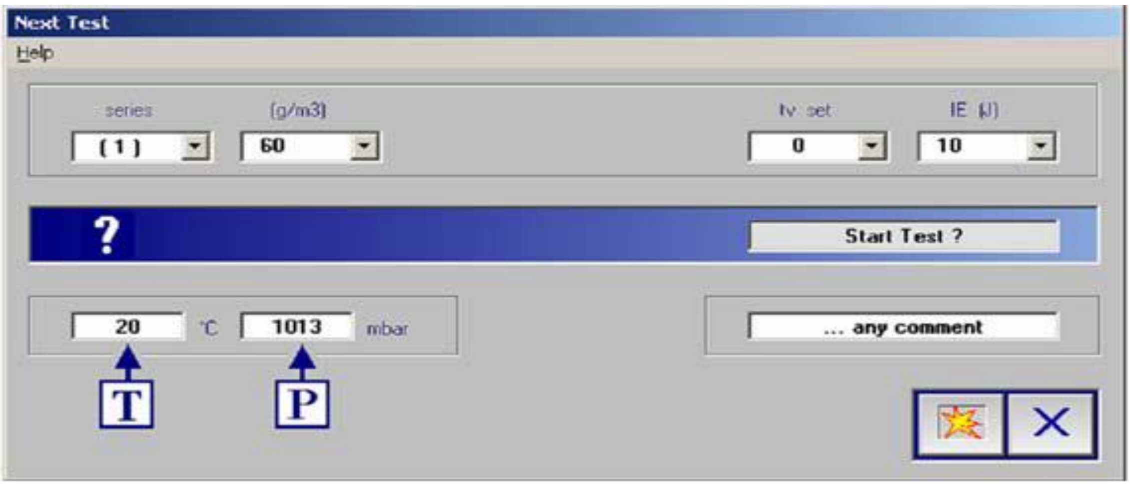

Figure 3.5: KSEPT 6.0

Source: Cesana and Siwek (2009)

The C_2H_2 and CO_2 fuel from cylinder storage were fed in to the vessel via the outlet valve and nozzle together with air from surrounding. The valve (L) at pressure gauge was closed. The gas mixture was ignited. After ignition, the pressure evolution was measured by pressure transducer as pressure versus time by the software. After each test, the ball valve (L) was opened to release exhaust gas and pressure in the vessel. The ignition line (Z) was disconnected and the safety switch (S) was opened. The bayonet –ring (B) was turned over anti-clock vise to open the cover sphere. The cover vessel was lifted off in order to clean-up inside the explosion. The vessel was cleaned up using gas vacuum cleaner. The burn-out igniter was removed and the electrode rods were cleaned. The burn-out igniter was placed with a new igniter. The cover vessel was closed and the bayonet-ring (B) was turned in the final position. The same procedure was repeated for other percentage of C_2H_2. Figure 3.6 shows the workflow of the experiment.

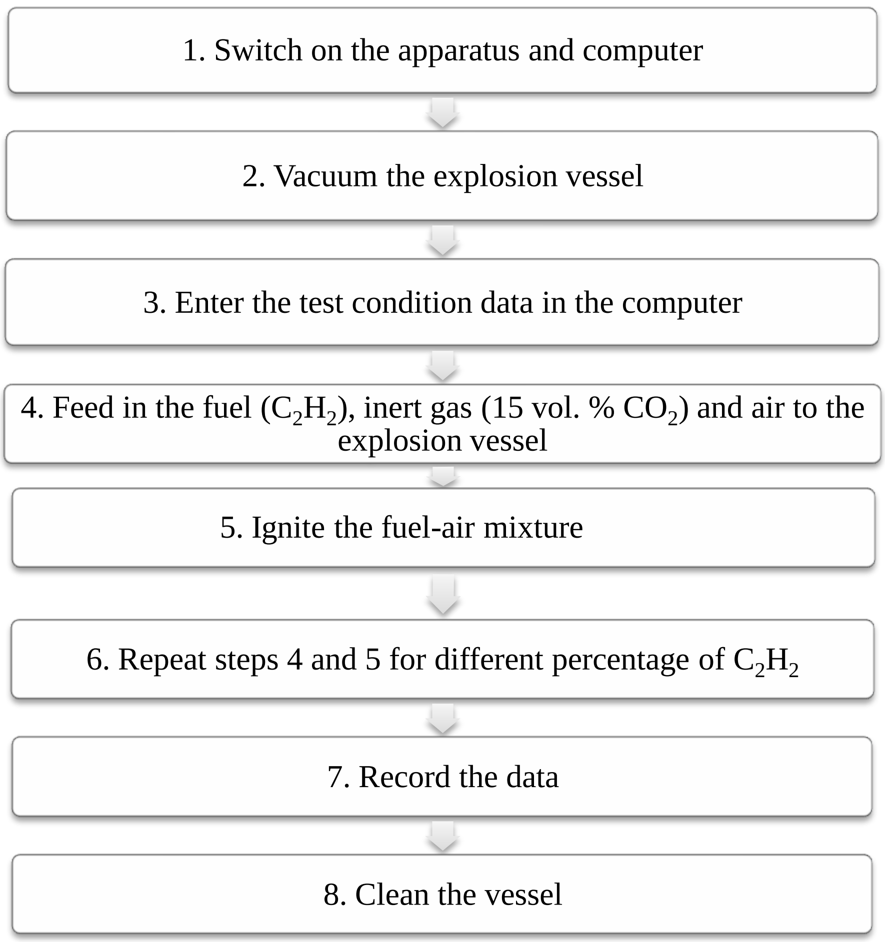

Figure 3.6: Experimental Work Flows

CHAPTER 4

RESULTS AND DISCUSSION

This experiment was carried out to determine the flammability limit of the fuel, in this case is acetylene (C_2H_2); with and without the presence of diluents, which is carbon dioxide (CO_2). Through this experiment, the lower flammability limit (LFL) and upper flammability limit (UFL) have been obtained.

The experiment was carried out in 20-L-fire explosion unit with operating pressure 1 bar and temperature 20 °C. The maximum pressure (P_{max}) was obtained at optimum fuel concentration. The pressure was determined from wide range of fuel concentration used in this experiment.

4.1 Explosion of acetylene (C_2H_2) without the Presence of Diluents

This experiment was carried out for determining flammability limits of C_2H_2 without the presence of CO_2. Table 4.1 and Figure 4.1 show the result obtained from explosion of C_2H_2 without the presence of diluents.

Table 4.1: Summary of P_m and dP/dt of Acetylene Explosion

Vol % C_2H_2	$P_{C_2H_2}$	Vol % Air	P_{Air}	P_m (bar)	dP/dt
1	0.02	99	0.98	0.00	0
2	0.03	98	0.97	1.00	10
3	0.04	97	0.96	2.00	82
4	0.05	96	0.95	2.20	136
5	0.06	95	0.94	2.80	198
6	0.07	94	0.93	3.10	239

Table 4.1: Continued

Vol % C_2H_2	$P_{C_2H_2}$	Vol % Air	P_{Air}	P_m (bar)	dP/dt
7	0.08	93	0.92	3.50	375
8	0.09	92	0.91	3.60	372
9	0.10	91	0.90	3.80	460
10	0.11	90	0.89	3.80	452
11	0.12	89	0.88	3.90	553
12	0.13	88	0.87	4.00	515
13	0.14	87	0.86	3.90	319
14	0.15	86	0.85	3.80	230
17	0.18	83	0.82	3.70	230
19	0.19	81	0.81	3.30	210
21	0.22	79	0.78	3.10	152
25	0.26	75	0.74	3.20	154
29	0.30	71	0.70	3.30	160
40	0.41	60	0.59	3.50	167
60	0.61	40	0.39	3.40	92
65	0.66	35	0.34	3.10	130
70	0.71	30	0.29	2.90	116
75	0.76	25	0.24	2.90	94
77	0.78	23	0.22	0.00	0

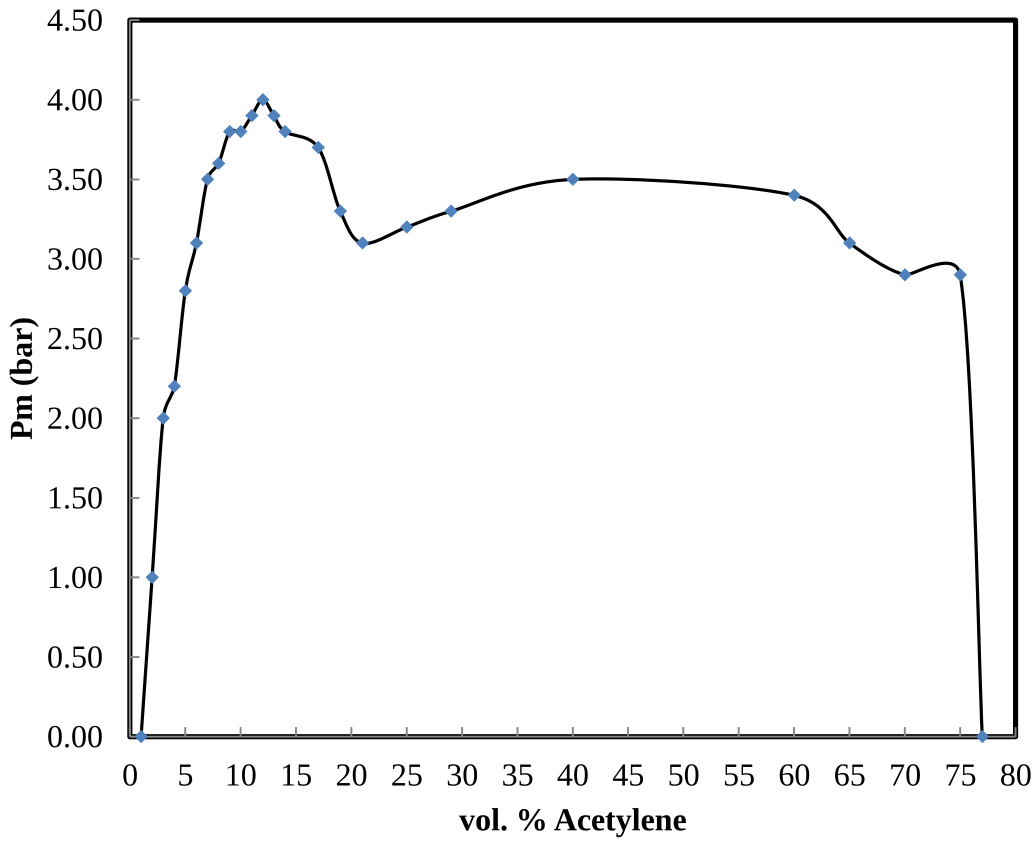

Figure 4.1: Graph of corrected Pressure, P_m (bar) versus vol. % Acetylene

From the data obtained, the lower flammability limits (LFL) and upper flammability limits (UFL) were determined. From Figure 4.1, LFL for C_2H_2 is 2 vol % of C_2H_2 and UFL is 75 vol % of C_2H_2. The maximum pressure of C_2H_2 explosion is 4 bar at 12 vol % C_2H_2.

The experimental results were just slightly different with the previous study done by Coward and Jones (1952). From the previous study, the flammability range of C_2H_2 was from 2.5 – 81 vol. %, while flammability range obtained from this experiment was from 2 – 75 vol. %. This results show a reasonable agreement with the previous study. The different between both limits may be due to an error during the experiment. The different in equipment used also affect the results obtained. As from study done by Zlochower and Green (2009), the flammability limits for the same fuel is different when use different type of vessel.

The shape of the graph in Figure 4.1 shows bell-shaped graph. This shape of graph shows an agreement with the flammability graph from Michaels et al. (2012). The explosion only occurs in the area below the graph. At first, the limits is increasing with increasing of fuel concentration, but after reach the optimum point, the limits decreased until there is no explosion can happen at that particular concentration.

4.2 Explosion of Acetylene (C_2H_2) with Presence of 15 vol. % of Carbon Dioxide (CO_2)

This experiment was studied to determine the flammability limits of C_2H_2 with presence of 15 vol % of CO_2. CO_2 is an inert gas that acts as diluents in this explosion. Based on the results obtained, it shows that CO_2 does affect the explosion of C_2H_2. In this experiment, CO_2 act as a suppression agent where it reduces the amount of oxygen present in the air, thus mitigating the explosion to the minimum pressure.

Table 4.2 and Figure 4.2 show the results for explosion of C_2H_2 with presence of CO_2 which is commonly used in the suppression system. From these results, LFL of C_2H_2 is at 3 vol. % and the UFL is at 35 vol. %. The maximum pressure obtained for explosion of C_2H_2 with presence of CO_2 is 2.9 bar.

Table 4.2: Summary of P_m and dP/dt of Acetylene Explosion

Vol % C_2H_2	$P_{C_2H_2}$	Vol % CO_2	P_{CO_2}	Vol % Air	P_{Air}	Pm (bar)	dP/dT
1	0.02	15	0.15	84	0.83	0.00	0
2	0.03	15	0.15	83	0.82	0.00	0
3	0.04	15	0.15	82	0.81	1.00	10
4	0.05	15	0.15	81	0.80	1.70	8
5	0.06	15	0.15	80	0.79	2.40	142
6	0.07	15	0.15	79	0.78	2.60	119
7	0.08	15	0.15	78	0.77	2.90	112
9	0.10	15	0.15	76	0.75	2.80	80
10	0.11	15	0.15	75	0.74	2.60	75
13	0.14	15	0.15	72	0.71	2.60	62

Table 4.2: Continued

Vol % C_2H_2	$P_{C_2H_2}$	Vol % CO_2	P_{CO_2}	Vol % Air	P_{Air}	Pm (bar)	dP/dT
19	0.20	15	0.15	66	0.65	2.30	40
24	0.25	15	0.15	61	0.60	2.00	22
35	0.36	15	0.15	50	0.49	2.00	22
40	0.41	15	0.15	45	0.44	0.00	0
50	0.51	15	0.15	35	0.34	0.00	0

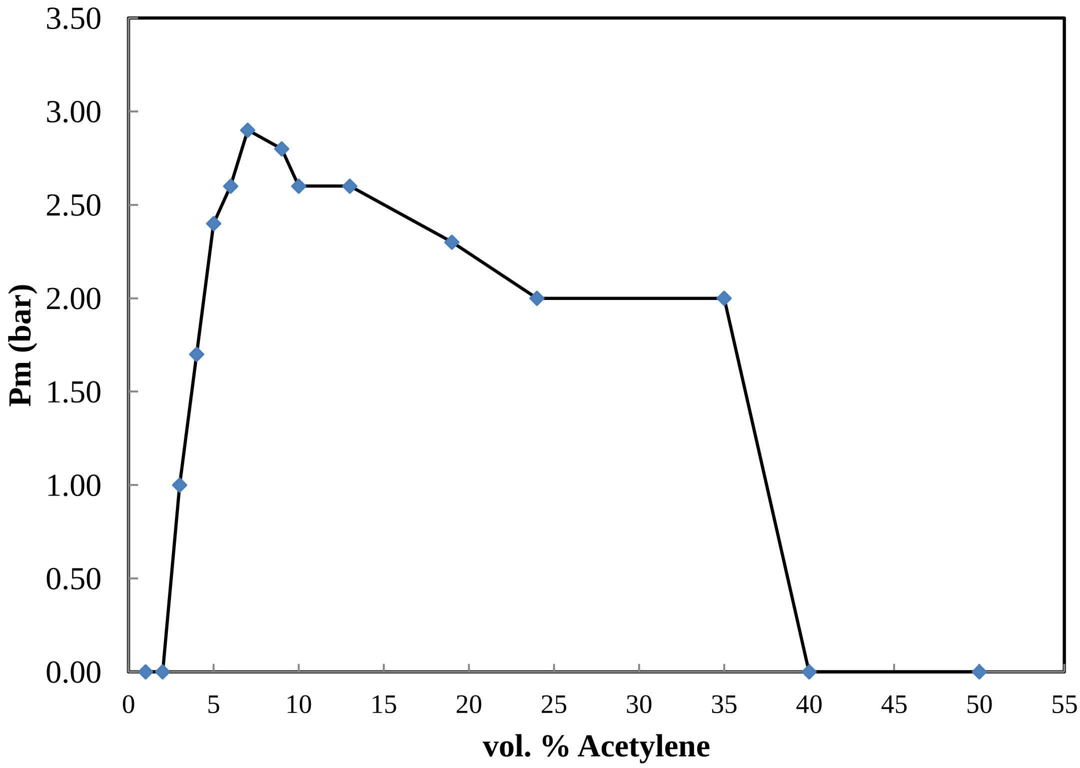

Figure 4.2: Graph of corrected Pressure, P_m (bar) versus vol % Acetylene

4.3 Comparison of the Data

Based on the results obtained, the comparison between explosion of acetylene without the presence of CO_2 and explosion of C_2H_2 with the presence of 15 vol % CO_2 were done.

From the data of acetylene explosion without carbon dioxide, the flammability range is 2 – 75 vol %. The maximum pressure of 4.0 bar is obtained at 12 vol % of acetylene.

Flammability range for explosion of acetylene with the presence of 15 vol % carbon dioxide is 3 – 40 vol %. The maximum pressure of 2.9 bar is obtained at 7 vol % of acetylene. Table 4.3 summaries the comparison between explosion of C_2H_2 with and without the presence of CO_2.

Table 4.3: Comparison data of LFL, UFL, P_{max} and dP/dt between Explosion of Acetylene with and without the Presence of Carbon Dioxide

No.	**Fuel**	**Diluents**	**LFL (vol %)**	**UFL (vol %)**	**P_{max} (bar)**	**dP/dt (bar/s)**
1	Acetylene (C_2H_2)	Without Carbon Dioxide (CO_2)	2	75	4.0	515
2	Acetylene (C_2H_2)	15 vol % Carbon Dioxide (CO_2)	3	40	2.9	112

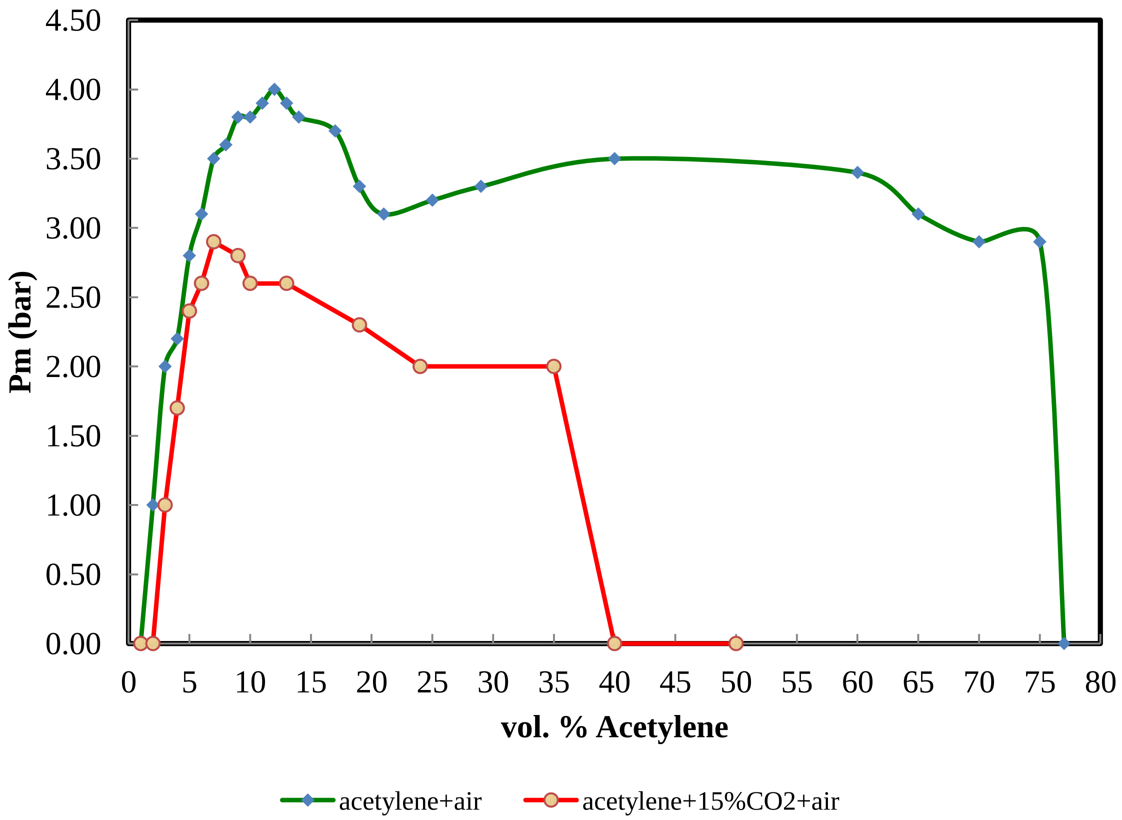

Figure 4.3: Comparison between explosion of acetylene with and without presence of CO_2.

Based on the Table 4.3, the flammability limits of acetylene were altered by the presence of CO_2. CO_2 reduce the concentration of oxygen below LOC, thus lowering the explosion/flammability limits. At UFL, flammable material does not undergo complete combustion.

Figure 4.3 clearly shows the alteration of flammability range of C_2H_2 with the presence of CO_2. The LFL of C_2H_2 was increased with the presence of CO_2, from 2 % to 3 %. The UFL was decreased with the presence of CO_2, from 75 % to 35 %. The lower limit was barely affected while the upper limit was visibly affected. This result shows an excellent agreement with the previous study done by Li et al. (2010).

The area of explosion of C_2H_2 also decreased with the presence of CO_2. This is due to lowering of oxygen concentration which also leads to lowering the risk of explosion. By adding inert gases, such as nitrogen, N_2, or carbon dioxide, CO_2, the explosion hazard was reduced. (Bjerketvedt et al., 1998).

The maximum explosion pressure of C_2H_2 also decreased with the presence of CO_2 from 4 bar to 2.9 bar. This result shows an excellent agreement with the previous study done by Movileaunu et al. (2009). From Movileaunu et al. (2009), the maximum explosion pressure decreased with the increasing of inert gas concentration. In this case, the maximum explosion pressure of C_2H_2 with the presence of CO_2 is lower than maximum explosion pressure of C_2H_2 without the presence of CO_2. Thus, CO_2 does lower the risk of explosion.

4.4 Comparison with Previous Work

The results obtained from this experiment were being compared to the previous work on flammability limits of gaseous mixture. There are two experiments that have been carried out by Zlochower and Green (2009) and Kondo et al. (2006). Zlochower and Green (2009) studied the effect of CO_2 on limiting oxygen concentration (LOC) of various gases using 120-L and 20-L vessels. Kondo et al. (2006) studied the extended Le Chatelier's formula for measuring the CO_2 dilution effect on the flammability limits of various gases. Table 4.4 shows the summary of all the study.

Table 4.4: Comparison between present studies with previous study

Journal	Fuel (F)	Inert	Method	LFL	UFL
Coward and Jones (1952)	Methane	-	Vessel	5.3 (vol.%)	15 (vol.%)
	Acetylene	-	Vessel	2.5 (vol.%)	81 (vol.%)
Zlochower	Methane	2 mol (O_2/F)	20-L vessel	4.9 (vol.%)	15.9 (vol.%)
Kondo et al. (2006)	Methane	0 mol (CO_2/F)	Extended Le Chatelier	4.90 (vol.%)	15.8 (vol.%)
		0.2 (CO_2/F)	Extended Le Chatelier	5.05 (vol.%)	14.06 (vol.%)

Table 4.4: Continued

Journal	Fuel (F)	Inert	Method	LFL	UFL
		0.4 (CO_2/F)	Extended Le Chatelier	5.15 (vol.%)	12.2 (vol.%)
		0.6 (CO_2/F)	Extended Le Chatelier	5.35 (vol.%)	10.08 (vol.%)
		0.7 (CO_2/F)	Extended Le Chatelier	5.65 (vol.%)	8.7 (vol.%)
Present	Acetylene	-	20-L vessel	2.0 (vol.%)	75 (vol.%)
		0.15 vol.% (CO_2/ CO_2+F)	20-L vessel	3.0 (vol.%)	35 (vol.%)

From Table 4.4, it was clearly stated that with the increasing of CO_2, the LFL of methane increase, while UFL decreased. From Kondo et al. (2006), for methane with 0.7 mole CO_2/mole fuel, LFL is 5.65 and UFL is 8.7 vol. %. Compared with Coward and Jones (1952), for pure methane, LFL is 5.3 vol. % and UFL is 15 vol. %. This clearly shows that CO_2 does narrowing the flammability range of the gaseous mixture.

As for C_2H_2, Coward and Jones (1952) data shows that pure C_2H_2 has LFL 2.5 vol. % and UFL 81 vol. %, while based on this study, acetylene with 15 vol. % CO_2 has LFL 3.0 vol. % and UFL 35 vol. %. This shows that CO_2 has increased the LFL of C_2H_2 and decreased the UFL of C_2H_2. The presence of CO_2 reduces the effective heating value of the fuel mixture when the energy releases by the oxidation reactions of the fuel component is shared with diluents (Shresta and Karim, 2000). This cause the flammability limits to be lower with the presence of CO_2.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on the results obtain from the study, flammability limits of substances is a crucial knowledge. By understanding the flammability limits and basic requirements for explosion to occur, any explosion or fire can be avoided.

In this study, the effect of CO_2 on the C_2H_2 was studied. The increasing of CO_2 as diluents in flammable gaseous (acetylene) increases its LFL and decreases its UFL. Therefore, the range of flammability of the acetylene was reduced. When the range of flammability was reduced, the possibility of catching fire or explode is low.

5.2 Recommendations

There are some recommendations for the next future study in order to improve the results obtained.

(i) Provided the vessel with high speed camera in order to capture the propagation of flame inside the vessel so that the further and details study can be made.

(ii) Use more various concentration of C_2H_2 to get more accurate data.

(iii) Compare the effect between different types of inert gases such as nitrogen and steam.

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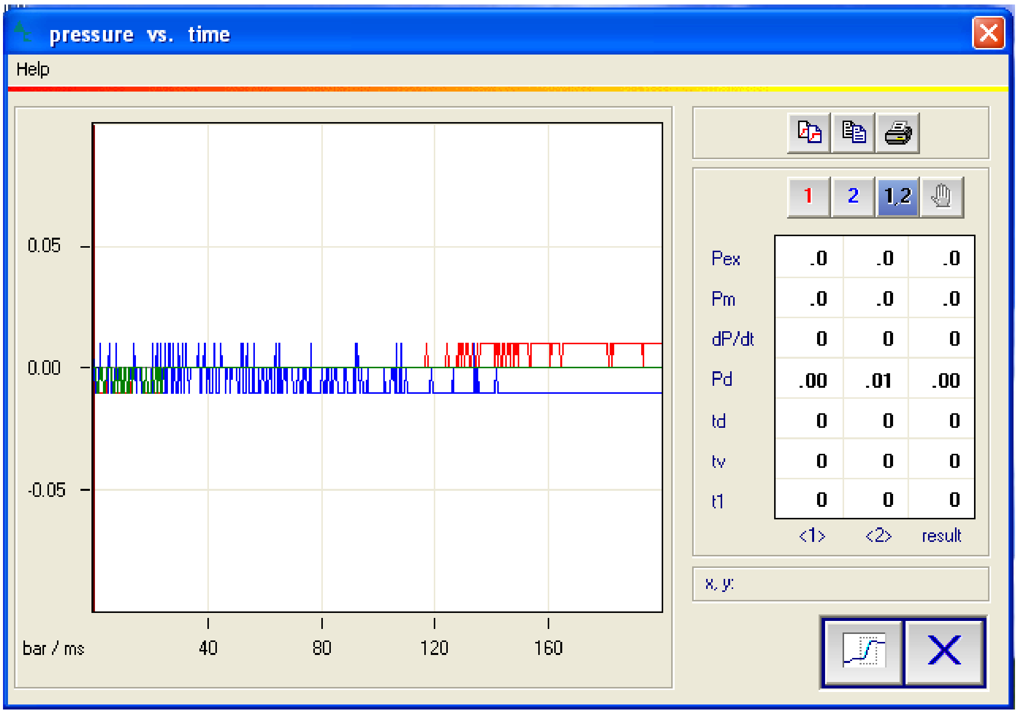
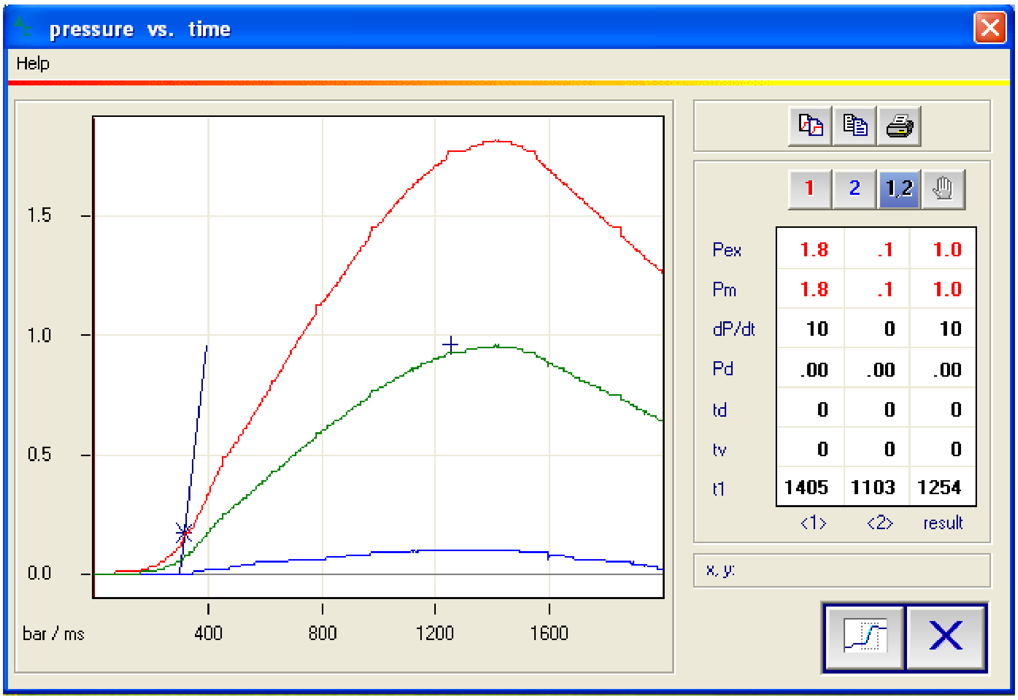
APPENDIX A

Data from software for pure Acetylene + air at operating pressure 1 bar

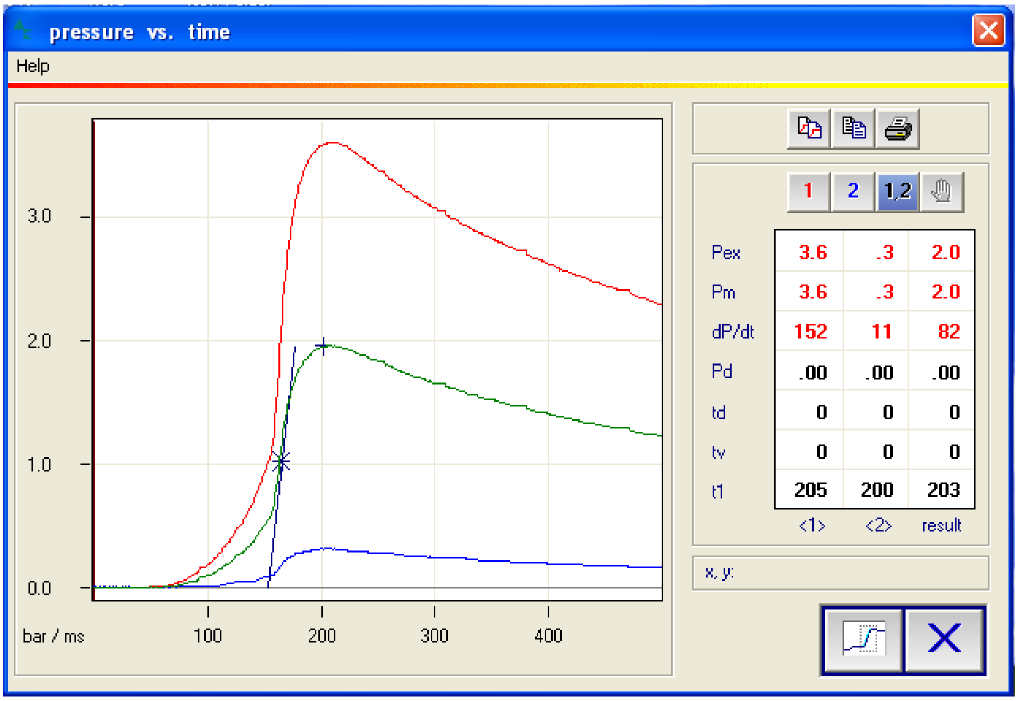
1. 1 % C_2H_2



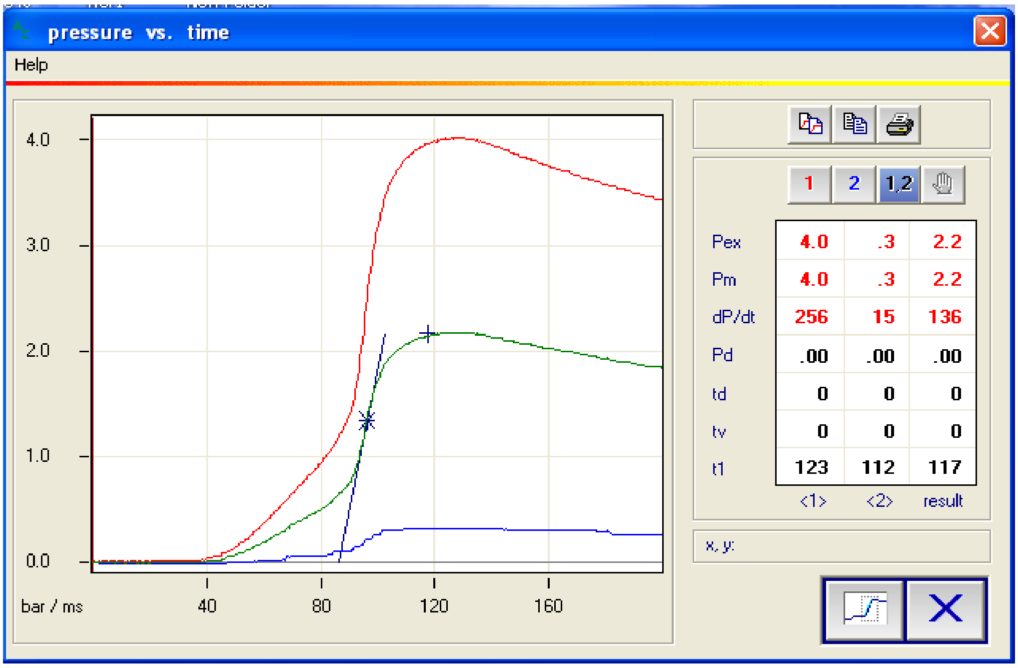
2. 2 % C_2H_2



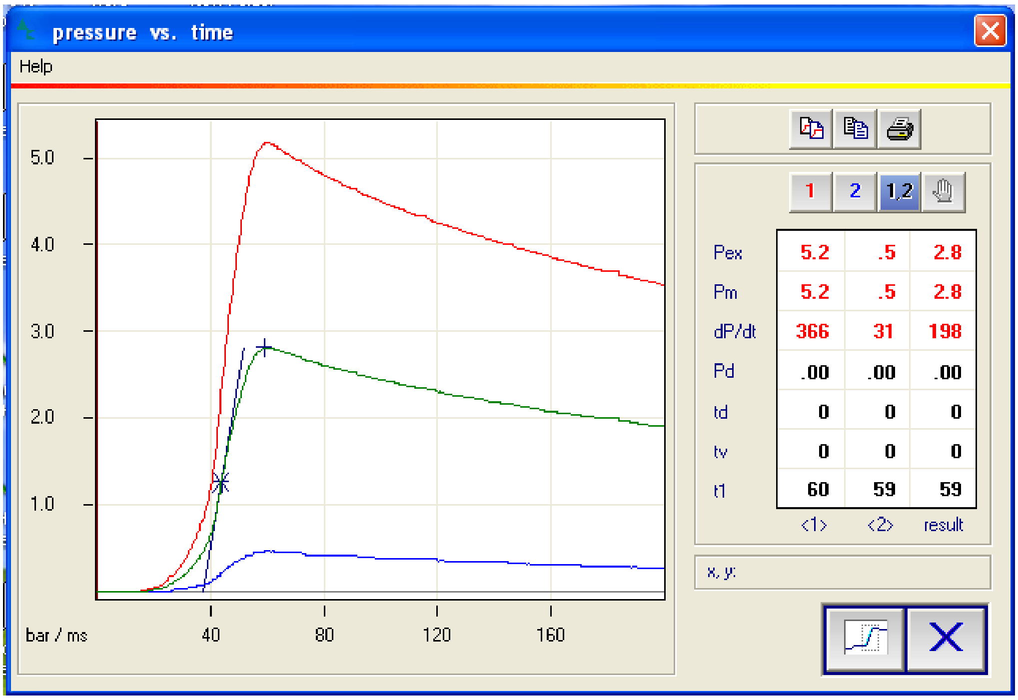
3. 3 % C_2H_2



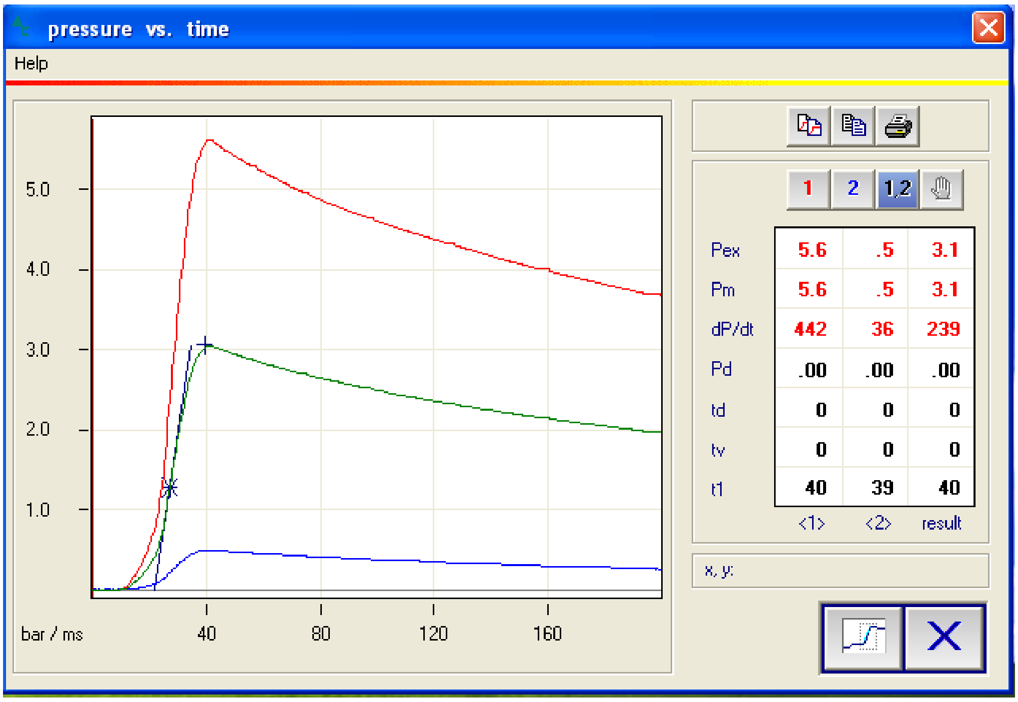
4. 4 % C_2H_2



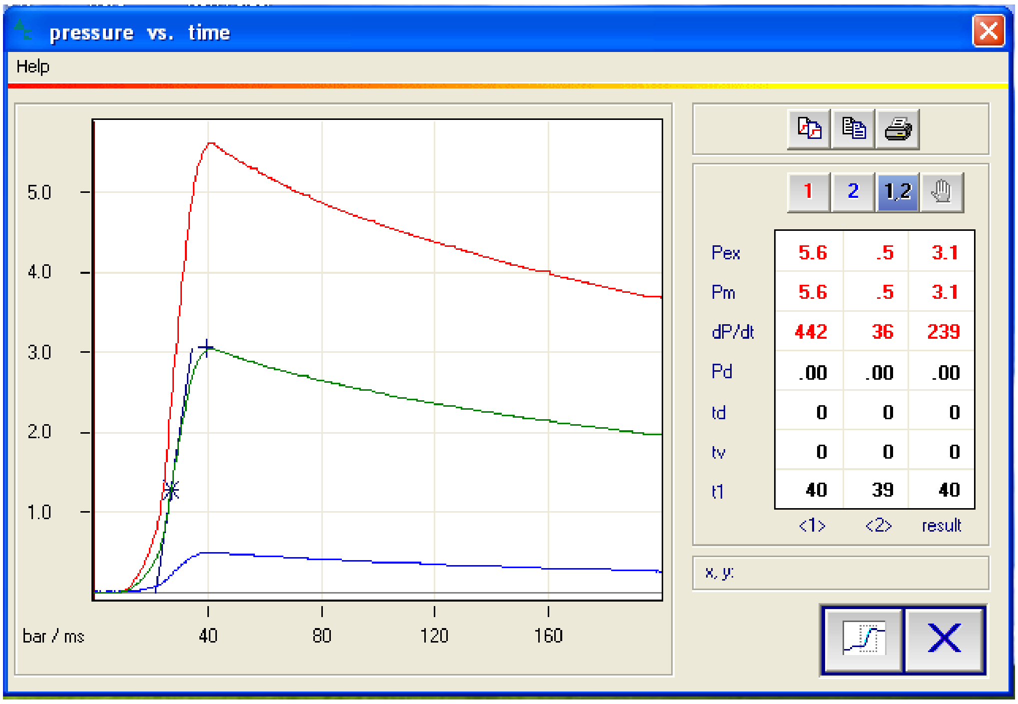
5. 5 % C_2H_2



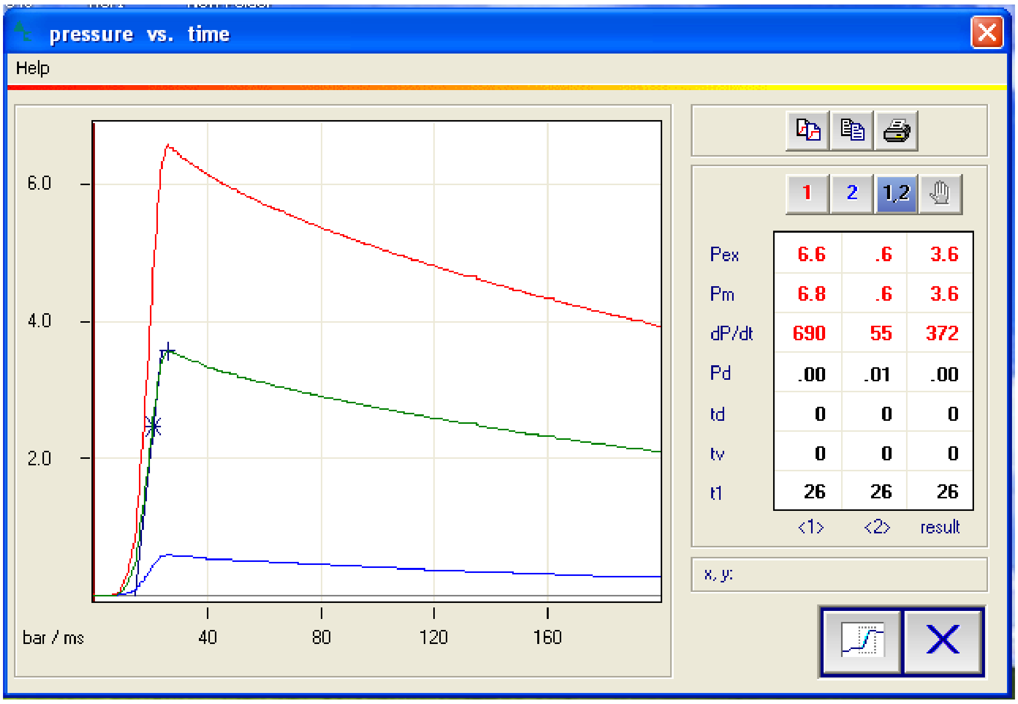
6. 6 % C_2H_2



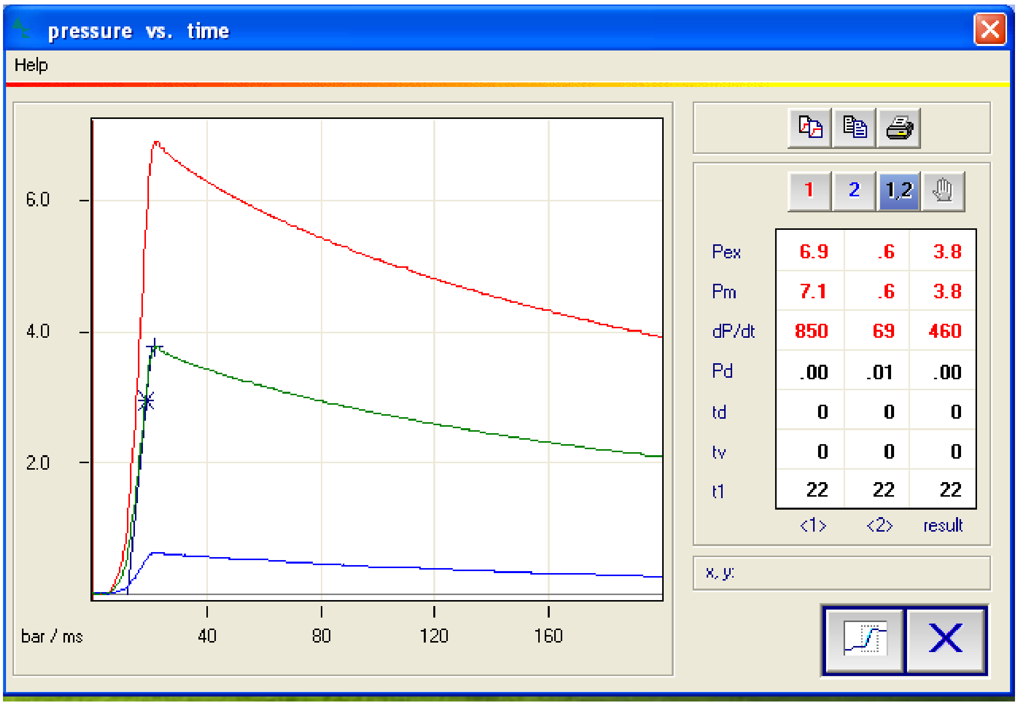
7. 7 % C_2H_2



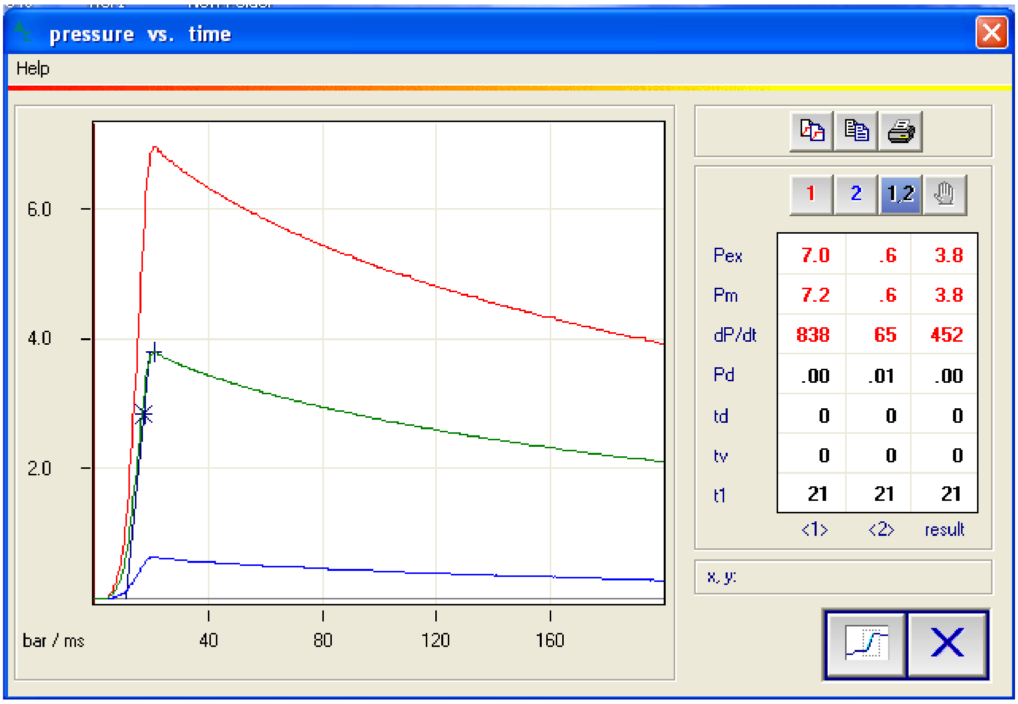
8. 8 % C_2H_2



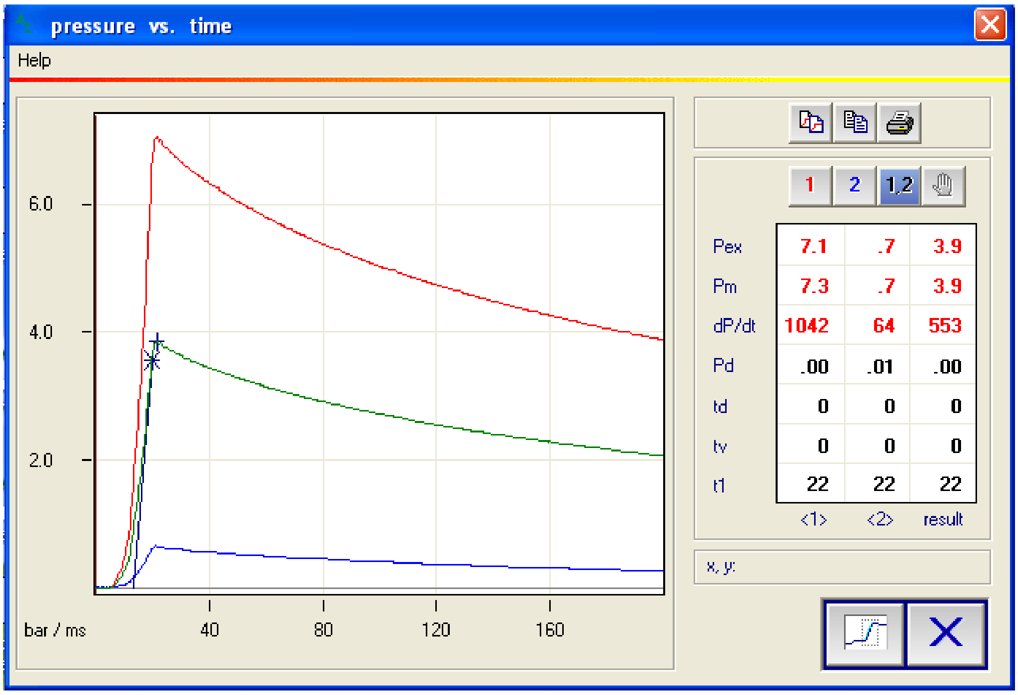
9. 9 % C_2H_2



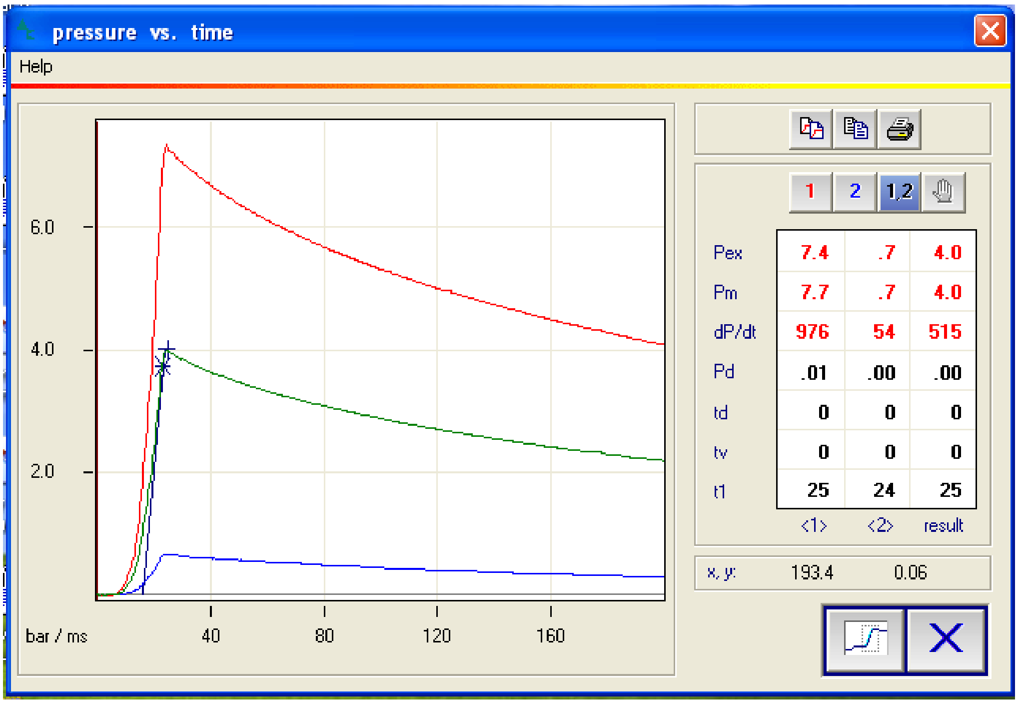
10. 10 % C_2H_2



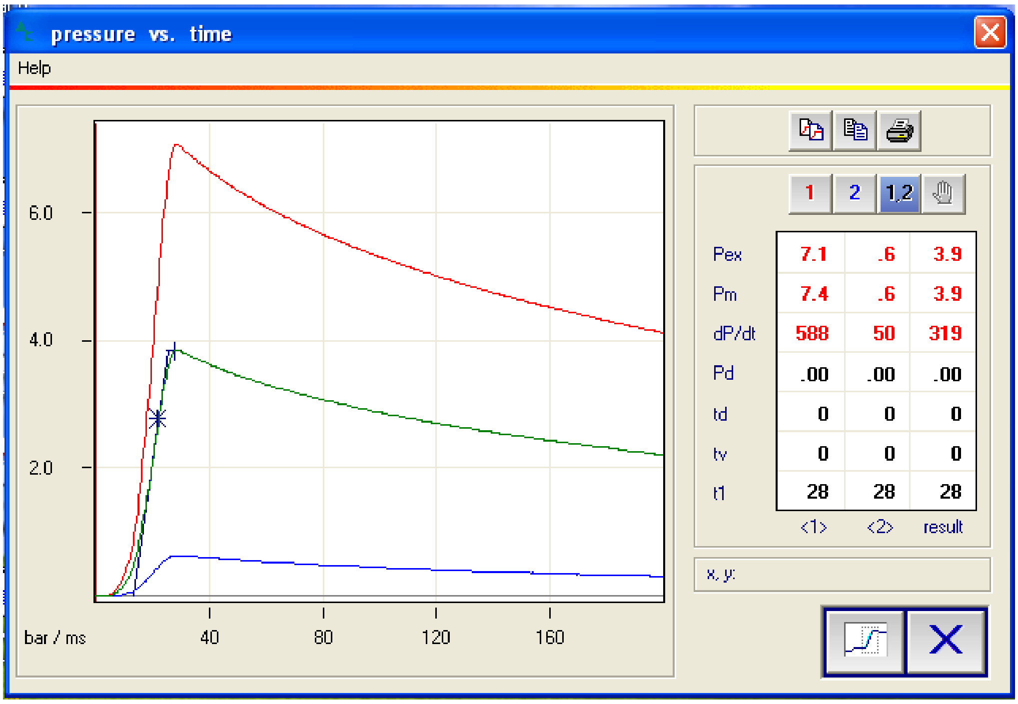
11. 11 % C_2H_2



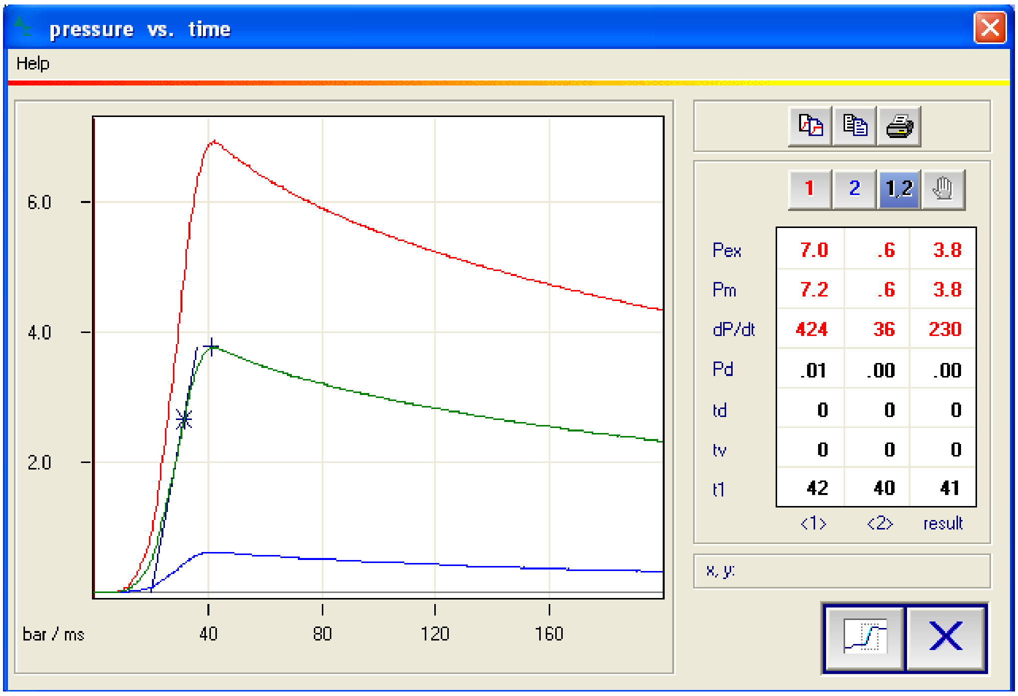
12. 12 % C_2H_2



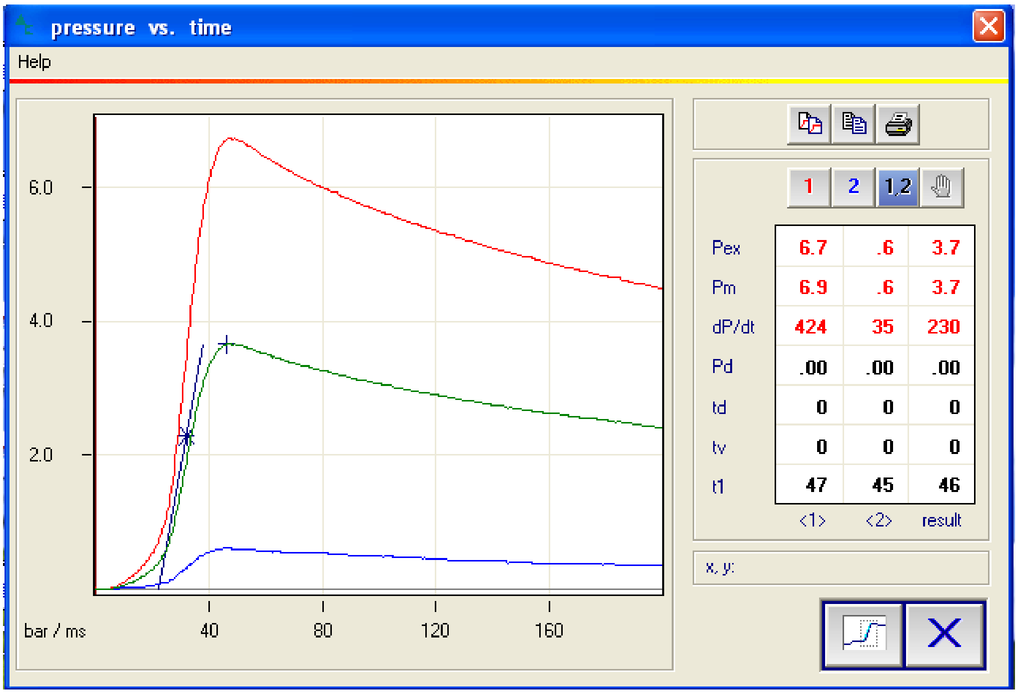
13. 13 % C_2H_2



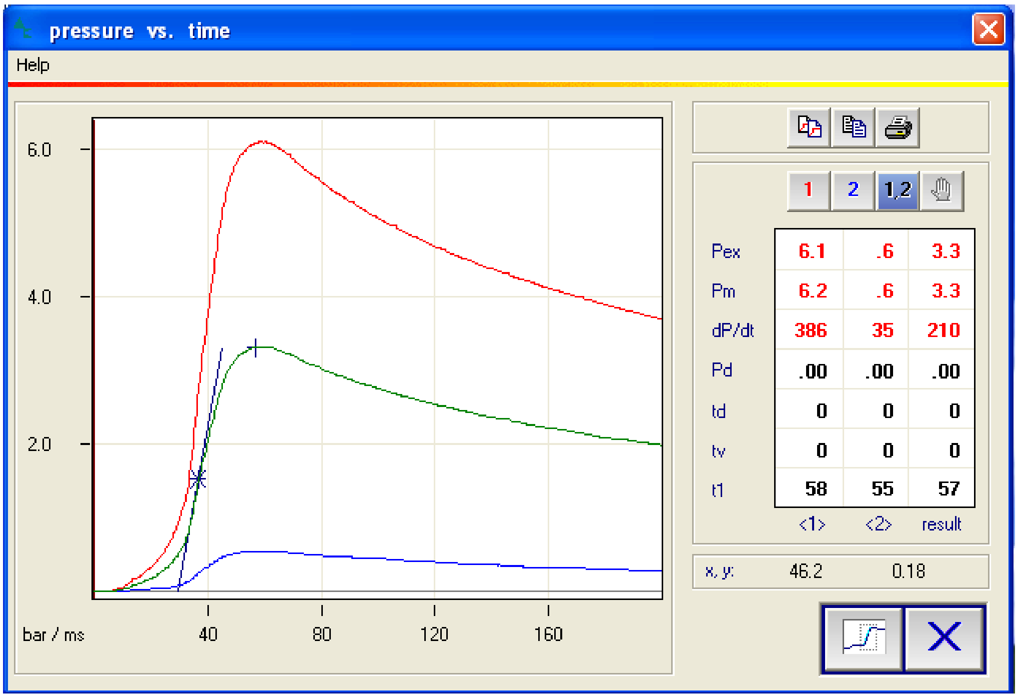
14. 14 % C_2H_2



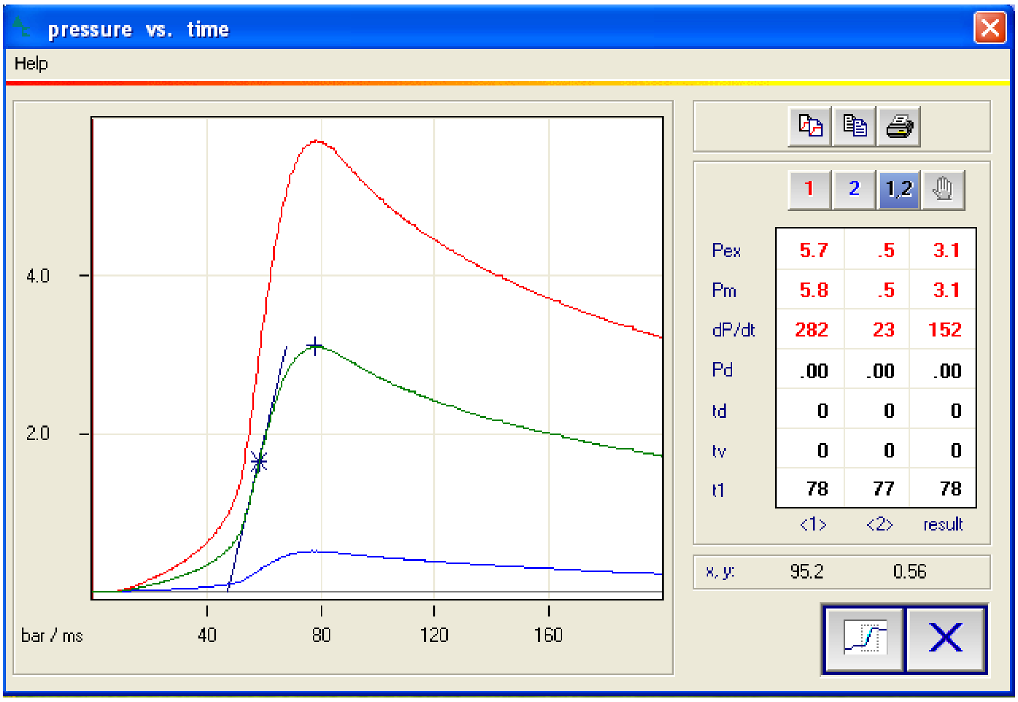
15. 17 % C_2H_2



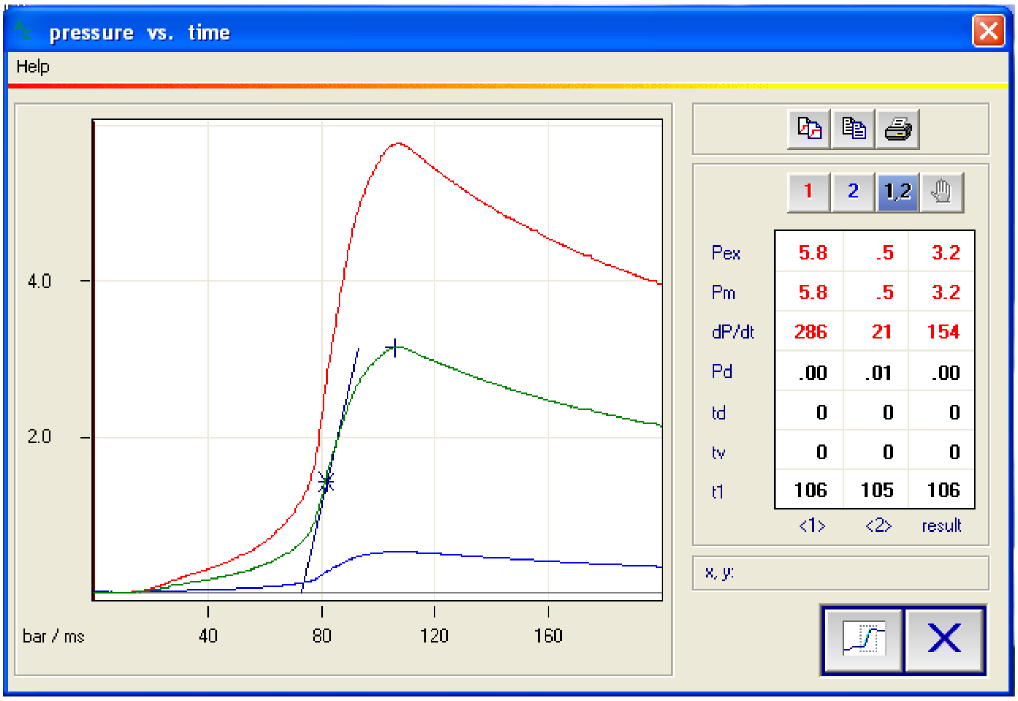
16. 19 % C_2H_2



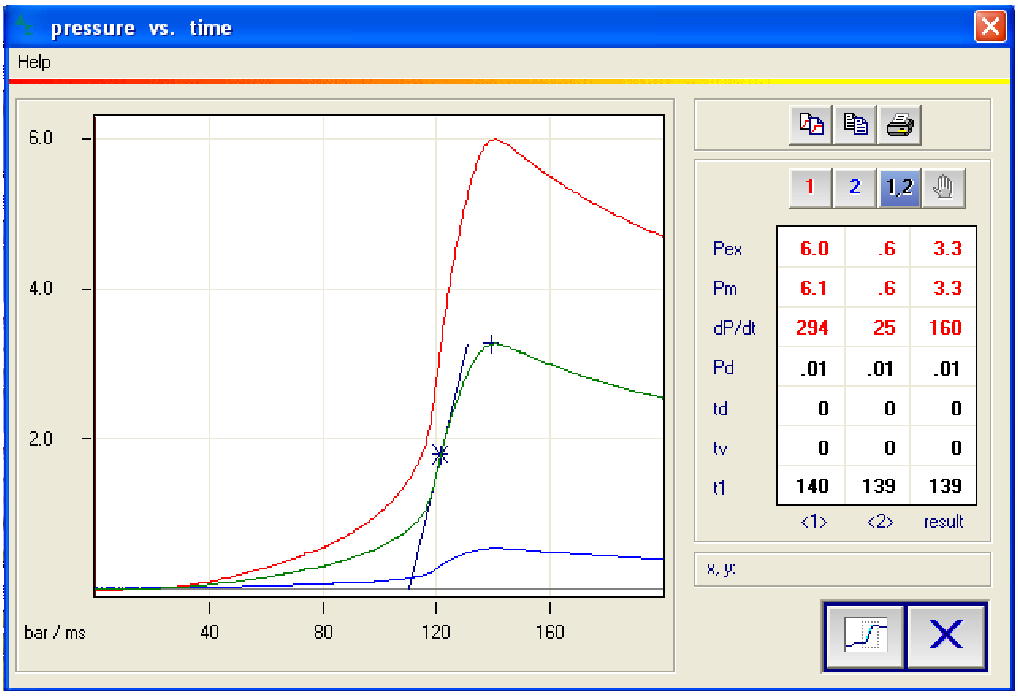
17. 21 % C_2H_2



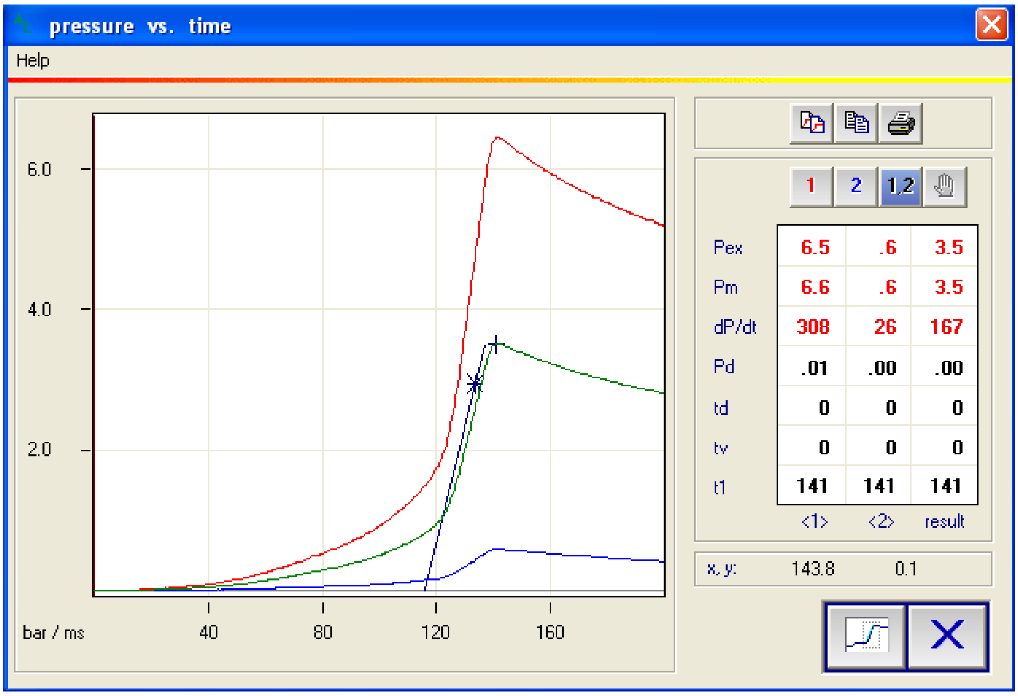
18. 25 % C_2H_2



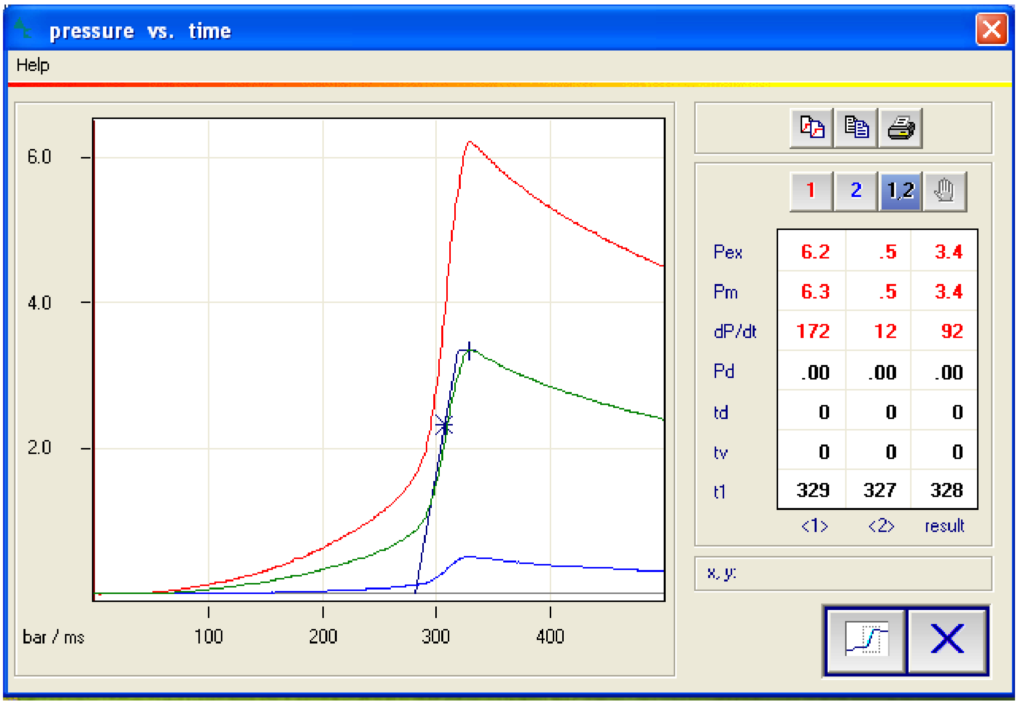
19. 29 % C_2H_2



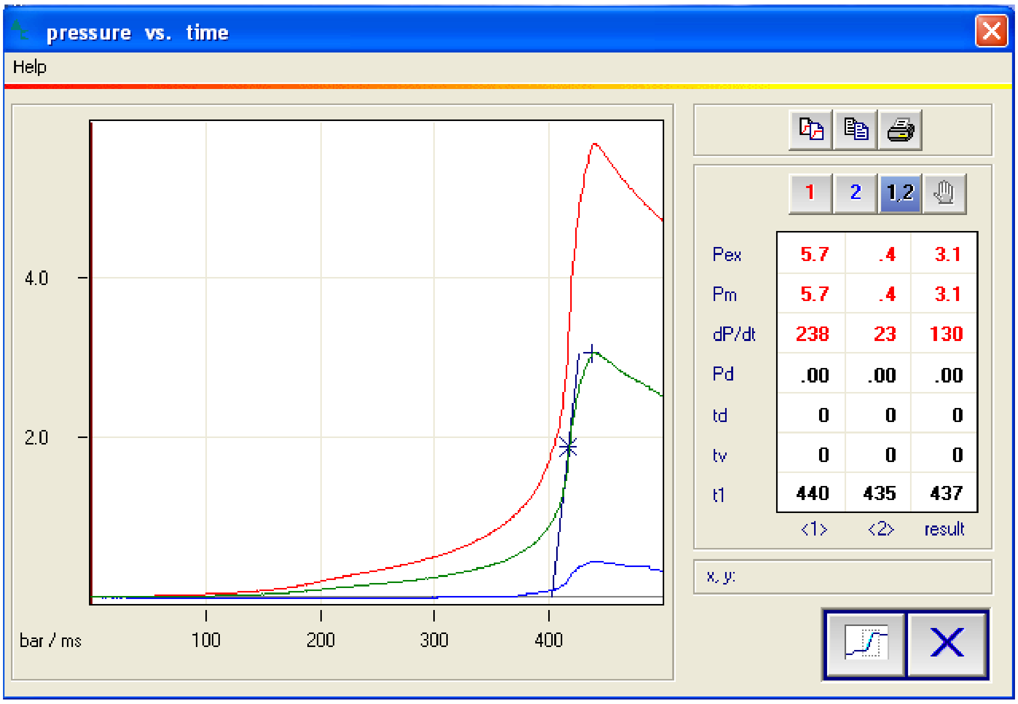
20. 40 % C_2H_2



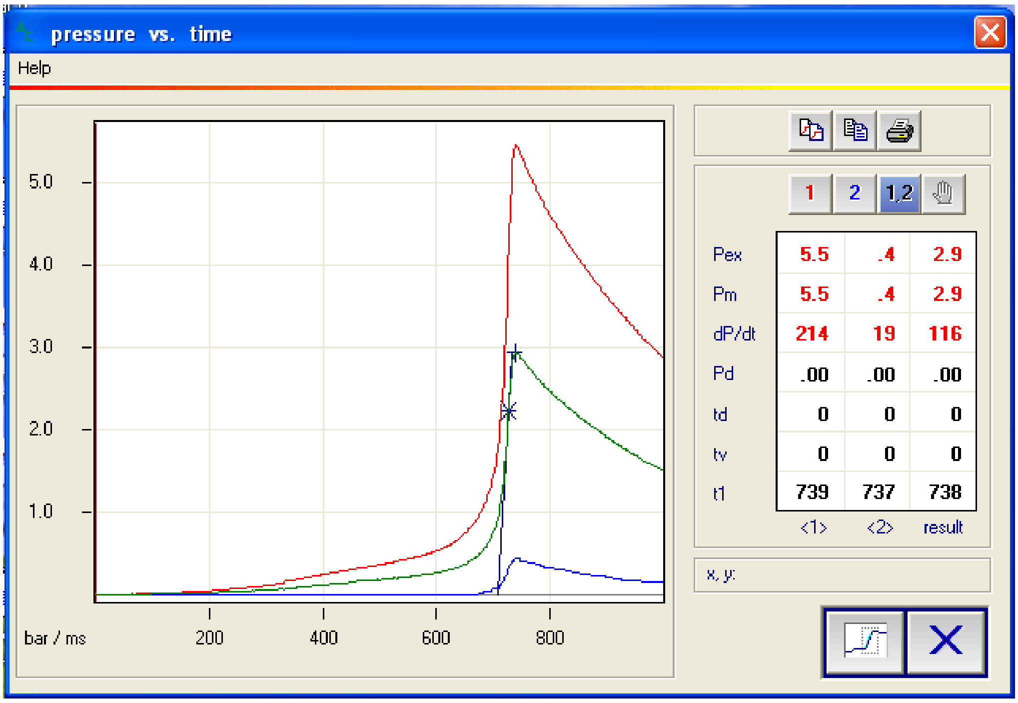
21. 60 % C_2H_2



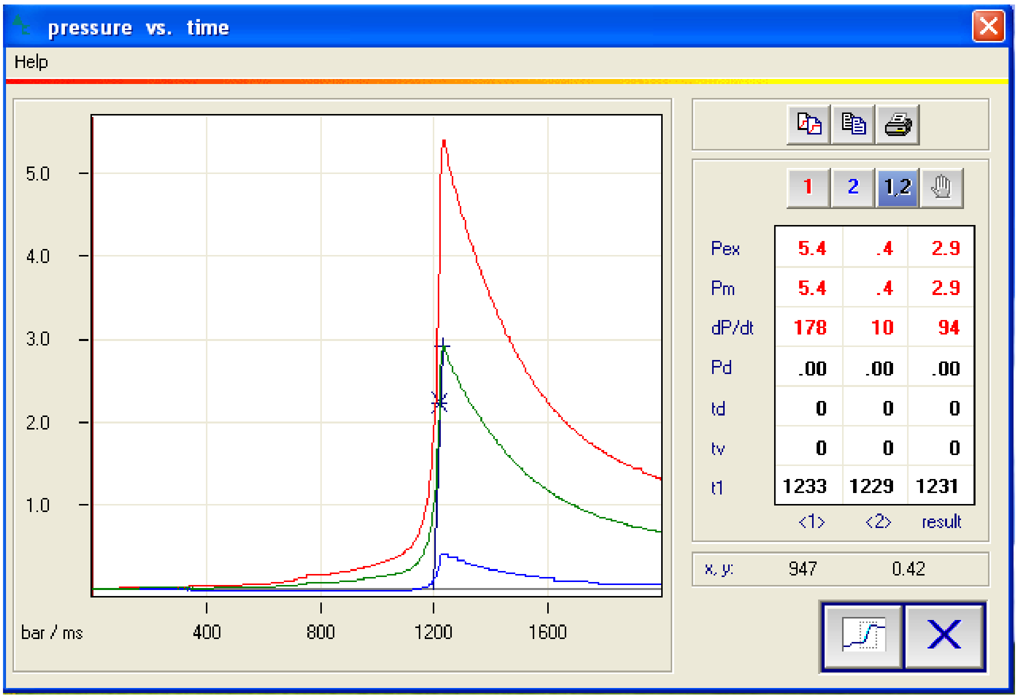
22. 65 % C_2H_2



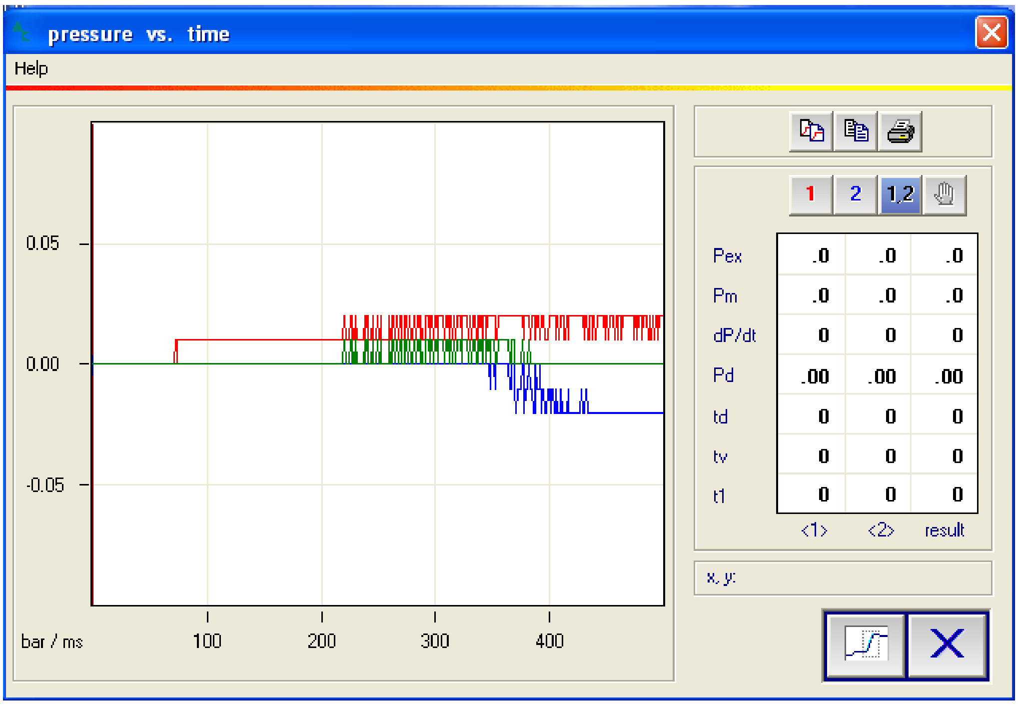
23. 70 % C_2H_2



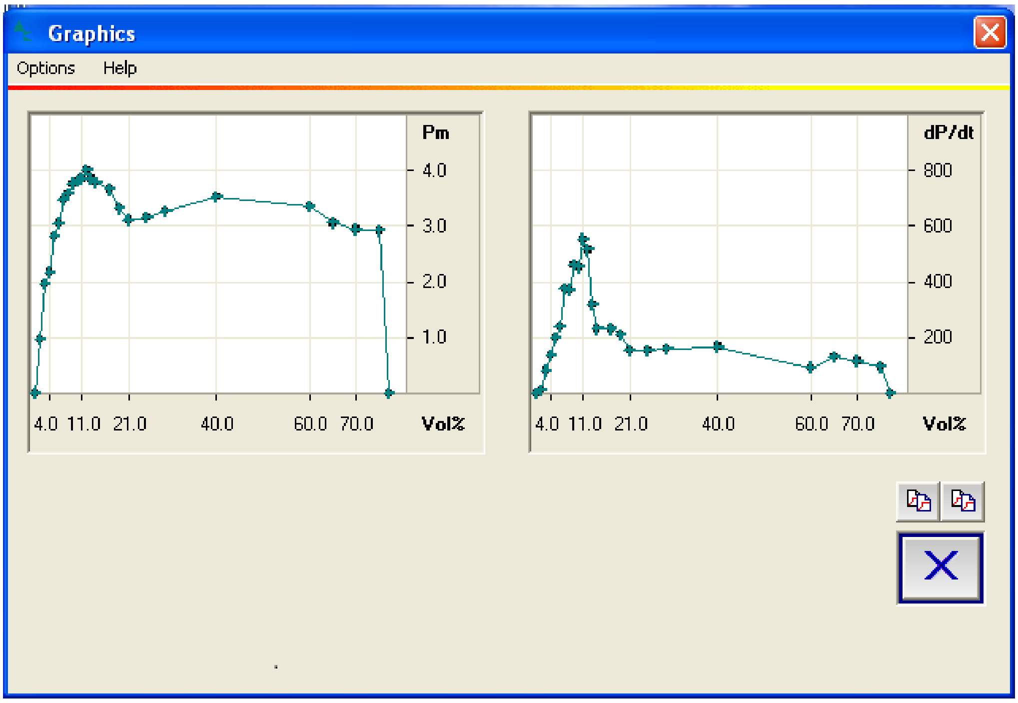
24. 75 % C_2H_2



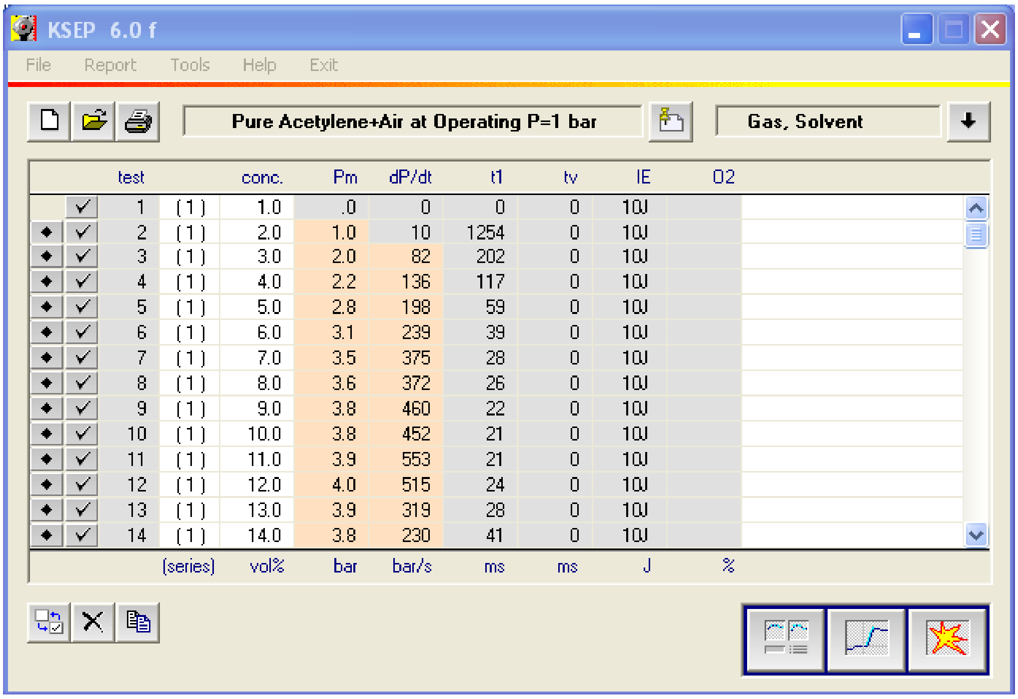
25. 77 % C_2H_2



26. Overall Graf

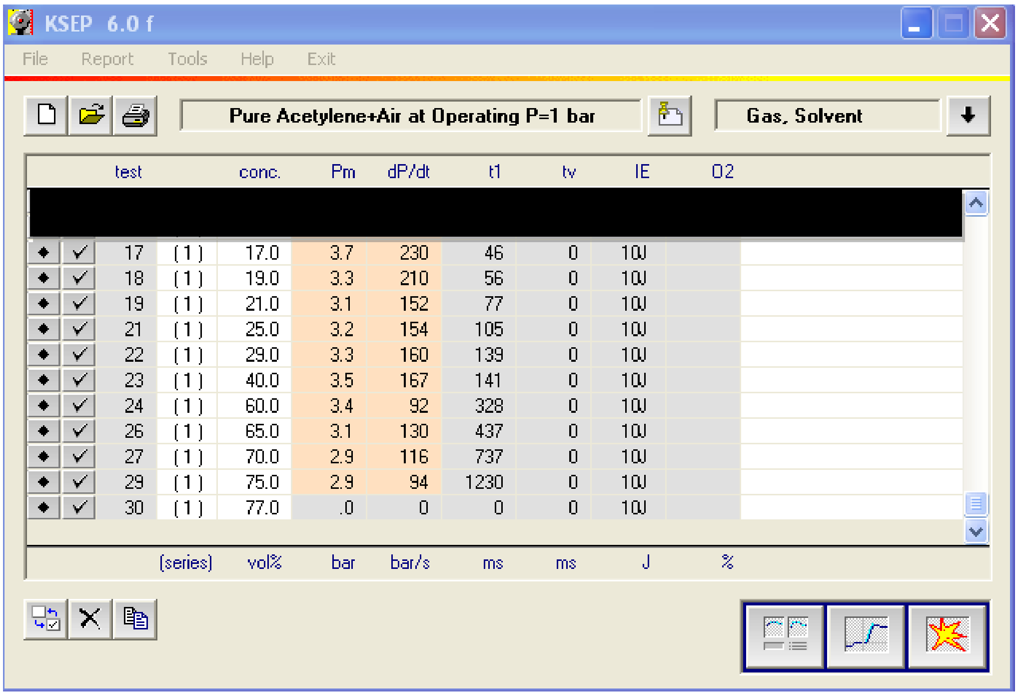


27. Table (1)



	test		conc.	Pm	dP/dt	t1	tv	IE	O2
✓	1	(1)	1.0	.0	0	0	0	10J	
✓	2	(1)	2.0	1.0	10	1254	0	10J	
✓	3	(1)	3.0	2.0	82	202	0	10J	
✓	4	(1)	4.0	2.2	136	117	0	10J	
✓	5	(1)	5.0	2.8	198	59	0	10J	
✓	6	(1)	6.0	3.1	239	39	0	10J	
✓	7	(1)	7.0	3.5	375	28	0	10J	
✓	8	(1)	8.0	3.6	372	26	0	10J	
✓	9	(1)	9.0	3.8	460	22	0	10J	
✓	10	(1)	10.0	3.8	452	21	0	10J	
✓	11	(1)	11.0	3.9	553	21	0	10J	
✓	12	(1)	12.0	4.0	515	24	0	10J	
✓	13	(1)	13.0	3.9	319	28	0	10J	
✓	14	(1)	14.0	3.8	230	41	0	10J	
		(series)	vol%	bar	bar/s	ms	ms	J	%

28. Table (2)

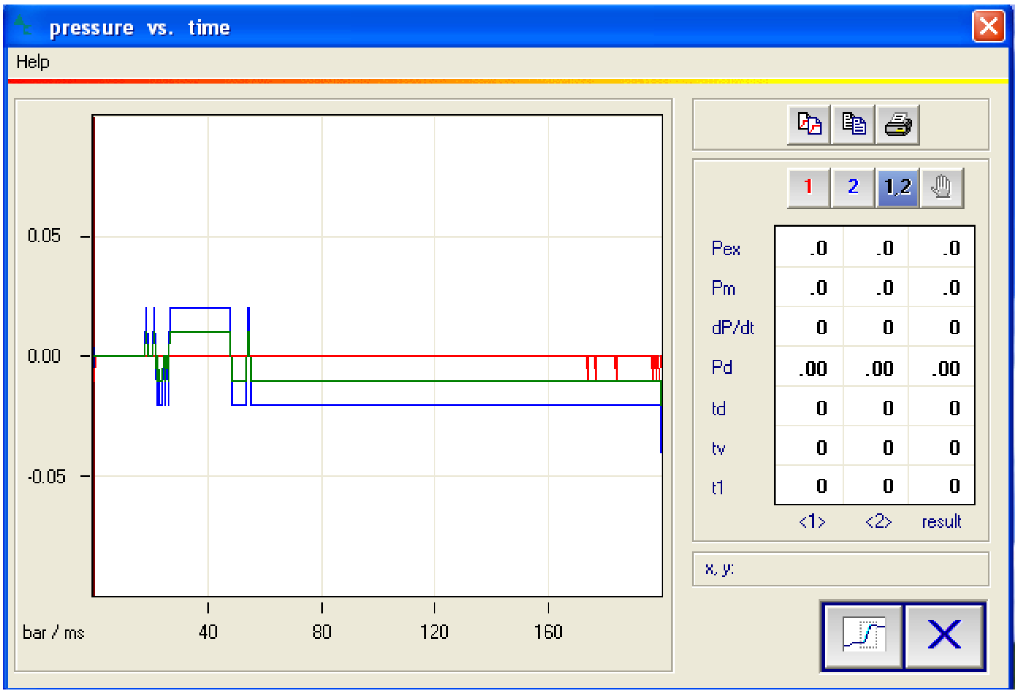


test		conc.	Pm	dP/dt	t1	tv	IE	O2
[redacted]								
17	(1)	17.0	3.7	230	46	0	10J	
18	(1)	19.0	3.3	210	56	0	10J	
19	(1)	21.0	3.1	152	77	0	10J	
21	(1)	25.0	3.2	154	105	0	10J	
22	(1)	29.0	3.3	160	139	0	10J	
23	(1)	40.0	3.5	167	141	0	10J	
24	(1)	60.0	3.4	92	328	0	10J	
26	(1)	65.0	3.1	130	437	0	10J	
27	(1)	70.0	2.9	116	737	0	10J	
29	(1)	75.0	2.9	94	1230	0	10J	
30	(1)	77.0	.0	0	0	0	10J	
	(series)	vol%	bar	bar/s	ms	ms	J	%

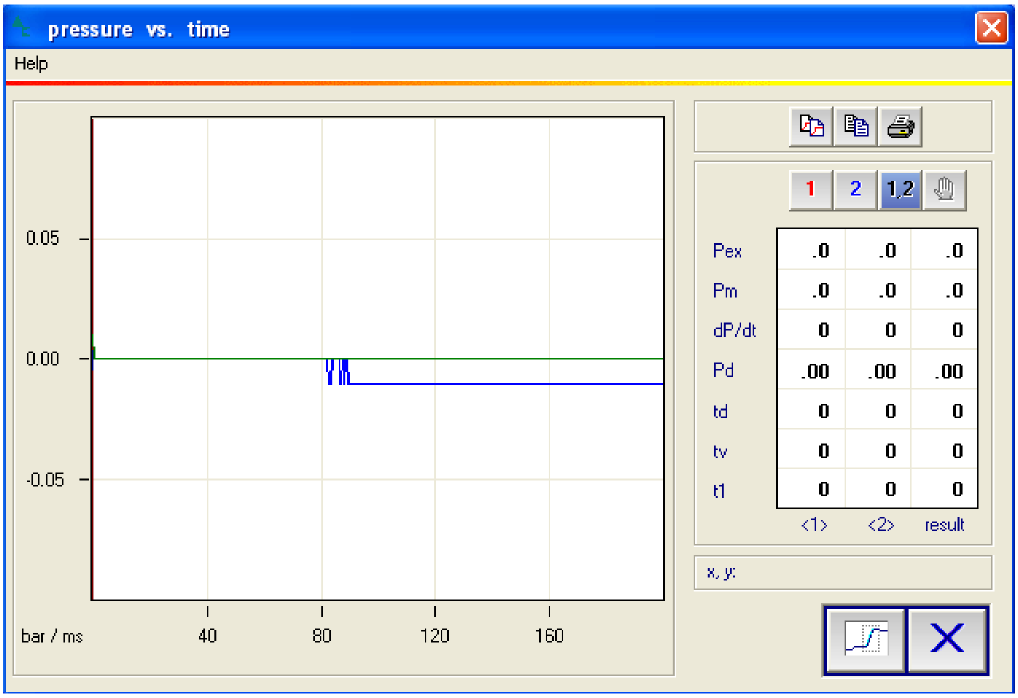
APPENDIX B

Data from software for acetylene + 15 % carbon dioxide + air at operating pressure 1 bar

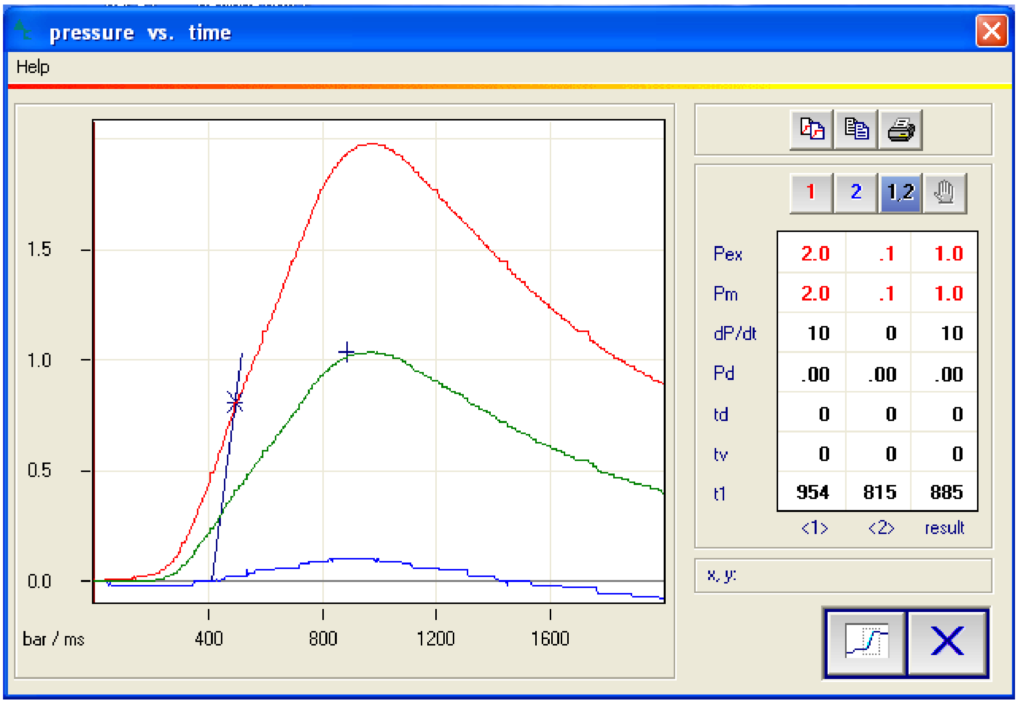
1. 1 % C_2H_2



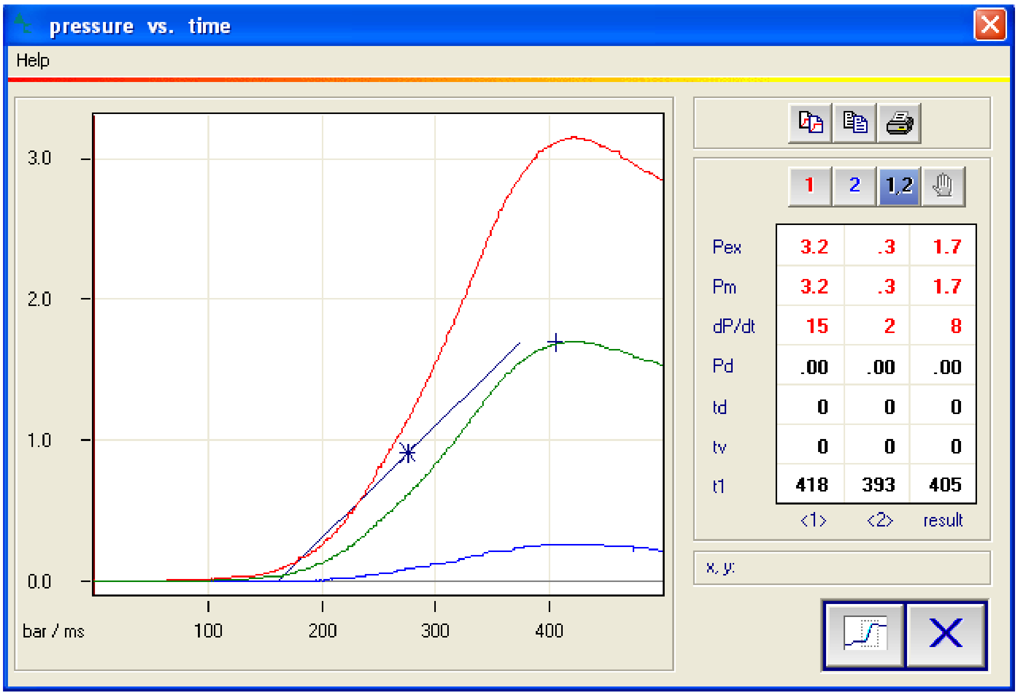
2. 2% C_2H_2



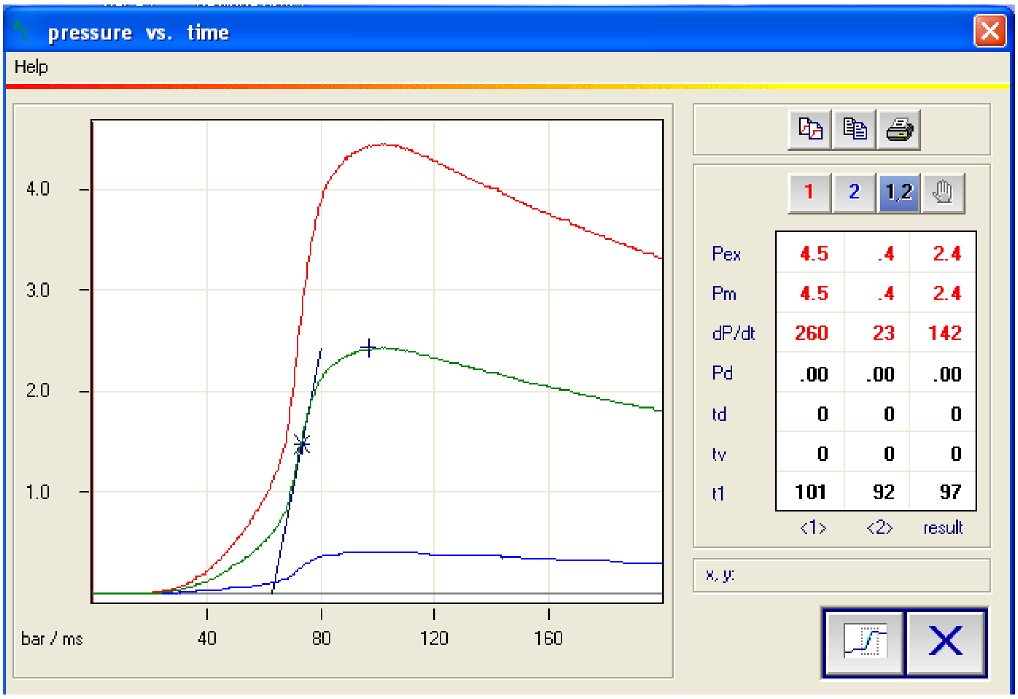
3. 3 % C_2H_2



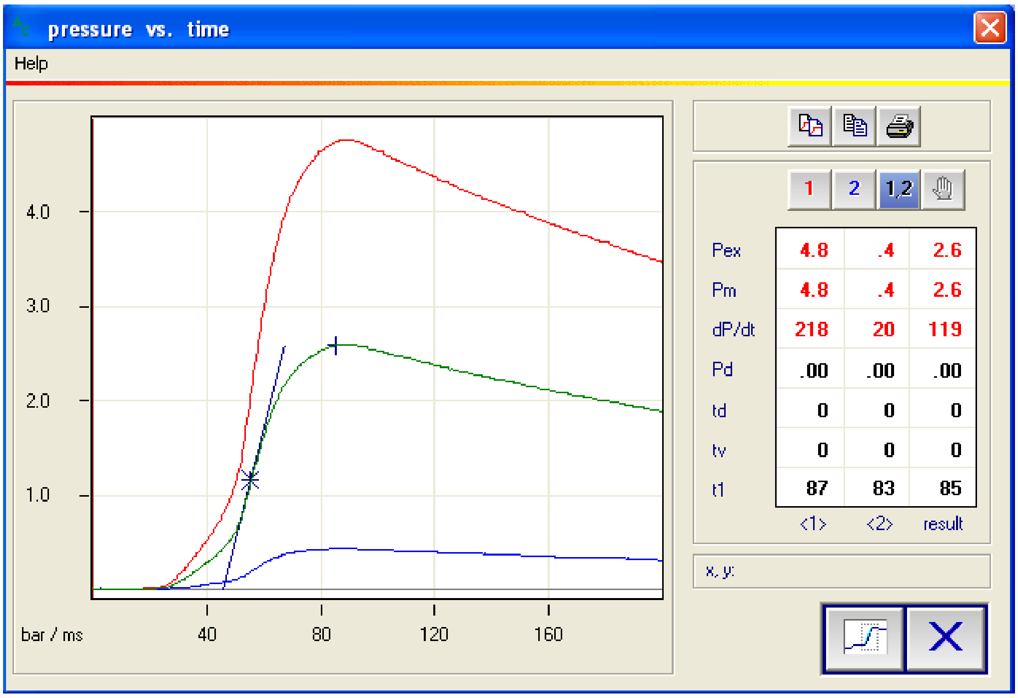
4. 4 % C_2H_2



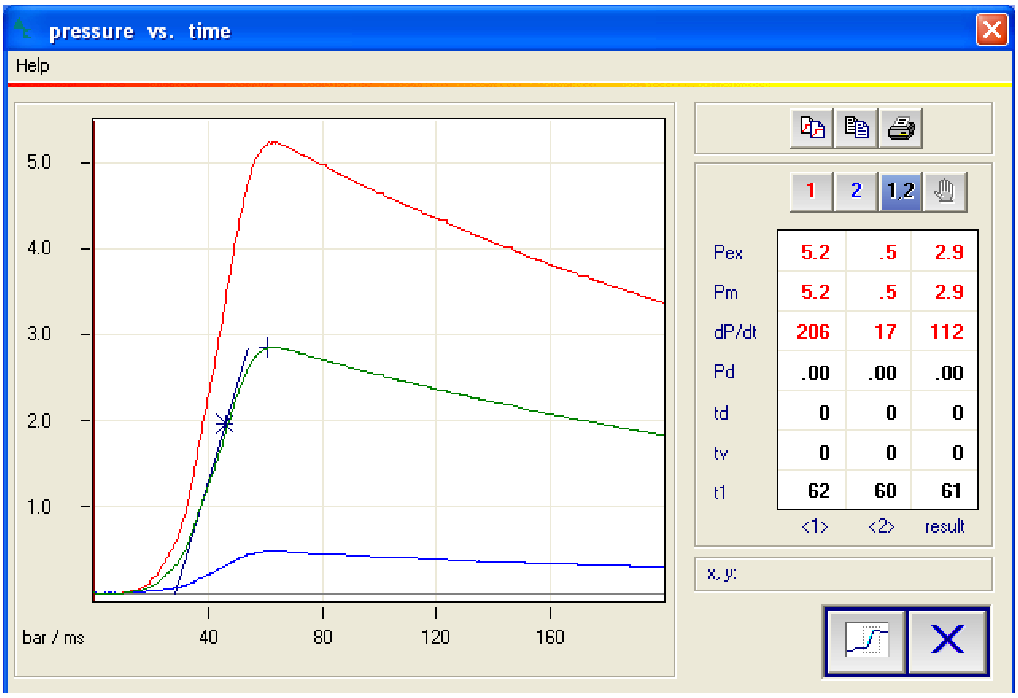
5. 5 % C_2H_2



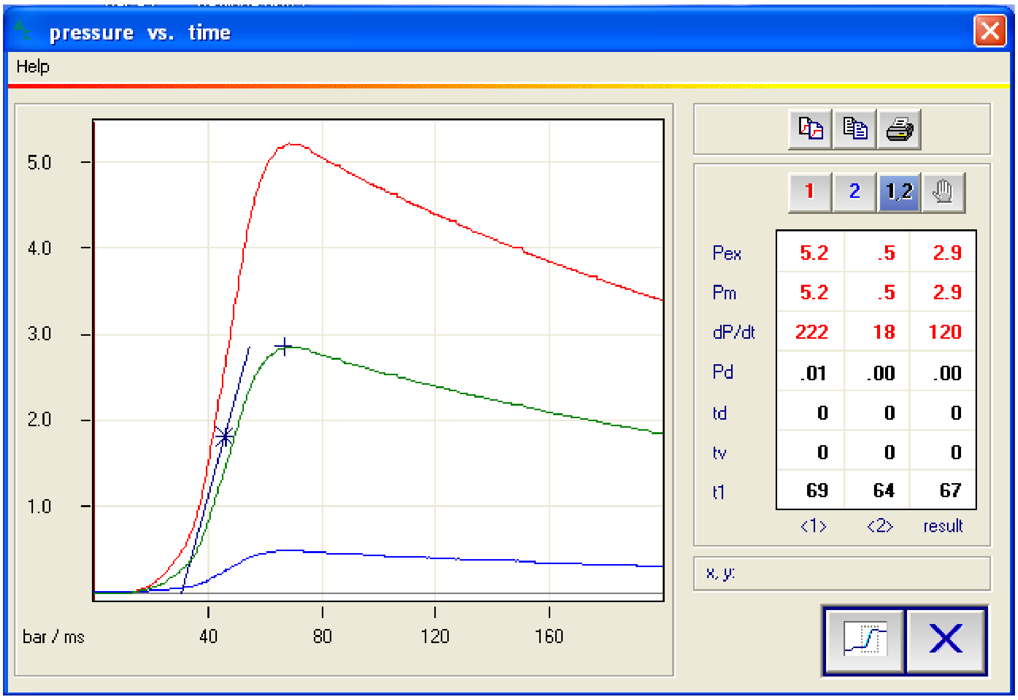
6. 6 % C_2H_2



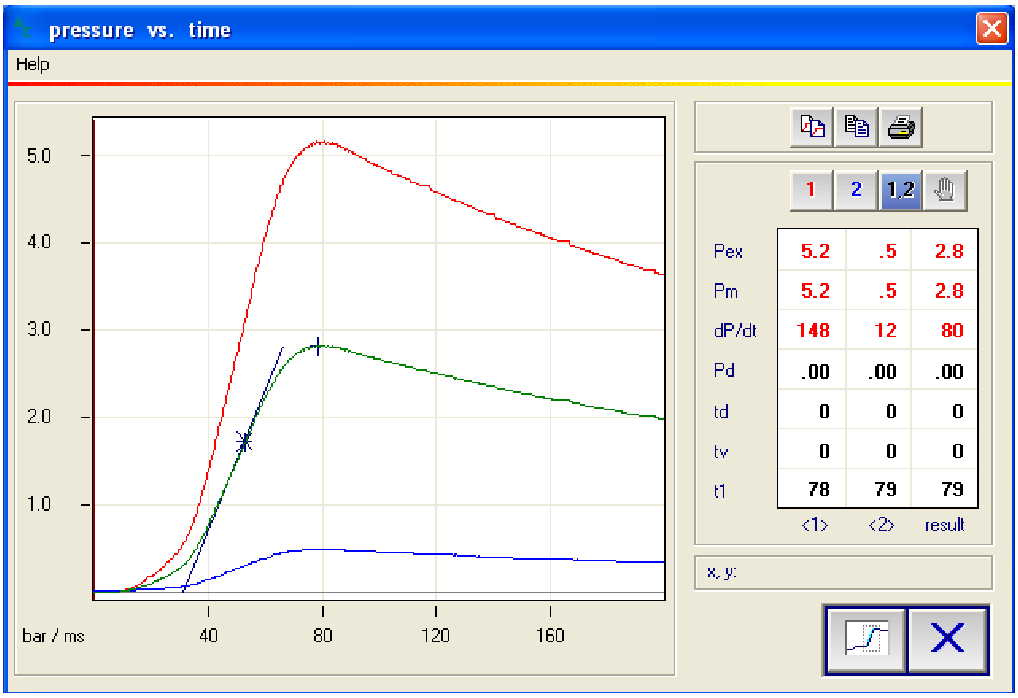
7. 7 % C_2H_2



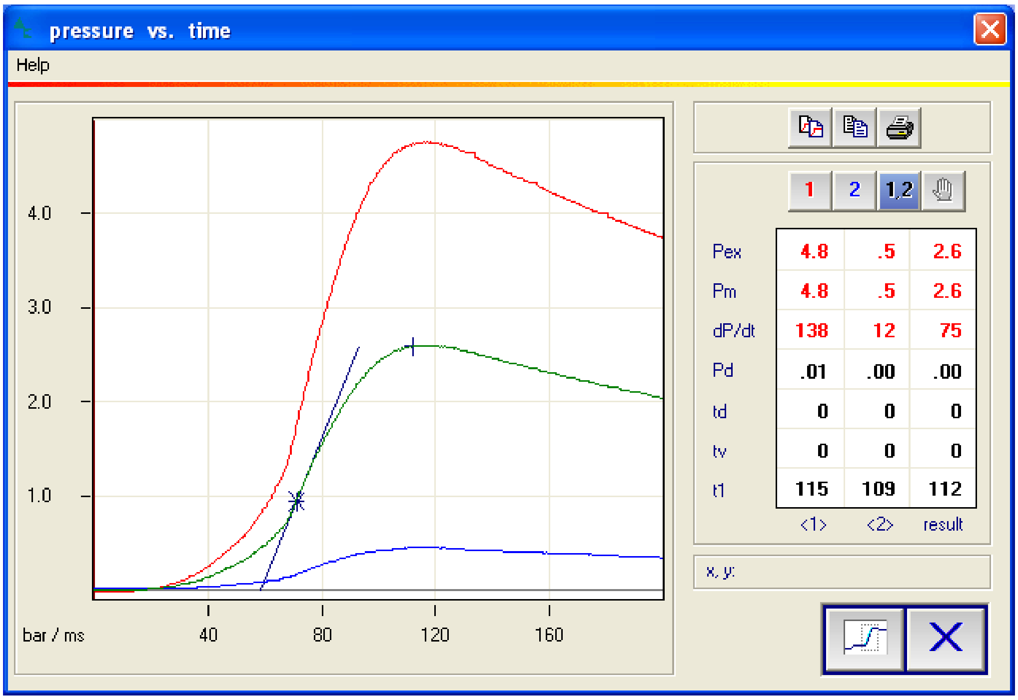
8. 8 % C_2H_2



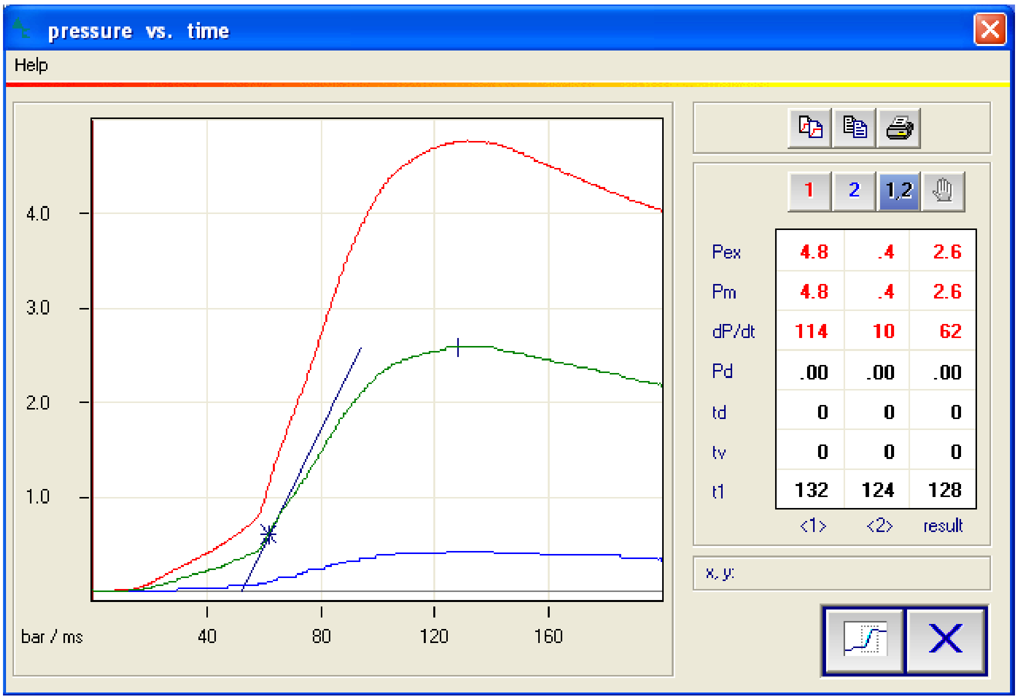
9. 9 % C_2H_2



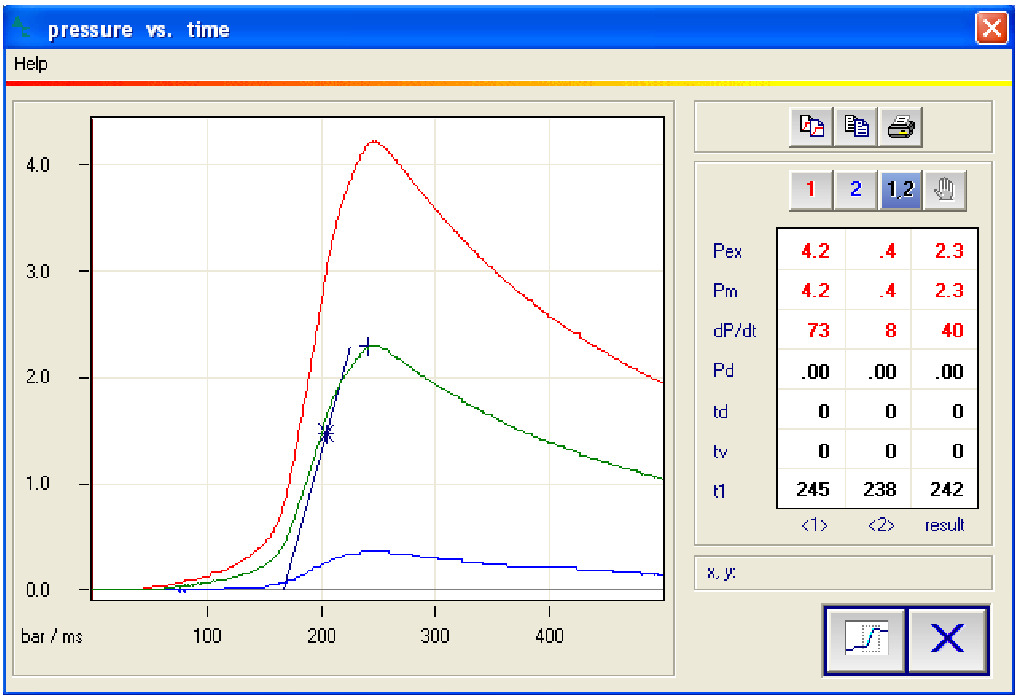
10. 10 % C_2H_2



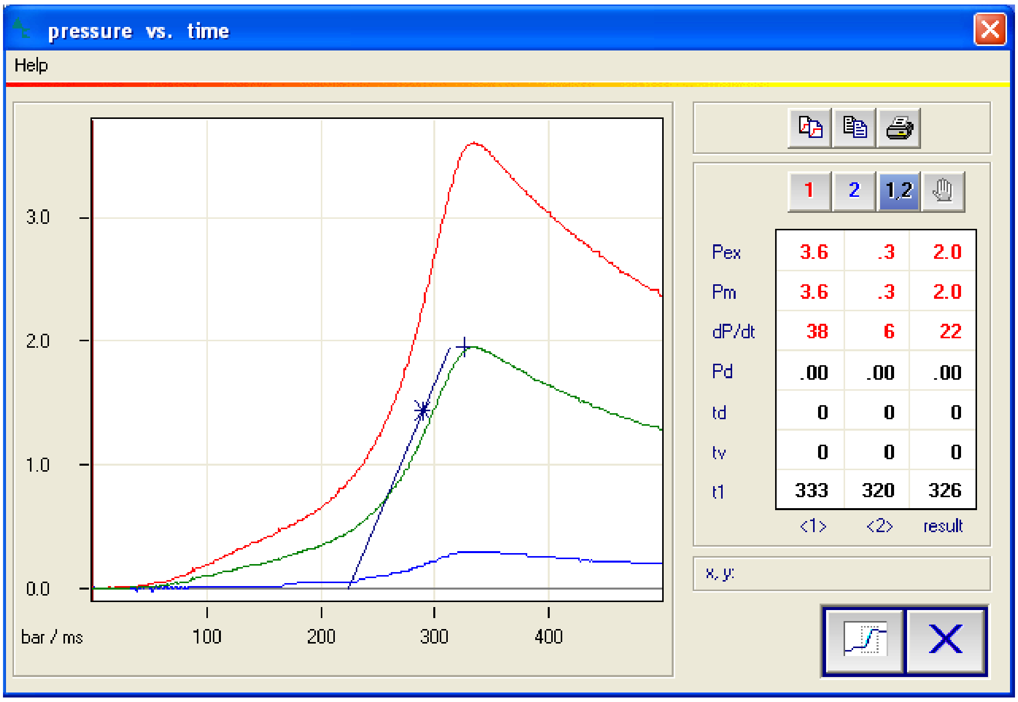
11. 13 % C_2H_2



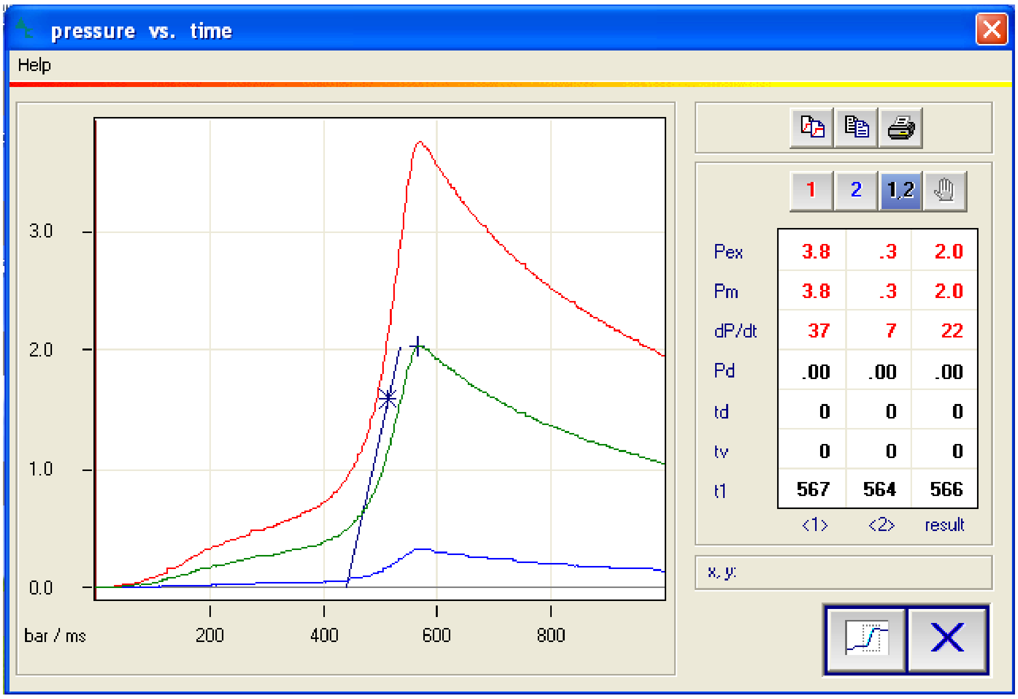
12. 19 % C_2H_2



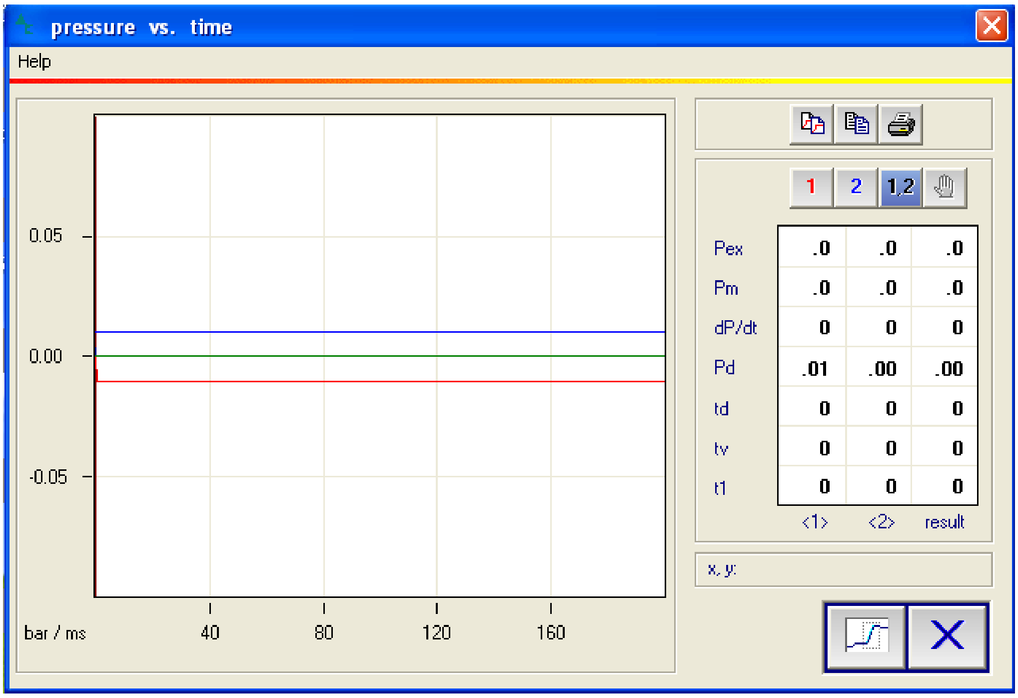
13. 24 % C_2H_2



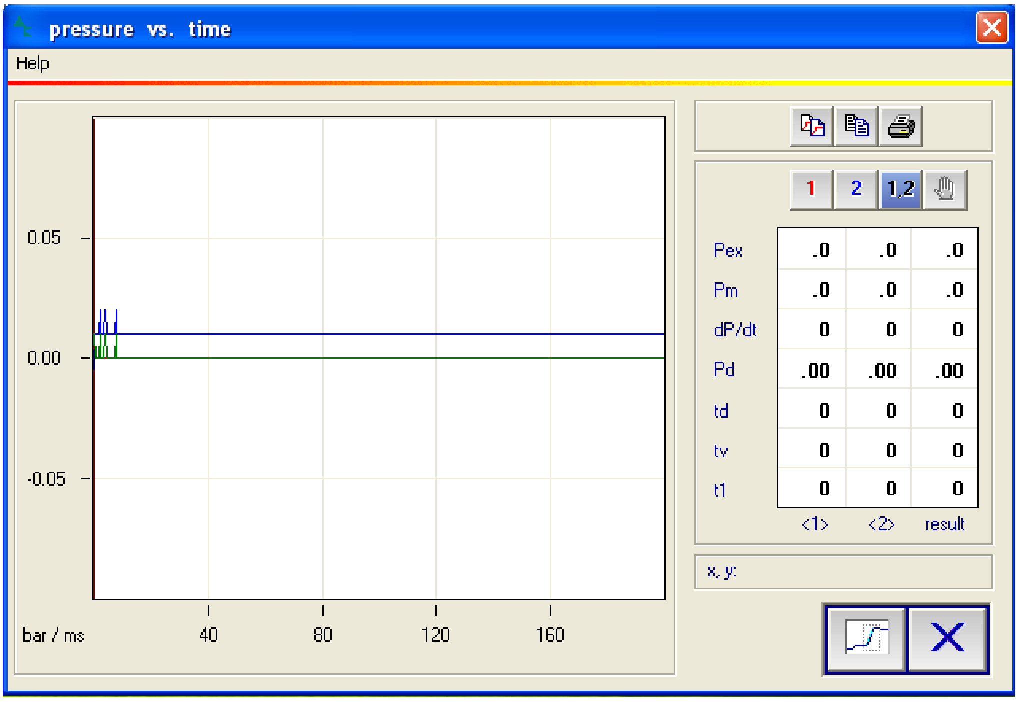
14. 35 % C_2H_2



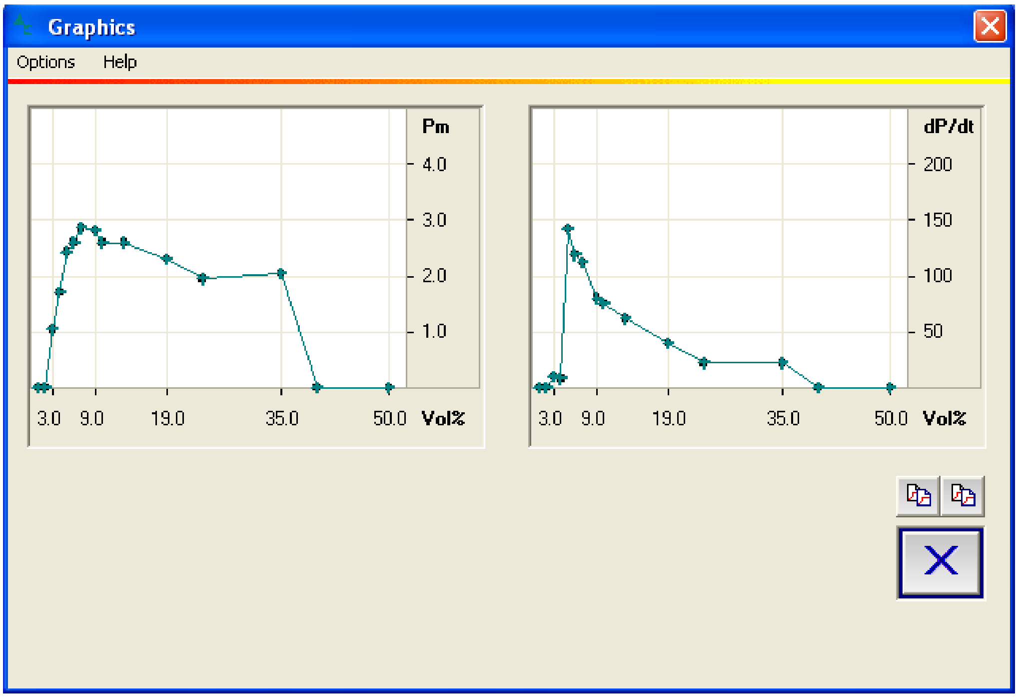
15. 40 % C_2H_2



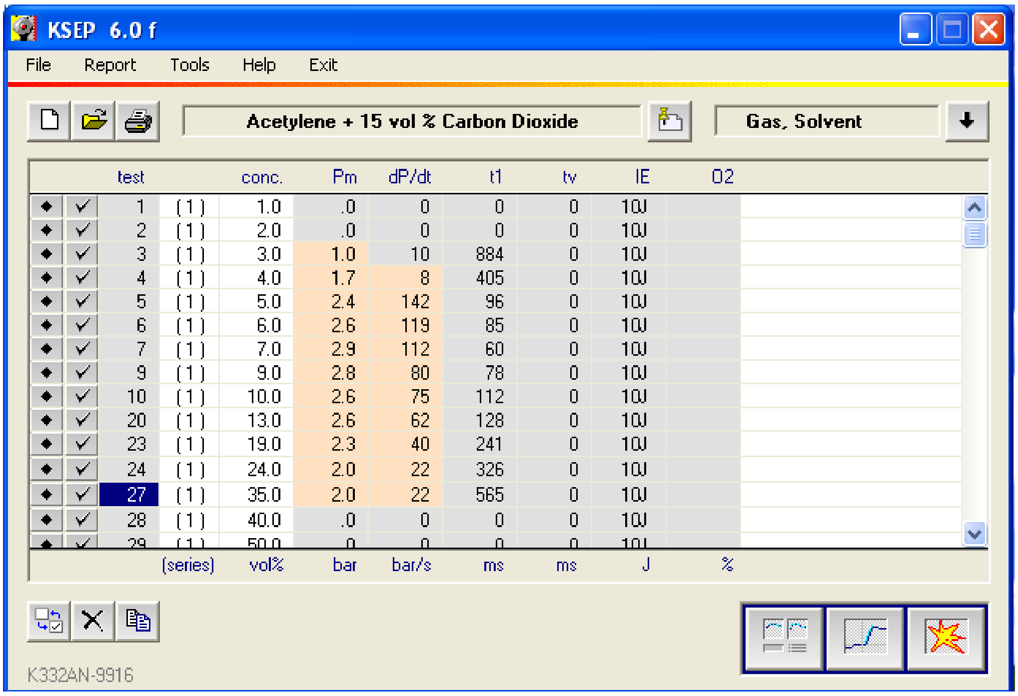
16. 50 % C_2H_2



17. Overall Graf

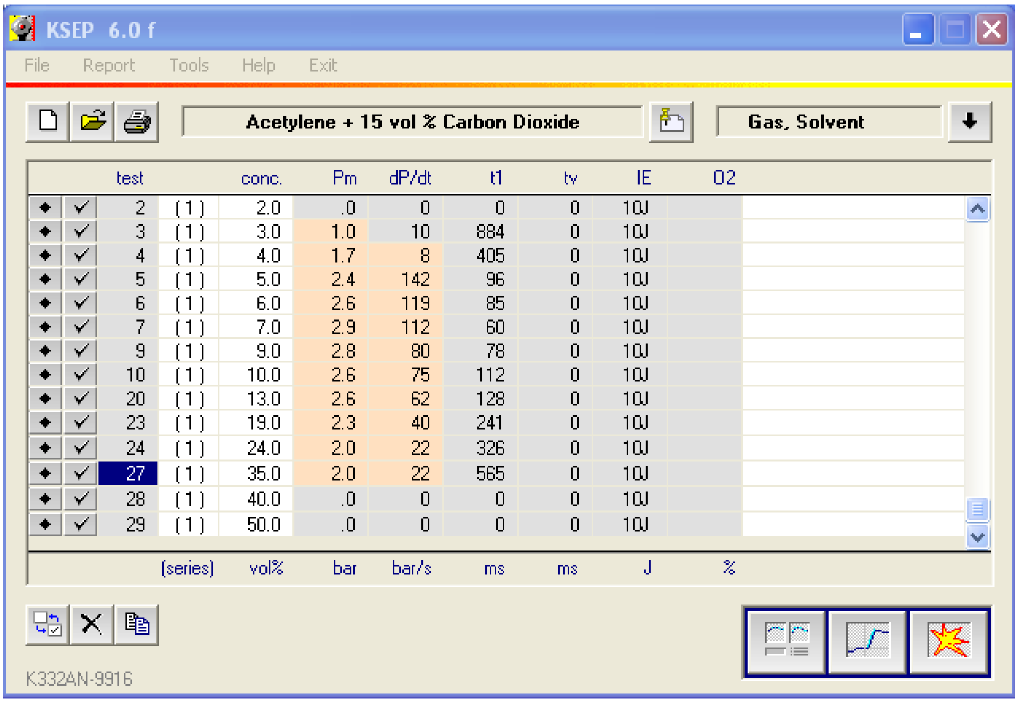


18. Table (1)



test		conc.	Pm	dP/dt	t1	tv	IE	O2
1	(1)	1.0	.0	0	0	0	10J	
2	(1)	2.0	.0	0	0	0	10J	
3	(1)	3.0	1.0	10	884	0	10J	
4	(1)	4.0	1.7	8	405	0	10J	
5	(1)	5.0	2.4	142	96	0	10J	
6	(1)	6.0	2.6	119	85	0	10J	
7	(1)	7.0	2.9	112	60	0	10J	
9	(1)	9.0	2.8	80	78	0	10J	
10	(1)	10.0	2.6	75	112	0	10J	
20	(1)	13.0	2.6	62	128	0	10J	
23	(1)	19.0	2.3	40	241	0	10J	
24	(1)	24.0	2.0	22	326	0	10J	
27	(1)	35.0	2.0	22	565	0	10J	
28	(1)	40.0	.0	0	0	0	10J	
29	(1)	50.0	.0	0	0	0	10J	
	(series)	vol%	bar	bar/s	ms	ms	J	%

19. Table (2)



test		conc.	Pm	dP/dt	t1	tv	IE	O2
2	(1)	2.0	.0	0	0	0	10J	
3	(1)	3.0	1.0	10	884	0	10J	
4	(1)	4.0	1.7	8	405	0	10J	
5	(1)	5.0	2.4	142	96	0	10J	
6	(1)	6.0	2.6	119	85	0	10J	
7	(1)	7.0	2.9	112	60	0	10J	
9	(1)	9.0	2.8	80	78	0	10J	
10	(1)	10.0	2.6	75	112	0	10J	
20	(1)	13.0	2.6	62	128	0	10J	
23	(1)	19.0	2.3	40	241	0	10J	
24	(1)	24.0	2.0	22	326	0	10J	
27	(1)	35.0	2.0	22	565	0	10J	
28	(1)	40.0	.0	0	0	0	10J	
29	(1)	50.0	.0	0	0	0	10J	
	(series)	vol%	bar	bar/s	ms	ms	J	%