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ELEVATED PRESSURE AND TEMPERATURE EFFECTS ON FLAMMABILITY HAZARD ASSESSMENT FOR ACETONE AND WATER SOLUTIONS

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Flammable chemicals are frequently encountered in industrial processes. Under the safe operation basis and for fire/explosion danger prevention, it is imperative to recognize the flammability characteristics of these processes, especially under the working scenarios for elevated pressure and temperature.

This study was conducted to investigate fire and explosion properties, including the explosion limits (LEL and UEL), maximum explosion overpressure (P_{max}), maximum rate of explosion pressure rise $(dP/dt)_{max}$, gas or vapor deflagration index (K_g) and explosion class (St) of various acetone/water solutions (100, 75, 50 and 25 vol.%) at higher initial pressure/temperature up to 2 atm and 200°C via a 20-L-Apparatus. We further discussed the safety-related parameters and fire/explosion damage degree variations in the above aqueous acetone within 1 atm and 150°C. The results offered a successful solution for evaluating the flammability hazard effect in such a relevant crucial process with elevated pressure and temperature.

Keywords: *acetone/water solutions, fire and explosion, flammability characteristics, flammability hazard, 20-L-Apparatus*

Introduction

Fire safety is, without question, one of the most important concerns for all industries. Fires and explosions can cause serious calamities, resulting in enormous damage and potential loss of life and property. The prevention of such accidents requires a familiarity with the fire/explosion properties, so the ‘inherent hazards’ of chemical materials might be realized beforehand [1]. Furthermore, the working conditions that flammable materials are operated inside must also be considered. Operators and engineers must especially pay attention recognizing the influence of changing surroundings on the flammability characteristics response under abnormal scenarios. Therefore, to ensure process safety and optimized operation, it is essential to have the critical information about the elevated pressure and temperature effects involved in a practical process [2].

Over the years engineers and researchers have attempted to establish effective procedures for flammability hazard protection and control, as the most critical objective for industrial disaster prevention and for human beings. Furthermore, as to the effects of elevated pressure and temperature, more complicated situations should be taken into account when combustible/flammable chemicals are encountered in industrial processes under higher pressure/temperature within their flammability limits. As we know, for a substance the lesser the lower flammability limit (LFL) or broader the flammability range, the greater the flammability hazard degree is, and likewise for its fire/explosion hazard degree. In the reference of 2002 [1], Crowl and Louvar further indicated that for gases and vapors in general, the flammability range (form LFL to upper flammability limit (UFL)) increases with enhanced temperature. With regard to the operating pressure, it has a specific effect on the LFL and UFL. Therefore, this shows that the knowledge of flammability limits and pressure properties under elevated loading temperatures and pressures practically is quite important for the process safety control system.

However, information for predicting flammability limits is well established but merely suitable for the circumstances with normal temperature and atmospheric pressure [2–5]. Up to date, no numerical procedure is capable of predicting the flammability limits in all circumstances [2] and much is still unknown. Since no adequate or sufficient awareness of referable flammability limit data yet has been proposed, only a few data are available at raised pressures and temperatures [2, 5–7], and experiments still have to be performed [2, 8]. Furthermore, explosion limits are easily

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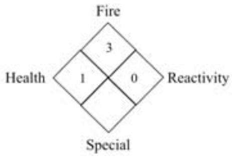
Table 1 Basic physical and chemical properties of acetone [9–11]

Characteristic	Acetone (99.5+%)
CAS No.	67-64-1
Chemical formula	CH_3COCH_3
Molecular mass	58.08 g mol^{-1}
Flash point	–20°C
Normal boiling point (1 atm)	56°C
Melting point	–94.6°C
Vapor pressure	247 mbar (20°C)
Specific gravity (H_2O=1)	0.791
Explosion limits	2.5 (LEL)–13.0 (UEL) vol.%
Flammability hazard (Liquids and solids that can be ignited under almost all ambient temperature conditions.)	The hazardous materials information system (HMIS) rating  Health=1, Flammability=3, Reactivity=0
Flammability liquid	Class IB (NFPA 30) [12, 13]

measured, if not under stringent conditions. Experimental determination is always recommended [1, 3].

In this study, the fire and explosion properties of acetone and water solutions (acetone$_{\text{(aq)}}$s) were investigated experimentally at increased initial temperature/pressure up to 2 atm and 200°C, respectively. We detected the lower/upper explosion limits (LEL and UEL), maximum explosion overpressure (P_{max}), maximum rate of explosion pressure rise $(\mathrm{d}P/\mathrm{d}t)_{\text{max}}$, gas or vapor deflagration index (K_g) and explosion class (St) of various acetone/water mixtures (100, 75, 50 and 25 vol.%) via a 20 L spherical explosion apparatus (or so called 20-L-Apparatus) for simulating and comparing those flammability characteristics under the reciprocal interactions of experimental arrangements (testing temperatures and pressures of 150, 200°C; 1, 2 atm) in a plant.

Through our deliberate attempts, the outcomes led to the conclusion that the above safety-related parameters of experimental samples depended upon surrounding temperature and pressures, accordingly. The results offered a successful solution evaluating the flammability hazard effect with elevated pressure and temperature, and help lead to a better understanding for the particular combustion process of acetone and water mixed liquids in relevant industrial plants.

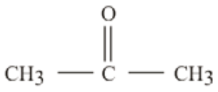
Experimental

Materials

Reagent

Acetone (so-called 2-methyl ketone) is a clear, colorless but irritant liquid at room temperature. It plays an important role as an intermediate chemical for producing MIBK (methyl isobutyl ketone), methacrylate ester and for medical purposes. The most well-known household use of acetone is as the active ingredient in nail polish remover [9, 10].

Figure 1 displays its chemical structure (CH_3COCH_3). The fundamental physical and chemical properties of acetone are given in Table 1 [9–11]. Due to the low flash point (FP) of –20°C and normal boiling point (BP) of 56°C [12–14], acetone is viewed as a ‘flammable liquid IB’ with potential flammability hazard. It flames and propagates quite readily when in contact with an effective ignition source, so vapors should be avoided as the particular explosion limits are reached.



$$CH_3 - \overset{\overset{\displaystyle O}{\|}}{C} - CH_3$$

Fig. 1 Chemical structure of acetone [9, 10]

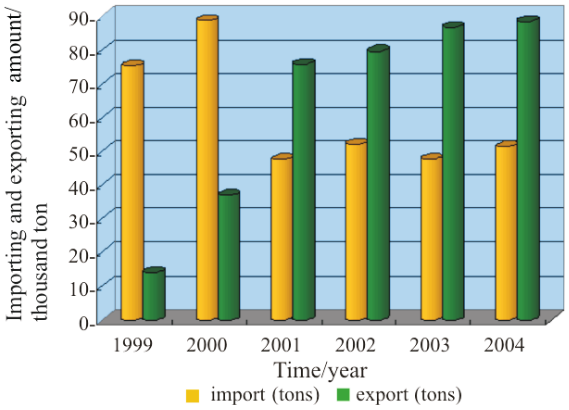


Fig. 2 Annual importing and exporting amount of acetone in Taiwan [15]

However, to date the only safety-related information proposed in the references is illustrated in Table 1 [9–11]. Several important flammability characteristics at elevated temperature and pressure (up to 200°C and 2 atm) are still lacking. Therefore, in this study, we attempted to discover those crucial parameters and understand the effects of raised temperature and pressure.

The chemical process industry worldwide is filled with major accidents, not to mention numerous incidents and near misses. In Taiwan, this study with fire safety concerns and assessment of acetone has a particular significance. The petrochemical industry frequently uses flammable mixtures, such as acetone and its aqueous solution nowadays. Inevitably, these loading materials may cause serious fires and explosions, even under various unexpected abnormal scenarios; and their hazards may also be exacerbated by the demand for chemicals in processes. Figure 2 demonstrates the distribution of annual importing and exporting amounts of acetone in Taiwan, showing the growth of demand for acetone in recent years (up to 2004), indicating the quantity of output is quite substantial and also implying a potential hazard if not operated suitably [15].

Preparation of mixing acetone/water vapor

The experimental samples available from Lee Chang Yung Chemical Industry Corp. [11] were four acetone/water mixing solutions, i.e., 100/0 (pure acetone), 75/25, 50/50 and 25/75 vol.%. They were chosen to realize the influence of changing temperature and pressure on fire and explosion properties in this study. Herein, the 100/0 component of acetone/water mixture meant that more than 99.5% acetone (99.5+%) was employed for presenting the ‘pure’ acetone solution sample, i.e., 100 vol.% acetone$_{(aq)}$ approximately, to our flammability testing series. These four vapor ratios of 100, 75, 50 and 25 vol.% acetone$_{(aq)}$s are delineated in Table 2.

Table 2 Four simulated concentrations (vapor mixing ratios) for acetone and water vapor

	Mixing vapor ratios			
	vol.%	vol.%	vol.%	vol.%
Acetone	100	75	50	25
Water vapor	0	25	50	75

As for the experimental initial conditions, we established an initial pressure of 1, 2 atm, along with an initial temperature of 150, 200°C and various vapor mixing ratio samples and various oxygen concentrations (21, 17, 14...vol.%) for the fire testing task. We purposely set a higher testing pressure (2 atm) and temperature (200°C) for surveying the foregoing featured flammability parameters at such crucial operating situations and further desired to compare the fire/explosion damage degree variations in those within 1 atm and 150°C conditions. To exceed both the normal boiling points of acetone (56°C) and water (100°C) when dosing our samples, the initial temperature was set more than 150°C. In that way, we could generate total flammable acetone vapors and steam, i.e., $H_2O_{(g)}$ and then ensure a well mixed state in the gas phase during this test [16].

Methods

20 L spherical explosion vessel

Figures 3 and 4 individually present the appearance of our experimental apparatus of a 20 L spherical explosion vessel (20-L-Apparatus) and its control system sections [17–19], which was purchased from Adolf Kühner AG and was feasible for flammability surveys of this

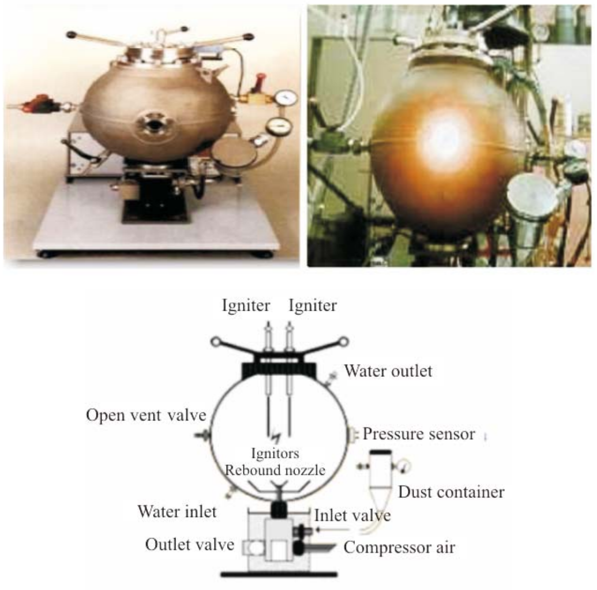


Fig. 3 The experimental 20 L spherical explosion vessel (20-L-Apparatus) for this study [17–19]

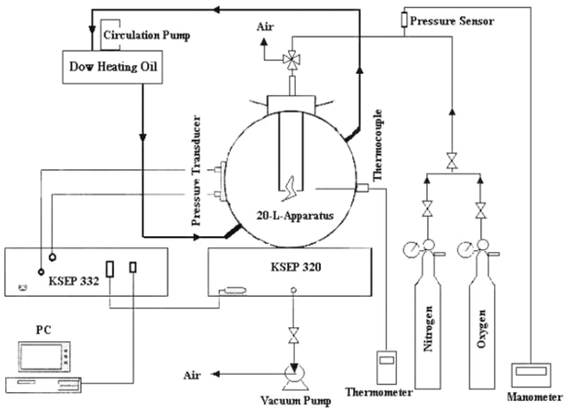


Fig. 4 Schematic diagram of the 20-L-Apparatus and its control system sections [17–19]

study. The 20-L test chamber is a stainless steel hollow sphere. The top of the cover includes holes for the lead wires to the ignition system. The opening provides for ignition by a condenser discharging with an auxiliary spark gap, which is dictated by a KSEP 320 unit of the 20-L-Apparatus [20, 21]. The mixtures are ignited by a pyrotechnic igniter, which consists of a total of 10 J electric current employed as ignition source for the gas/vapor system and is placed at the center of this vessel [20, 22]. The KSEP 332 unit uses piezoelectric pressure sensors to measure the pressure as a function of time [20]. In addition, a personal transmission computer interface was established for catching the explosion pressure–time corresponding records after an explosion. A comprehensive software package KSEP 6.0 was available which allowed safe operation of the test equipment and an optimum evaluation of the explosion test results [23, 24].

The test system enables one to determine the inherently safer properties in accordance with internationally recognized test procedures, e.g., ASTM 1226 (American Society for Testing and Materials, USA) and VDI 2263 (Verein Deutscher Ingenieure, Germany) [25]. Essentially, it allows observing explosion behaviors of combustible materials, such as solvent vapors, flammable gases, or combustible dusts. The flammability properties of LEL, UEL, P_{max}, $(dP/dt)_{max}$, K_g index, explosion class (*St*) and minimum oxygen concentration (MOC), etc. are detected in a series of testing procedures.

LEL and UEL for gas and solvent vapors

Generally speaking, by the definition of ASTM E 681–04, the lower flammability limit (LFL) and upper flammability limit (UFL) are also referred to as the lower explosion limit (LEL) and upper explosion limit (UEL), respectively [26]. Hence, the explosion range is from LEL to UEL of a specific substance. Vapor-air mixtures will ignite and combust only over a well-specified range of compositions. Commonly used units are volume percent fuel (percentage of fuel plus air, vol.%) [1]. In this study, we investigated the explosion limits and the testing series was continued with a systematic increase and decrease of the sample concentration until a concentration was reached at which no ignition was observed in three successive tests [20, 24].

Maximum explosion overpressure (P_{max}), maximum rate of explosion pressure rise $(dP/dt)_{max}$ and gas or vapor deflagration index (K_g)

The peak values that accompany the explosion of a combustible vapor are the P_{max} and $(dP/dt)_{max}$. Experimentally, they can be obtained from tests over a wide range of concentrations ignited by an electric spark [1]. In this test work, P_{max} and $(dP/dt)_{max}$ are defined as the mean values of the maximum values of all three series [20, 24].

Subsequently, the gas or vapor deflagration index (K_g) is calculated from $(dP/dt)_{max}$ by means of the cubic law [27]:

$$V^{1/3}(dP/dt)_{max}=K_g \qquad (1)$$

where K_g and V are the maximum gas explosion constant specific to the gas and the volume of test apparatus (i.e., 0.02 m^3), respectively.

As there are many gas products in industrial practices, it is appropriate to assign this maximum constant to one of several explosion classes (*St*), as given in Table 3 and to use these as a basis for identifying explosive relief according to NFPA 68 [20, 21, 27].

Table 3 K_g and explosion classes (*St*) [21, 22, 27]

K_g/m bar s^{-1}	Explosion classes/*St*
<1	St-0
1–200	St-1
201–300	St-2
>300	St-3

Results and discussion

Inert steam effect of different concentrations of acetone$_{(aq)}$s

A series of flammability investigations were carefully performed with the 20-L-Apparatus device. Various components of vapor mixtures of acetone and water, i.e., the 100, 75, 50 and 25 vol.% acetone$_{(aq)}$s, brought different outcomes under our reciprocal interactions of experimental arrangements under testing temperatures and pressures of 150, 200°C; 1, 2 atm. First, the experimental data indicated that the observed fire and explosion properties changed with their different components of acetone/water. By increasing the proportion of water vapor (steam), the explosion range which was from LEL to UEL became narrow and small; so did the explosion pressure which signified the flammability hazard degree. In other words, the 'inert' effect of steam on those flammability characteristics for acetone$_{(aq)}$ samples was revealed as a novel finding there. Figures 5–8 illustrate the relationship of explosion limits (vol.%) *vs.* to explosion pressure (bar) for four unlike loading fuel concentrations of acetone$_{(aq)}$s, in each scenario of testing temperature and pressure (150, 200°C; 1, 2 atm) and all at 21 vol.% oxygen, demonstrating the effect of inert steam. In these schemes, one can see the expanded bell-type curves with explosion pressure *vs.* many acetone$_{(aq)}$ concentrations: of which one curve, the highest concentration is UEL and the lowest one is LEL. The largest explosion pressure among them is called the P_{max}.

Effect of initial pressures

Focusing on the effect on initial pressures, the results of the flammability investigation indicated that the explosion range, UEL, P_{max}, $(dP/dt)_{max}$, K_g and explosion class (*St*) properties were all increased with the operating pressure. According to the above experimentally-derived data, variations are observed between initial pressures of 1 and 2 atm, as shown in Tables 4 and 5. They reveal the differences of the initial pressures by comparing those flammability features, in the case of 100 vol.%

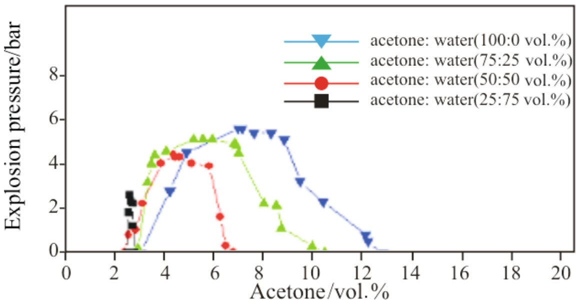


Fig. 5 Explosion pressure *vs.* acetone$_{(aq)}$ with four vapor mixing ratios at 150°C, 1 atm and 21 vol.% oxygen

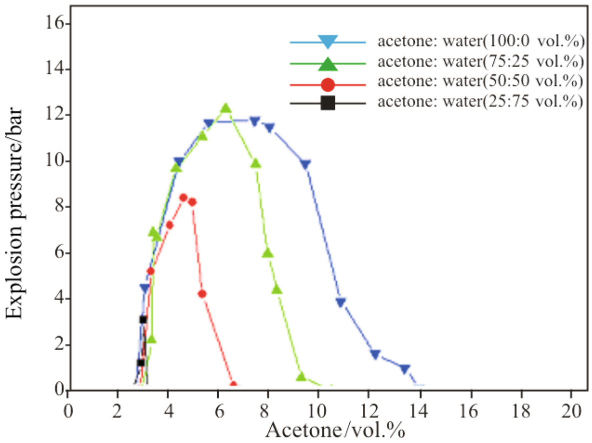


Fig. 6 Explosion pressure *vs.* acetone$_{(aq)}$ with four vapor mixing ratios at 150°C, 2 atm and 21 vol.% oxygen

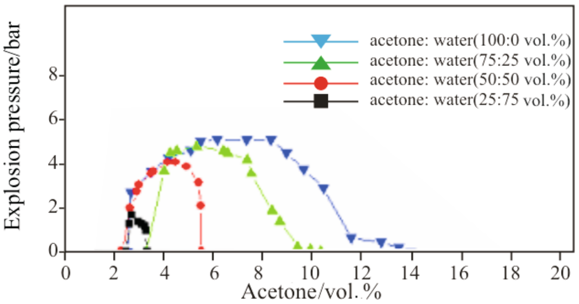


Fig. 7 Explosion pressure *vs.* acetone$_{(aq)}$ with four vapor mixing ratios at 200°C, 1 atm and 21 vol.% oxygen

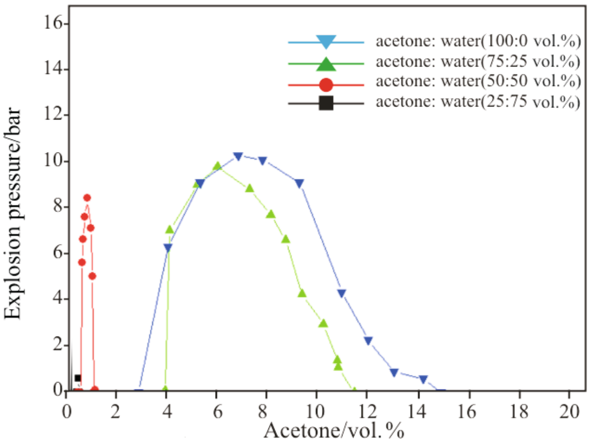


Fig. 8 Explosion pressure *vs.* acetone$_{(aq)}$ with four vapor mixing ratios at 200°C, 2 atm and 21 vol.% oxygen

Table 4 Comparisons of flammability characteristics for 100 vol.% acetone$_{(aq)}$ at 150°C, 21 vol.% O_2, 1 and 2 atm

Initial pressure	1 atm	2 atm	Effect
Explosion range	10.11	12.32 vol.%	Rose by 21.86%
UEL	12.80	14.90 vol.%	Rose by 17.19%
P_{max}	5.60	11.50 bar	Rose by 105.36%
$(dP/dt)_{max}$	374.00	827.00 bar s^{-1}	Rose by 121.12%
K_g	101.52	224.48 m bar s^{-1}	Rose by 121.12%
Explosion class (*St*)	St-1	St-2	Rose by one class

Table 5 Comparisons of flammability characteristics for 100 vol.% acetone$_{(aq)}$ at 200°C, 21 vol.% O_2, 1 and 2 atm

Initial pressure	1 atm	2 atm	Effect
Explosion range	11.32	16.66 vol.%	Rose by 47.17%
UEL	13.80	18.47 vol.%	Rose by 33.84%
P_{max}	4.90	12.40 bar	Rose by 153.06%
$(dP/dt)_{max}$	382.00	868.00 bar s^{-1}	Rose by 127.23%
K_g	103.69	235.61 m bar s^{-1}	Rose by 127.23%
Explosion class (*St*)	St-1	St-2	Rose by one class

Table 6 Comparisons of flammability characteristics for 100 vol.% acetone$_{(aq)}$ at 1 atm, 21 vol.% O_2, 150 and 200°C

Initial pressure	150°C	200°C	Effect
Explosion range	10.11	11.32 vol.%	Rose by 11.97%
UEL	12.80	13.80 vol.%	Rose by 7.81%
$(dP/dt)_{max}$	374.00	382.00 bar s^{-1}	Rose by 2.14%
K_g	101.52	103.69 m bar s^{-1}	Rose by 2.14%
Explosion class (*St*)	St-1	St-1	Without change

Table 7 Comparisons of flammability characteristics for 100 vol.% acetone$_{(aq)}$ at 2 atm, 21 vol.% O_2, 150 and 200°C

Initial pressure	150°C	200°C	Effect
Explosion range	12.32	16.66 vol.%	Rose by 35.28%
UEL	14.90	18.47 vol.%	Rose by 23.96%
$(dP/dt)_{max}$	827.00	868.00 bar s^{-1}	Rose by 4.96%
K_g	224.48	235.61 m bar s^{-1}	Rose by 4.96%
Explosion class (*St*)	St-2	St-2	Without change

acetone$_{(aq)}$, 21 vol.% of oxygen and both at 150 and 200°C, respectively. The above typical properties were all raised while increasing the higher initial pressure to 2 atm. Particularly, the change of *St* explosion class, which implies the flammability hazardous degree for a material from St-1 (K_g index, 100–200 m bar s^{-1}), grew to St-2 class (K_g index, 201–300 m bar s^{-1}).

From Tables 4 and 5, we can clearly recognize the influence of initial pressure on the damage of fire/explosion whenever the initial temperature was at 150 or 200°C, significantly indicating this variation on potential flammability dangerous level. Especially for a practical process, we should be more concerned and avoid this situation when loading a flammable material such as acetone under higher pressure.

Furthermore, we found that in this testing arrangement of higher initial pressure, while evaluating the initial temperature to 200°C simultaneously, that those flammability characteristics had the highest raising extent (compared with Table 4) and became the greatest flammability dangerous level in the process, as proven in Table 5. That is, the effect of elevated pressure and temperature simultaneously caused a ‘the worst scenario’ at 2 atm and 200°C for 100 vol.% acetone$_{(aq)}$ in our testing system. We strongly suggested that the engineers and operators should pay more attention to this condition.

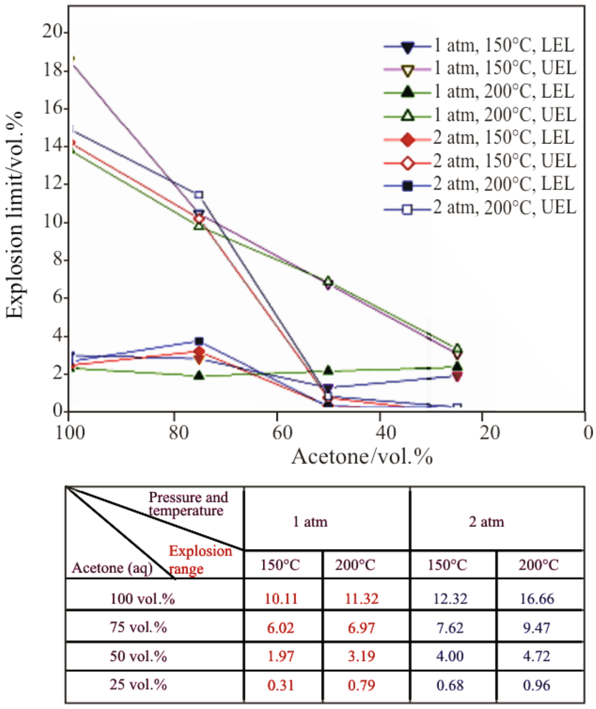
Effect of initial temperatures

As for the effect of initial temperatures, Tables 6 and 7 show the variations specifically by comparing the experimental results of the explosion range, UEL, $(dP/dt)_{max}$, K_g and explosion class (*St*). Similarly, while enhancing operating pressure, those features were all increased just like the affected consequence of enhancing operating pressure we just mentioned before. However, we noticed that the increased degrees in safety-related parameters as enhancing the initial temperature from 150 to 200°C were less than the ones when enhancing the pressure (compared with Tables 5 and 6) both in 1 (Table 6) and 2 atm (Table 7). Via the two testing series of affected pressure and temperature, we concluded that, for a flammable loading material in a plant of acetone, the influence from working pressure was more significant than the temperature in this study. So, from the view of the fire/explosion hazard prevention, the ‘pressure’ control procedure might be more imperative than the temperature. This statement is further proven in Table 7, the comparisons of flammability characteristics for 100 vol.% acetone$_{(aq)}$ at 2 atm, 21 O_2 vol.% on 150 and 200°C, i.e., no matter what in the environment of the two observed temperatures, once the initial pressure reached to 2 atm, the explosion class was in the St-2 degree, showing the flammability damage level was increased.

Influence on explosion limits

The explosion limit represents a peculiar and individual property for a material. Generally speaking, vapor–air mixtures will explode upon encountering an effective ignition source [1]. Many explosions that happen in a process or plant often result from flammable chemicals located inside their explosion limits. Since most flammable liquids are normally stored and handled above their FP, they continuously give off vapors when the vapor–air mixture is within the explosion limits [14]. Furthermore, the lesser the LEL or broader the explosion range, the greater the flammability hazard degree for a substance is [28].

With this view in mind, we specially transferred the experimentally derived data of explosion limit into a concrete scheme, forming an 'explosion area' schematic picture (Fig. 9). Figure 9 depicts the comparison of explosion limits of acetone$_{(aq)}$s with four vapor mixing ratios all under 150/200°C, 1/2 atm and 21 vol.% oxygen circumstances. In this scheme, clearly, the explosion area is inside two well-specified boundaries of LEL and UEL. Therefore, the flammability hazard degree in all scenarios for this study could be easily compared by a measure of the area. This scheme's



Pressure and temperature / Explosion range / Acetone (aq)	1 atm		2 atm	
	150°C	200°C	150°C	200°C
100 vol.%	10.11	11.32	12.32	16.66
75 vol.%	6.02	6.97	7.62	9.47
50 vol.%	1.97	3.19	4.00	4.72
25 vol.%	0.31	0.79	0.68	0.96

Fig. 9 Comparison of explosion limits for acetone$_{(aq)}$s at 150, 200°C, 1, 2 atm and 21 vol.% oxygen

Table 8 Flammability properties for different acetone/water mixing vapors at 150°C, 1 atm and 21 vol.% O_2

O_2/vol.%	LEL/vol.%	UEL/vol.%	P_{max}/bar	$(dP/dt)_{max}$/bar s^{-1})	K_g/m bar s^{-1})	Explosion class (*St*)
			acetone/water (100/0 vol.%)			
21	2.69	12.80	5.60	374.00	101.52	St-1
			acetone/water (75/25 vol.%)			
21	3.76	9.78	5.10	248.00	67.32	St-1
			acetone/water (50/20 vol.%)			
21	2.38	4.35	4.40	110.00	29.86	St-1
			acetone/water (25/75 vol.%)			
21	2.49	2.80	2.60	3.00	0.81	St-0

Table 9 Flammability properties for different acetone/water mixing vapors at 150°C, 2 atm and 21 vol.% O_2

O_2/vol.%	LEL/vol.%	UEL/vol.%	P_{max}/bar	$(dP/dt)_{max}$/bar s^{-1}	K_g/m bar s^{-1}	Explosion class (*St*)
			acetone/water (100/0 vol.%)			
21	2.58	14.90	11.50	827.00	224.48	St-2
			acetone/water (75/25 vol.%)			
21	2.83	10.45	12.30	495.00	134.36	St-1
			acetone/water (50/50 vol.%)			
21	2.76	6.76	8.40	132.00	35.83	St-1
			acetone/water (25/75 vol.%)			
21	2.40	3.08	6.20	102.00	27.69	St-1

Table 10 Flammability properties for different acetone/water mixing vapors at 200°C, 1 atm and 21 vol.% O_2

O_2/vol.%	LEL/vol.%	UEL/vol.%	P_{max}/bar	$(dP/dt)_{max}$/bar s^{-1}	K_g/m bar s^{-1}	Explosion class (*St*)
			acetone/water (100/0 vol.%)			
21	2.48	13.80	4.90	382.00	103.69	St-1
			acetone/water (75/25 vol.%)			
21	3.22	10.19	4.60	255.00	69.22	St-1
			acetone/water (50/50 vol.%)			
21	2.23	5.42	3.90	122.00	33.12	St-1
			acetone/water (25/75 vol.%)			
21	2.41	3.20	1.60	3.00	0.84	St-0

Table 11 Flammability properties for different acetone/water mixing vapors at 200°C, 2 atm and 21 vol.% O_2

O_2/vol.%	LEL/vol.%	UEL/vol.%	P_{max}/bar	$(dP/dt)_{max}$/bar s^{-1}	K_g/m bar s^{-1}	Explosion class (*St*)
			acetone/water (100/50 vol.%)			
21	1.81	18.47	12.40	868.00	235.61	St-2
			acetone/water (75/25 vol.%)			
21	1.95	11.42	9.90	750.00	203.58	St-2
			acetone/water (50/50 vol.%)			
21	2.16	6.88	8.50	250.00	67.86	St-1
			acetone/water (25/75 vol.%)			
21	2.39	3.35	6.20	140.00	38.00	St-1

outcome would be very useful and quite significant for industrial process safety to keep chemical plants from fire/explosion accidents. We should carefully avoid setting the concentration of the loading fuels into this dangerous explosion zone.

In addition, the LEL and UEL parameters are all summarized in a table list next to the coordinate in Fig. 9. It was also concluded that the elevated pressure and temperature made the explosion range (form LEL–UEL) broader and wider. Practically speaking, temperature is also an important safety factor [19]. Based upon the state notes from Zabetalis (1965) and Vanderstraeten (1997) [2, 29], the UFLs of common hydrocarbons increase with enhanced temperature but LFLs are alleviated, instead. Further in 2002, Crowl and Louvar [1], indicated that, in general, the flammability range of gases and vapors increases with enhanced temperature. We made the same discovery to prove this by observing the variations of explosion limits in 150 and 200°C, as shown in Tables 4–7 and Fig. 9. The explosion ranges of acetone$_{(aq)}$ with four vapor mixing ratios all got increased clearly, even in the different setting pressures of 1, 2 atm. About the effect of initial pressures, Crowl and Louvar mentioned that the UFL increases significantly as the pressure is increased, broadening the flammability range, but for the LFL, pressure has little effect on it. Totally reviewing our investigations, which almost fitted with the announcements of above-mentioned opening reference and besides being shown in Tables 4–7 and Fig. 9, also prove in Tables 8–11, the flammability properties for different acetone/water mixing vapors at 150/200°C, 1/2 atm and various O_2 vol.%.

From those tests, we recognized the effects and affected consequences of elevated initial temperatures and pressures on ‘explosion limit’ specifically and realized their implied meaning. This provided the crucial safety-related parameters to protect the relevant existing process plants from flammability hazards.

Conclusions

In this research, we surveyed several critical flammability properties of acetone$_{(aq)}$ solutions with various components of acetone/water vapor mixtures, i.e., the 100/0, 75/25, 50/50 and 25/75 vol.% under initial conditions of 150, 200°C, 1, 2 atm and 21 O_2 vol.%, reciprocally. In particular, the influences of inert steam, elevated temperatures/pressures for these samples were discovered by our well-organized experimental investigations and further discussions.

While augmenting the inert steam, enhancing the component of water proportion, the explosion range and pressure became small and narrow and so did the implied flammability hazard degree, evidently. As for elevating the operating temperatures and pressures, most flammability properties except the LEL were becoming greater and our investigations also showed that accorded with the opening references by other researchers in the past. Especially, we found that in the case of 2 atm and 200°C would be 'the worst scenario' in this study. To apply for the process, we strongly suggested that engineers and operators should pay more careful attention to the relevant process in this situation. In addition, an 'explosion area' schematic illustration, Fig. 9, was proposed to realize the comparisons of explosion limits of different acetone$_{(aq)}$s at all simulating circumstances. This would be very useful and quite significant for industrial process safety to keep chemical plants from fire/explosion calamities, by avoiding the concentration of the loading fuels into this dangerous explosion zone.

Through prudent surveys and suggestions in this paper, which were able to identify, we compared the flammability hazard specifically, so as to recommend procedures for a practical process safety control system, for help forestall flammability hazards from further occurring in the relevant existing process plants.

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Nomenclature

BP	boiling point/°C
$(\mathrm{d}P/\mathrm{d}t)_{\max}$	maximum rate of explosion pressure rise/bar s^{-1}
$(\mathrm{d}P/\mathrm{d}t)$	rate of explosion pressure rise/bar s^{-1}
FP	flash point/°C
LEL	lower explosion limit/vol.%
LFL	lower flammability limit/vol.%
MOC	minimum oxygen concentration/vol.%
$P_{\max}$	maximum explosion overpressure/bar
UEL	upper explosion limit/vol.%
UFL	upper flammability limit/vol.%

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