



## Short Communication

## Alkaline subcritical water gasification of dairy industry waste (Whey)

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## ABSTRACT

The near-critical water gasification of dairy industry waste in the form of Whey, a product composed of mixtures of carbohydrates (mainly lactose) and amino acids such as glycine and glutamic acid, has been studied. The gasification process involved partial oxidation with hydrogen peroxide in the presence of NaOH. The reactions were studied over the temperature range from 300 °C to 390 °C, corresponding pressures of 9.5–24.5 MPa and reaction times from 0 min to 120 min. Hydrogen production was affected by the presence of NaOH, the concentration of H<sub>2</sub>O<sub>2</sub>, temperature, reaction time and feed concentration. Up to 40% of the theoretical hydrogen gas production was achieved at 390 °C. Over 80% of the Whey nitrogen content was found as ammonia, mainly in the liquid effluent.

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## 1. Introduction

The dairy industry has grown in many countries in the world as well as in Europe because of consumer demand and it is one of the largest sources of industrial effluents, which contain dilutions of whole milk, separated milk and Whey (Arvanitoyannis, 2008). In most countries of the World, dairy processing has been considered as the largest source of food processing effluents (Oreopoulou and Russ, 2007). Whey is the liquid by-product with up to 94% water content (Pesta et al., 2007) produced from the manufacture of cheese after the removal of cheese curds. Worldwide Whey wastewater production is estimated to 145 million tonnes per year (Audic et al., 2003; Güven et al., 2008) and approximately half of that is disposed into the surface water (Gonzalez-Siso, 1996; Güven et al., 2008). Whey constitutes about 33% of total wastewater volume from the cheese production process, it is of very high organic load and consequently, has a very strong polluting potential and is therefore not allowed for direct disposal on land or water courses (Gelegenis et al., 2007).

The gasification process in subcritical water or supercritical water is considered as a potential technology to convert wet biodegradable wastes into high-energy value gases including hydrogen or methane (Mozaffarian et al., 2004; Osada et al., 2008; Williams and Onwudili, 2006).

Many researchers have studied hydrothermal gasification of carbohydrates and/or proteins as model compounds to produce hydrogen gas (Okajima et al., 2007; Xu et al., 2009). However, there

are few data in relation to real-world food wastes. Whey is a real-world waste product composed of mixtures of carbohydrates and amino-acids (proteins). Dried Whey (powder) contains about 12–18% proteins (with free amino-acid such as glutamic acid, proline, lysine, aspartic acid and arginine), 8–14% minerals (ash) and 77–80% carbohydrates mainly lactose (Mavropoulou and Kosikowski, 1973; Pesta et al., 2007).

In this paper the hydrothermal gasification of Whey has been researched in relation to the production of fuel gas products such as hydrogen gas. The conversion of Whey was investigated in near-critical water using partial oxidative gasification in the presence of sodium hydroxide (NaOH) additive.

## 2. Experimental

Whey was in the form of powder and was sourced from an animal food products industry in Thailand, characterised and used as received. The proximate analysis of the sample was 5.7 wt.% moisture, 86.6 wt.% volatiles, 10 wt.% fixed carbon and 3.4 wt.% ash. The elemental composition of the Whey powder was C, 37.5 wt.%; H, 5.94 wt.%; N, 2.69 wt.% and O, 53.9 wt.%. The empirical formula of the Whey powder in terms of carbon, hydrogen, nitrogen and oxygen could be assumed as C<sub>6</sub>H<sub>12</sub>N<sub>0.4</sub>O<sub>7</sub>. Based on this formula, the theoretical total organic carbon (TOC) of 5 g of Whey powder dissolved in 100 ml of deionized water (main feed concentration) was calculated as 17,860 mg/L (Stander and Theodore, 2008). The experimental value of the TOC of the same solution of Whey powder was obtained as 16,800 mg/L. The Whey was reacted in a closed batch autoclave reactor with hydrogen peroxide as the oxidant under subcritical water gasification conditions. Since the

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**Table 1**  
Total mass balance of products in relation to reaction conditions during Whey gasification (1.67 M NaOH).

Temp (°C)	Pressure (MPa)	Time (min)	H <sub>2</sub> O <sub>2</sub> (wt.%)	H <sub>2</sub> (mg)	NH <sub>4</sub> <sup>+</sup> (mg)	CO (mg)	CO <sub>2</sub> (mg)	CH <sub>4</sub> (mg)	C <sub>2</sub> -C <sub>4</sub> (mg)	Solid residue (mg)	TWSP <sup>a</sup> (mg)	H <sub>2</sub> O (mg)	% mass balance
300	9.5	0	1.50	5.20	78.3	-	-	0.20	0.20	220.0	11520.0	840.5	96.2
300	9.5	60	1.50	29.0	80.2	-	-	0.80	1.50	180.0	10998.8	1054.7	93.7
300	9.5	120	1.50	51.1	82.0	-	-	0.50	3.80	190.0	10340.4	1254.0	90.5
330	13.5	0	1.50	37.5	99.7	-	-	0.40	0.90	110.0	10295.3	1131.8	88.7
330	13.5	60	1.50	93.5	113.2	-	-	0.70	5.20	180.0	10899.7	1635.9	98.2
330	13.5	120	1.50	109.4	115.8	-	-	0.90	6.10	100.0	9851.1	1779.1	90.8
350	17.5	0	1.50	39.7	107.4	-	-	0.60	1.70	150.0	10866.3	1151.1	93.5
350	17.5	60	1.50	113.8	134.6	-	-	1.50	7.90	180.0	11123.7	1818.2	102
350	17.5	120	1.50	118.8	137.6	-	-	2.50	12.0	240.0	11084.4	1863.6	103
370	21.8	0	1.50	86.7	122.2	-	-	1.70	5.60	190.0	10225.7	1574.6	92.7
370	21.8	60	1.50	120.1	133.1	-	-	4.10	7.70	250.0	11100.9	1874.6	102
370	21.8	120	1.50	129.4	139.3	-	-	4.60	9.90	200.0	10548.7	1958.5	98.6
390	24.5	0	1.50	103.7	94.4	-	-	3.60	6.40	190.0	9990.5	1727.5	92.0
390	24.5	120	1.50	147.0	143.3	-	-	14.2	16.5	190.0	11018.0	2116.8	104
330	13.5	120	0.00	92.3	95.4	-	-	2.90	12.1	150.0	10424.5	830.4	99.5
330	13.5	120	3.00	103.5	157.6	7.30	3.10	0.70	6.20	160.0	11782.6	2519.8	101
330	13.5	120	5.67	70.5	130.1	-	-	6.50	4.10	130.0	12317.3	3636.6	94.3

Product mass balance during the investigation of the effect of feed concentration at 330 °C, 13.5 MPa and 120 min													
Feed Concentration (%w/v)	H <sub>2</sub> O <sub>2</sub> (%wt)	H <sub>2</sub> (mg)	NH <sub>4</sub> <sup>+</sup> (mg)	CO (mg)	CO <sub>2</sub> (mg)	CH <sub>4</sub> (mg)	C <sub>2</sub> -C <sub>4</sub> (mg)	Oil/tar (mg)	Solid residues/char (mg)	TWSP <sup>a</sup> (mg)	H <sub>2</sub> O (mg)	% mass balance	
2.5	1.50	55.6	77.9	-	-	0.70	2.20	-	90.0	9196.8	1294.3	100	
5.0	1.50	109.4	115.8	-	-	0.90	6.10	-	100.0	9851.1	1779.1	90.8	
10.0	1.50	110.0	256.8	-	5.10	2.00	15.2	2276.2	320.0	12228.9	1784.1	93.6	
15.0	1.50	113.4	303.9	14.3	516.3	5.40	28.5	3138.7	690.0	16165.9	1814.7	98.4	

<sup>a</sup> TWSP = total water soluble product containing both organic and inorganic compounds.

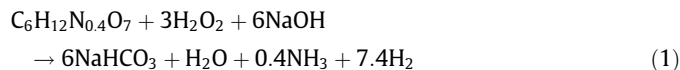
reactor was a closed system, increasing temperatures led to pressures of between 9.5 and 24.5 MPa. Product gases were analysed off-line by gas chromatography. The liquid sample (including any tar formed) and solid residue were separated by vacuum filtration and the total water soluble products (TWSP) were extracted from the liquid sample using ethyl acetate. This ethyl acetate extract (organic phase) was quantitatively collected and evaporated with a gentle stream of nitrogen gas, placed in a desiccator to dry off the moisture overnight, and then weighed to determine the total mass of oil/tar produced. The aqueous fraction was dried and analysed using X-ray diffraction (XRD), identifying any crystalline substances present. The presence of ammonia or ammonium ion in the liquid effluents was determined using a Dionex ion chromatograph. The experimental and analytical system and procedures have been described previously (Onwudili and Williams, 2009a,b; Muangrat et al., 2010a,b).

### 3. Results and discussion

Table 1 presents the total mass balance of all products obtained during the Whey gasification with 1.67 M NaOH catalyst. Apart from the mass of water, which was calculated based on the initial amount of hydrogen peroxide used, the mass of other products was obtained via analyses or through direct weighing. It can be seen that solid residues/char contributed the most to the product mass balances. Table 2 illustrates carbon, hydrogen and nitrogen mass balances of products during Whey hydrothermal gasification. For nitrogen mass balance, it can be seen that most of the N atoms in Whey were converted to NH<sub>4</sub><sup>+</sup> ion depending on the reaction conditions.

#### 3.1. Effect of hydrogen peroxide

The effect of hydrogen peroxide concentration on the subcritical water gasification of Whey by maintaining the concentration of NaOH at 1.67 M was studied (Fig. 1). The effects of oxidant loading obtained from hydrogen peroxide as the oxygen source on the gas yield was investigated at a temperature of 330 °C and 120 min of reaction time. The maximum theoretical hydrogen gas produced from Whey (C<sub>6</sub>H<sub>12</sub>N<sub>0.4</sub>O<sub>7</sub>) could be evaluated using the following Eq. (1).



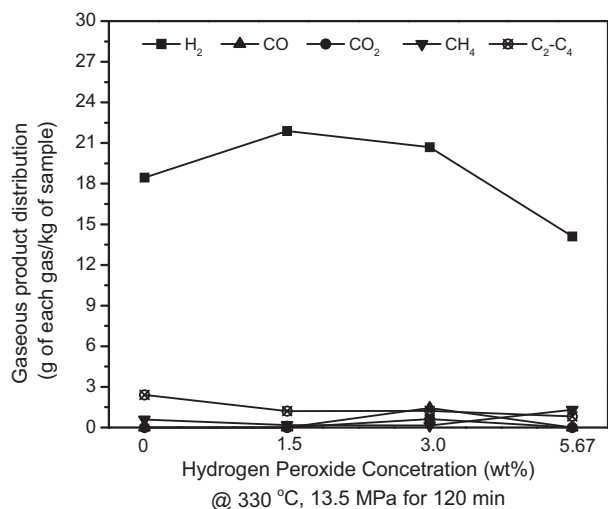
According to Eq. (1), which is based on the reaction scheme of Onwudili and Williams (2009a), theoretically, 73.4 g of H<sub>2</sub> gas would be produced from the gasification of 1 kg Whey. Eq. (1) also recognizes the possible loss of hydrogen gas due to the formation of ammonia from amino-nitrogen (Onwudili and Williams, 2009b). Ordinarily, hydrogen peroxide would decompose to produce water and oxygen gas, but the equation shows that both the oxygen and some of the water produced could participate in the gasification reaction. Hence, the equation suggests the participation of the stoichiometric reacting water (Onsager et al., 1996; Onwudili and Williams, 2009a). Fig. 1 shows that the experimental H<sub>2</sub> yield was found to increase from 18.0 to 21.8 g kg<sup>-1</sup> of Whey when the H<sub>2</sub>O<sub>2</sub> concentration increased from 0.0 to 1.5 wt.%. After that the H<sub>2</sub> gas yield gradually dropped to 13.3 g kg<sup>-1</sup> of Whey at 5.67 wt.% of H<sub>2</sub>O<sub>2</sub> loading. At 1.5 wt.% of H<sub>2</sub>O<sub>2</sub>, Whey was gasified to form the highest level of H<sub>2</sub> product at around 21.8 g kg<sup>-1</sup> of sample due to the combined effect of the alkali and hydrogen peroxide. In essence, in the presence of the alkali alone, almost 25% of the theoretical hydrogen gas yield was obtained. However, this increased to almost 30% of the theoretical prediction with the addition of 1.5 wt.% hydrogen peroxide. In practice, it is almost

**Table 2**

Carbon, Hydrogen and Nitrogen mass balance in relation to temperature and reaction time conditions during Whey powder gasification with 1.67 M NaOH catalysts.

Carbon mass balance										
Temp (°C)	Time (min)	H <sub>2</sub> O <sub>2</sub> (wt.%)	CO (mg)	CO <sub>2</sub> (mg)	CH <sub>4</sub> (mg)	C <sub>2</sub> -C <sub>4</sub> (mg)	Solid residues (mg)	TWSP <sup>a</sup> (mg)	% mass balance	
300	0	1.50	-	-	0.20	0.20	23.9	1525.6	82.7	
300	120	1.50	-	-	0.40	3.30	42.6	1587.5	87.1	
330	0	1.50	-	-	0.30	0.70	25.1	1568.5	85.0	
330	120	1.50	-	-	0.70	5.20	16.1	1610.1	87.0	
350	0	1.50	-	-	0.40	1.40	29.4	1649.5	90.0	
350	120	1.50	-	-	1.90	10.3	34.1	1737.4	95.1	
370	0	1.50	-	-	1.30	4.80	22.1	1663.4	90.2	
370	120	1.50	-	-	3.40	8.40	23.6	1648.7	89.8	
390	0	1.50	-	-	2.70	5.40	44.7	1463.7	80.9	
390	120	1.50	-	-	10.7	14.0	36.3	1704.8	94.2	
330	120	0.00	-	-	2.20	10.3	34.4	1536.7	84.5	
330	120	3.00	3.10	0.80	0.50	5.20	16.5	1752.0	94.8	
330	120	5.67	-	-	4.90	3.50	12.6	1761.1	95.0	
Hydrogen mass balance										
Temp (°C)	Time (min)	H <sub>2</sub> O <sub>2</sub> (wt.%)	H <sub>2</sub> (mg)	NH <sub>4</sub> <sup>+</sup> (mg)	CH <sub>4</sub> (mg)	C <sub>2</sub> -C <sub>4</sub> (mg)	Solid residue (mg)	TWSP <sup>a</sup> (mg)	H <sub>2</sub> O (mg)	% mass balance
300	0	1.50	5.20	17.4	-	-	4.00	419.0	93.4	97.6
300	120	1.50	51.1	18.2	0.10	0.60	5.20	249.0	139.3	84.0
330	0	1.50	37.5	22.2	0.10	0.10	4.10	287.9	125.8	86.5
330	120	1.50	109.4	25.7	0.20	0.90	2.30	148.9	197.7	87.9
350	0	1.50	39.7	23.9	0.10	0.20	3.90	286.4	127.9	87.3
350	120	1.50	118.8	30.6	0.60	1.80	3.60	152.1	207.1	93.2
370	0	1.50	86.7	27.2	0.40	0.80	2.40	183.5	175.0	86.2
370	120	1.50	129.4	31.0	1.10	1.50	2.60	145.0	217.6	95.7
390	0	1.50	103.7	21.0	0.90	1.00	4.90	169.6	191.9	89.3
390	120	1.50	147.0	31.8	3.60	2.60	3.60	151.6	235.2	104
330	120	0.00	92.3	21.2	0.70	1.80	4.30	251.8	92.3	100
330	120	3.00	103.5	35.0	0.20	0.90	0.90	184.1	280.0	94.4
330	120	5.67	70.5	28.9	1.60	0.70	1.40	170.0	404.1	85.0
Nitrogen mass balance										
Temp (°C)	Time (min)	H <sub>2</sub> O <sub>2</sub> (wt.%)	NH <sub>4</sub> <sup>+</sup> (mg)	Solid residues (mg)	TWSP <sup>a</sup> (mg)	% mass balance				
300	0	1.50	60.9	2.00	45.5	80.6				
300	120	1.50	63.8	1.40	49.7	85.4				
330	0	1.50	77.6	0.60	34.4	83.8				
330	120	1.50	90.1	0.60	20.4	82.6				
350	0	1.50	83.5	0.70	31.8	86.2				
350	120	1.50	107	1.50	32.3	105				
370	0	1.50	95.0	1.20	16.1	83.5				
370	120	1.50	109	1.40	20.5	96.8				
390	0	1.50	73.4	0.50	67.9	105				
390	120	1.50	115	0.60	30.6	106				
330	120	0.00	74.2	1.10	51.3	94.1				
330	120	3.00	123	1.00	19.3	106				
330	120	5.67	102	0.70	24.3	93.8				

<sup>a</sup> TWSP = total water soluble product containing both organic and inorganic compounds.



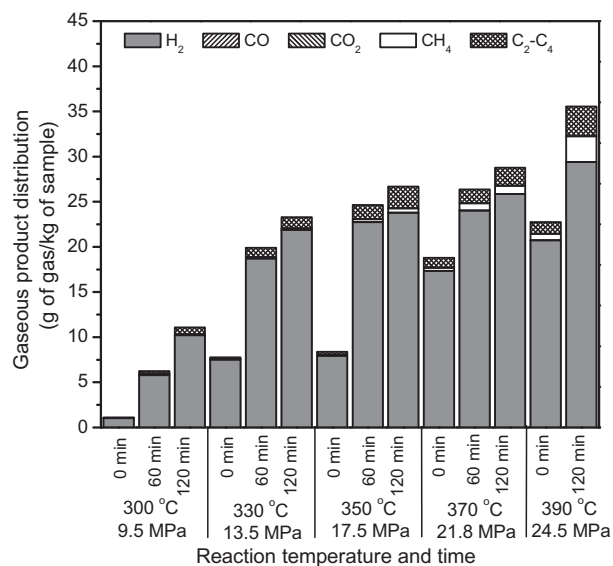
**Fig. 1.** The effect of hydrogen peroxide concentration on subcritical water gasification of Whey, 1.67 M NaOH, 330 °C, 13.5 MPa and 120 min of reaction time.

impossible to achieve the maximum theoretical H<sub>2</sub> because of the possibility of various simultaneous competing reactions and/or incomplete conversion of Whey during this process. These side reactions would include the formation of other products such as solid residues and unconverted dissolved intermediate compounds. However, no tar or oil was produced during these reactions. With the highest concentration of the oxidant used, hydrogen gas yield fell to just over 18% of what Eq. (1) predicted. With increasing hydrogen peroxide loading, it appeared that oxidation became more predominant than gasification via the water–gas shift reaction. Hence, CO<sub>2</sub> rather than CO would be produced directly via oxidation as a consequence of higher H<sub>2</sub>O<sub>2</sub> loading. No significant yield of gaseous CO<sub>2</sub> was observed, and this could be due to its capture by the added NaOH. NaOH was added primarily to accelerate the reaction rate of the water–gas shift reaction forward to the right hand side, if CO was produced (CO + H<sub>2</sub>O → CO<sub>2</sub> + H<sub>2</sub>) by removing the CO<sub>2</sub> to form sodium carbonate. However, it would also react with the CO<sub>2</sub> produced by direct oxidation of Whey at increased oxidant loading. Additionally, the yields of hydrocarbon gases (C<sub>2</sub>–C<sub>4</sub>) decreased and only small traces of CH<sub>4</sub> was detected with rising hydrogen peroxide concentration.

### 3.2. Effect of temperature and reaction time

The effects of temperature and reaction time on subcritical water gasification of Whey were investigated at a fixed hydrogen peroxide concentration of 1.5 wt.% and NaOH at 1.67 M (Fig. 2). Increasing both temperature and reaction time led to an increase in gaseous products, such that the main gaseous products were H<sub>2</sub> and hydrocarbon gases (C<sub>1</sub>–C<sub>4</sub>). Generally, hydrogen gas and CH<sub>4</sub> were the major gases produced at higher temperature and longer reaction time. However, short reaction time at higher temperature; for example, at 370 °C or 390 °C for 0 min, aided the formation of higher yields of H<sub>2</sub> gas compared with long reaction time and low temperature (300 and 330 °C for 120 min). No tar or oil formation was observed during these experiments in relation to reaction temperature and time.

Hydrogen gas yield reached a maximum of 29.4 g kg<sup>-1</sup> of Whey at 390 °C for 120 min of reaction time, corresponding to 40% of the theoretical prediction (Eq. (1)). The increase in hydrogen yield could be attributed to higher conversion of Whey and its degradation products with increasing temperature and reaction time. The



**Fig. 2.** Gaseous product distribution as a function of temperature and reaction time from Whey (1.67 M NaOH and 1.5 wt.% H<sub>2</sub>O<sub>2</sub>).

decomposition of Whey to various products including gaseous species would increase with higher activation energy as a consequence of increasing temperature and reaction time. The decomposition of heavier carbon containing hydrocarbon gases (C<sub>2</sub>–C<sub>4</sub>) can also take place at longer reaction time (Sricharoenchaikul, 2009). The larger yields of H<sub>2</sub> and CH<sub>4</sub> could have resulted from the decomposition of intermediate sodium formate and sodium acetate, respectively (Onwudili and Williams, 2009a). Thus, the predominant methane formation could be from the reaction of water with sodium acetate (CH<sub>3</sub>COONa + H<sub>2</sub>O → CH<sub>4</sub> + NaHCO<sub>3</sub>) especially with increasing temperature (Muangrat et al., 2010b).

### 3.3. Effect of Whey feed concentration

The effect of increasing feed concentration on gas production was investigated where the concentrations of hydrogen peroxide and sodium hydroxide were kept constant. Increasing the Whey concentration led to a significant increase in the CO<sub>2</sub> gas yield while H<sub>2</sub> gas yield slowly declined. The yields of other gases, including CO, CH<sub>4</sub>, other hydrocarbon gases (C<sub>2</sub>–C<sub>4</sub>), increased when Whey was fed into the reactor at higher concentrations. A feed concentration of 5%w/v produced the highest H<sub>2</sub> product of 21.8 g kg<sup>-1</sup> of Whey, and no CO and CO<sub>2</sub> was detected. Above a Whey concentration of 5%w/v, H<sub>2</sub> production became nearly constant (~22 g kg<sup>-1</sup> of Whey) however there was an appreciable increase of total hydrocarbon gases at higher feed concentration from 0.58 g kg<sup>-1</sup> up to 6.79 g kg<sup>-1</sup> of Whey.

Based on Eq. (1), if feed concentrations were 5, 10 and 15%w/v, the calculated theoretical NaOH concentrations were 1.49, 2.98 and 4.46 M, respectively. Thus, keeping the concentration of NaOH at 1.67 M in this section of the investigation implied that the concentration of the alkali became insufficient with increasing Whey loadings of 10 and 15%w/v. One of the major advantages of adding NaOH catalyst into the system is that NaOH alkali prevents tar/oil formation. To significantly reduce tar/oil formation, the mass ratio of biomass feed to alkali should be 1/1.2 (Onwudili and Williams, 2009a; Muangrat et al., 2010a). The shortfall in alkali could be responsible for formation of higher tar/oil which reached 45.5 and 62.8%w/w of the initial Whey feed for the 10% and 15% feed loadings, respectively. Polymerization



often leads to loss of gasifiable material and a decrease in the amount of hydrogen gas formed. Also, the high proportion of CO<sub>2</sub> and CO in the gaseous effluent at high feed concentration indicates a suppression of the role of sodium hydroxide in the water–gas shift chemistry. Additionally, the dramatic increase in methane gas yield could be as a result of pyrolytic reactions rather than the formation and subsequent decomposition of sodium acetate.

#### 3.4. Fate of nitrogen in Whey

Ultimate analysis of the Whey sample showed it contained approximately 2.69% of nitrogen and this was expected to be in the form of amino acid. Literature suggests that organo-nitrogen groups such as nitriles, amines and amides are usually converted to ammonia during hydrothermal treatment (Okajima et al., 2007; Onwudili and Williams, 2009a). In this work, it was found that ammonia was produced during the hydrothermal reactions of Whey. An attempt was made to measure ammonia both in the gas phase and as ammonium ion in the liquid effluents. It should be noted that the pH of the liquid effluents were highly basic due to the presence of soluble sodium carbonate, or even unreacted sodium hydroxide. Theoretically, the maximum proportion of nitrogen atoms in Whey, based on the formula, would be approximately 27.8 g per kg of Whey. The value corresponds to an equivalent of 35.7 g dissolved ammonium ion kg<sup>-1</sup> of Whey. It was found that the ammonium ion concentration increased with both increasing temperature and increasing reaction time. The highest concentration of ammonium ion measured was about 28.7 g kg<sup>-1</sup>, which was equivalent to 80.2% of the nitrogen content of Whey. This shows that much of the nitrogen, which was expected to be in the form of amino acid, was converted to ammonia possibly through the process of deamination.

Kruse and Gawlik (2003) studied the degradation of phytomass consisting of cooked carrots and potatoes as real biomass investigated in water in the ranges of 330–410 °C and 30–50 MPa and at 15 min of reaction time. They found that the concentration of some inorganic ions decreased with increasing temperature except that of NH<sub>4</sub><sup>+</sup> ion. The concentration of NH<sub>4</sub><sup>+</sup> ion increased with temperature indicating that the increase of NH<sub>4</sub><sup>+</sup> concentration might be a consequent effect of higher hydrolysis reaction of proteins as increasing temperature, and accelerated by a high hydrogen ion concentration (H<sup>+</sup>). With increasing temperature, the ionic product increases leading to the increase of hydrolysis reaction (Kruse and Gawlik, 2003). The formation of ammonia would indicate the loss of hydrogen atoms that would have formed hydrogen gas but this has been recognized in Eq. (1).

The presence of NH<sub>3</sub> in the gas phase was investigated by trapping the gas with 50 ml of deionized water. All gaseous products under the hydrothermal gasification of Whey at temperatures of 300, 330 and 350 °C for 0 min and temperature of 330 °C for 60 min. For the experimental conditions of set temperature of 300, 330 and 350 °C for 0 min, the amount of NH<sub>4</sub><sup>+</sup> ion were zero, 0.13 mg and 1.00 mg, respectively. Meanwhile, 4.60 mg of dissolved NH<sub>3</sub> gas was obtained at 330 °C for 60 min reaction time, which showed that gas phase ammonia increased with increased reaction time. However, though ammonia gas was found in the gas phase, the concentrations were largely insignificant compared to the concentrations measured in the liquid phase. XRD analysis of the dried and crystalline aqueous phase showed that some of the nitrogen atoms were present as nitrotriacetic acid disodium salt (C<sub>2</sub>H<sub>7</sub>NNa<sub>2</sub>O<sub>6</sub>). The XRD analysis also revealed the presence of sodium carbonate and sodium acetate in the dried water soluble product.

#### 4. Conclusions

The hydrothermal gasification of Whey in the presence of NaOH and H<sub>2</sub>O<sub>2</sub> showed increased hydrogen yield with increasing H<sub>2</sub>O<sub>2</sub> concentration up to 1.5 wt.%, giving ~30% at 330 °C, 13.5 MPa. At the highest temperature of 390 °C (24.5 MPa), yield of hydrogen gas increased to 40% in relation to theoretical prediction. Above 1.5 wt.% H<sub>2</sub>O<sub>2</sub> concentration, hydrogen gas yield dropped due to apparent predominantly oxidizing conditions. Hydrogen production from Whey was accelerated by increasing of temperature and reaction time. Ammonia production increased as both the reaction temperature and reaction time increased due to the conversion of the nitrogen in Whey. Approximately 80% of the ammonia predicted by the reaction equation was obtained during the temperature and reaction time studied.

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