

Effects of Vapor Pressure on Thermodynamic Equilibrium in Multiphase Flow for Thermochemical Hydrogen Production

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Abstract

This paper examines the effects of H₂O vapor pressure on the equilibrium conditions of a CuCl₂ hydrolysis reactor in the thermochemical Cu-Cl cycle of hydrogen production. A new predictive model is developed to determine the minimum steam requirement in the reactor based on the chemical equilibrium condition, reactor pressure and fraction of gaseous reactant. Experimental data, at three separate vapour pressures of steam, compared well with the new predictive formulation.

Nomenclature

f	fugacity, Pa
G	Gibbs free energy, kJ/mol
K	constant
N	number of moles
p	pressure, Pa
Q	quotient
RH	relative humidity

t time, s
 T temperature, °C

Greek

β nitrogen to water ratio
 ξ steam requirement
 $\hat{\xi}$ standardized steam requirement
 ρ density, kg/m³

Subscripts

e equilibrium
 H humidifier
 R reaction
 T total

1. Introduction

Thermochemical water splitting cycles are promising sustainable alternatives to traditional fossil fuel based methods of hydrogen production, such as steam methane reforming and coal gasification. These cycles consist of several steps to split water into hydrogen and oxygen, while continuously re-using and re-cycling all of the other chemicals in the cycle. After investigating the performance of 10 different thermochemical cycles, Andress et al. [1] reported thermal efficiencies from 35% to 49% for most of the cycles.

The Cu-Cl cycle consists of three main reactions: hydrolysis, thermolysis and electrolysis. In the hydrolysis step, superheated steam reacts with copper (II) chloride (CuCl₂) to produce two

compounds, hydrogen chloride (HCl) and copper oxychloride (Cu_2OCl_2), which are further reacted and re-cycled in the thermolysis and electrolysis steps. The chemical reaction of the hydrolysis process, without excess steam, is $2\text{CuCl}_{(s)} + \text{H}_2\text{O}_{(g)} = \text{Cu}_2\text{OCl}_{2(s)} + 2\text{HCl}_{(g)}$, at $\approx 375^\circ\text{C}$. In past studies by Wang et al. [2], solid Cu_2OCl_2 is produced within the reactor and moved to a thermolysis reactor where it decomposes to molten copper (I) chloride (CuCl) and oxygen (O_2). The gaseous HCl product flows to an electrolyzer to react with CuCl to produce aqueous CuCl_2 and hydrogen gas (H_2). The chemical processes in the Cu-Cl cycle are illustrated in Fig. 1.

Achieving a high conversion of CuCl_2 to Cu_2OCl_2 within the hydrolysis reactor is crucial to improve the effectiveness of Cu_2OCl_2 decomposition. Un-reacted CuCl_2 mixed with Cu_2OCl_2 in the oxygen production reactor would cause the undesired production of chlorine gas (Cl_2), which must be then replaced to replenish the CuCl_2 in the cycle [3]. Also, if the gaseous HCl, mixed with un-reacted steam, is below the concentration requirements of the electrolyzer, then an energy intensive concentrating process will be required, which would significantly reduce the efficiency of the cycle. For effective operation, current electrolyzer designs require 6 M to 11 M of HCl in H_2O [4-6]. Past studies have shown significant difficulties in obtaining high steam conversion within the hydrolysis reactor [7-9].

The gaseous product fraction and chemical equilibrium in the CuCl_2 hydrolysis reaction are investigated in this paper, to obtain new information regarding integration of the cycle's reactors and future scale-up of the system. Reducing the excess steam consumption in the hydrolysis reactor and achieving higher steam conversion are imperative to more efficiently provide high purity products to the electrolyzer and thermolysis reactors. These issues will be examined in this paper through new predictive models and experimental data.

2. Formulation of Chemical Equilibrium at Varying Pressure

In this section, Le Chatelier's principle will be applied and the effects of reactor pressure on the product yield will be formulated for the hydrolysis process. Altering the system pressure will cause the equilibrium point to shift. If the pressure is increased, the equilibrium will shift towards less gaseous compounds. Conversely, if the system pressure is reduced, the equilibrium point will shift towards more gaseous compounds. In the CuCl_2 hydrolysis reactor, reducing the system pressure will shift the equilibrium towards the products, producing more HCl gas and reducing the steam requirement.

If the system pressure is maintained constant, then the equilibrium can be adjusted by the addition of an inert gas. The saturation pressure can be determined from the temperature of the flow stream as follows [10]:

$$p_{sat,H_2O} = \exp\left(77.345 + 0.0057 \times (T_H) - \frac{7235}{T_H^{8.2}}\right) \quad (1)$$

where T_H represents the temperature of the fluid steam exiting the humidifier. The partial pressure p_{sat,H_2O} of H_2O (p_{H_2O}) is determined by

$$p_{H_2O} = RH \times p_{sat,H_2O} \quad (2)$$

where RH_H represents the relative humidity of the steam exiting the humidifier. The density of H_2O (ρ_{H_2O}) in a flow stream of humidified inert gas can be calculated from the measured temperature and partial pressure of H_2O as follows,

$$\rho_{H_2O} = 0.0022 \times \frac{p_{H_2O}}{T_H} \quad (3)$$

The equilibrium constant is represented in terms of the relative fugacities of the constituents [11],

$$K_e = \left[\frac{f_{CuO} f_{CuCl_2} f_{HCl}^2}{f_{CuCl_2}^2 f_{H_2O}} \right] \quad (4)$$

As illustrated in Fig 1, the Cu_2OCl_2 and CuCl_2 compounds remain solid during the reaction. For a solid, pressure variations have a negligible effect on fugacity, allowing $f_{\text{CuCl}_2}^2$ and $f_{\text{Cu}_2\text{OCl}_2}$ to be estimated as unity. At low pressures, close to ambient conditions, the gases can be regarded as ideal gases, so the difference between the gaseous compound fugacities and partial pressures are negligible, i.e., $f \approx p$, reducing Eq. (4) as follows,

$$K_e = \left(\frac{p_{\text{HCl}}^2}{p_{\text{H}_2\text{O}}} \right) \quad (5)$$

The partial pressure of the gaseous compounds can be represented in terms of the molar fraction by:

$$p_{\text{HCl}} = \frac{N_{\text{HCl}}}{N_T} p_T \quad (6)$$

and

$$p_{\text{H}_2\text{O}} = \frac{N_{\text{H}_2\text{O}}}{N_T} p_T \quad (7)$$

where N_T represents the total number of moles in the reactor. If an inert gas is present, then N_T can be represented by $N_T = N_{\text{HCl}} + N_{\text{H}_2\text{O}} + N_i$, where N_i represents the number of gaseous moles not participating in the reaction (e.g. an inert carrier gas). Substituting Eqs. (6) and (7) into Eq. (5) and rearranging yields

$$K_e = \frac{N_{\text{HCl}}^2}{N_{\text{H}_2\text{O}}} \left(\frac{p_T}{N_{\text{HCl}} + N_{\text{H}_2\text{O}} + N_i} \right) \quad (8)$$

An important consideration for achieving high conversion efficiencies is highlighted in Eqs. (5) and (8). As presented in Eq. (5), the addition of an inert gas to the reaction does not influence the equilibrium constant (if the system's total pressure is maintained constant). Since it will be present in the reactants and products, in equal amounts, the partial pressure terms of the inert gas will be unity in Eq. (5). However, as presented in Eq. (8), K_e can be formulated in terms

of N_T , where N_T will be affected by the addition of an inert gas. An inert carrier gas will increase the total number of moles in the system (N_T), which will promote HCl production, by increasing the ratio of $(N_{HCl}^2)/N_{H_2O}$ within the reactor. The value of K_e will determine the rate of change in HCl production, caused by the carrier gas.

Substituting nitrogen as the inert gas, Eq. (8) can be divided by N_{H_2O} and rearranged to yield

$$\left(\frac{N_{HCl}}{N_{H_2O}}\right)^2 - \frac{K_e}{p_T} \left(\frac{N_{HCl}}{N_{H_2O}}\right) - \frac{K_e}{p_T} \left(\frac{N_{N_2}}{N_{H_2O}} + 1\right) = 0 \quad (9)$$

Equation (4-15) represents a second degree polynomial in terms of $\left(\frac{N_{HCl}}{N_{H_2O}}\right)$, which can be expressed as:

$$\frac{N_{HCl}}{N_{H_2O}} = -\frac{1}{2} \frac{K_e}{p_T} \pm \frac{1}{2} \sqrt{\left(-\frac{K_e}{p_T}\right)^2 + 4 \frac{K_e}{p_T} \left(\frac{N_{N_2}}{N_{H_2O}}\right)} \quad (10)$$

This formulation, Eq. (10), represents a new method to predict the molar ratio of $\frac{N_{HCl}}{N_{H_2O}}$ in a $CuCl_2$ hydrolysis reactor with the addition of an inert gas.

The steam requirement (ξ) can be defined as the molar ratio of H_2O to HCl in the input flow stream,

$$\xi = \frac{N_{H_2O}}{N_{HCl}} \quad (11)$$

The steam requirement is equal to the inverse of Eq. (10), which is proportional to the molar ratio of N_2 and H_2O into the reactor (β),

$$\beta = \frac{N_{N_2}}{N_{H_2O}} \propto \xi \quad (12)$$

Substituting Eqs. (11) and (12) into Eq. (10) gives

$$\xi = \left[-\frac{1}{2} \frac{K_e}{p_T} \pm \frac{1}{2} \sqrt{\left(-\frac{K_e}{p_T} \right)^2 + 4 \frac{K_e}{p_T} (\beta)} \right]^{-1} \quad (13)$$

When an inert gas is absent, the minimum steam requirement can be predicted by the following equality, in terms of the Gibbs reaction energy and reactor pressure.

$$\xi(N_{N_2} = 0) = \left[-\frac{1}{2p_T} \exp\left(-\frac{\Delta G_R^\circ}{RT}\right) \pm \frac{1}{2} \sqrt{\left(-\frac{1}{p_T} \exp\left(-\frac{\Delta G_R^\circ}{RT}\right) \right)^2} \right]^{-1} \quad (14)$$

The standardized steam requirement ($\hat{\xi}$) can be determined from Eqs. (11), (13), and (14), as follows,

$$\hat{\xi} = \frac{N_{H_2O}}{N_{HCl}} + \xi(N_{N_2} = 0) - \xi \quad (15)$$

The above formulation provides a robust method to predict the minimum steam requirement in the CuCl_2 hydrolysis reactor, over a wide range of operating conditions.

The energy input for various steam requirements can be determined as follows,

$$\Delta H_T = f\left(\Delta H_{Cp,water}, \Delta H_{Cp,steam}, H_{latent,H_2O}, \Delta H_{Cp,CuCl_2}\right) \quad (16)$$

where $H_{Cp,water}$, $H_{Cp,steam}$, H_{latent,H_2O} , $H_{Cp,CuCl_2}$ represent the energy requirement to elevate the water temperature, to elevate the steam temperature, to convert water to steam, and to elevate the CuCl_2 temperature. The heat input for temperature elevation can be represented by

$$Q = nC_p\Delta T \quad (17)$$

where n , C_p , and ΔT represent the mole number, the heat capacity and the temperature change.

The H_2O phase change can be represented by

$$H_{latent} = n\beta \quad (18)$$

where β represents the enthalpy of vaporization coefficient.

3. Experimental Apparatus

This section presents the experimental configurations to acquire the CuCl_2 hydrolysis reactor data. It includes two separate reactors: a horizontal and vertical configuration. As illustrated in Fig. 2, both designs introduce humidified nitrogen into a packed bed of CuCl_2 particles. The same pre-processing equipment, up to and including the humidifier system, are used for both experiments. Also, the same scrubber and chlorine analyzer systems are used for both configurations. The horizontal reactor introduces a small flow rate of steam to a large mass of CuCl_2 . It allows for a high contact time with a 6 m long horizontal packed bed of CuCl_2 particles. In the horizontal reactor, the piping between the humidifier and reactor is heated, to allow operation of the humidifier above ambient temperatures, without condensation forming in the piping. The vertical reactor allows for a low residence time with a vertical bed of 100 to 450 mL of CuCl_2 packings. With the vertical reactor set-up, the humidifier is operated at ambient temperatures because the tubing between the humidifier and reactor is not heated.

The molar flow rate of steam in the reaction stream, $\dot{N}_{H_2O,in}$, is calculated based on measurements of a humidity sensor positioned after the humidifier, nitrogen flow rate and temperature measurements. The temperature and pressure of the nitrogen flow are measured before entering the hydrator, so the molar flow rate of N_2 is known. The hydrator piping is half filled with distilled water, which partially saturates the nitrogen as it flows through the heated hydrator piping and over the distilled water. The hydrator tubing is immersed in a water bath with temperature controls up to 100°C to maintain a consistent hydrator temperature throughout the experiment.

During the reaction, the reactor effluent passes through a scrubber, which is filled with distilled water and sodium hydroxide (NaOH) solution. It reacts with the product fluid stream, to

produce sodium chloride (NaCl). The chloride concentration of the scrubber solution is measured from the samples, at periodic intervals, during the reactor operation. The samples are checked for copper and iron, with negligible quantities identified in the solution. The hydrogen chloride production is calculated from the measured chloride concentrations and corrected for chlorine production, which will also produce chlorides in the scrubber solution. The chlorine production is measured during the reactor preheating by diverting the reactor effluent to a chlorine meter, instead of the scrubber, to determine the fraction of chlorine (X_{Cl_2}) in the fluid stream. During reactor preheating and purging, the nitrogen flow is directed around the hydrator system to avoid introducing steam into the reactor.

4. Results and Discussion

Results of the predictive formulation for the maximum steam conversion are compared with experimental data in this section. In Fig. 3, the minimum steam requirement for the hydrolysis reactor at various reactor pressures (Eq. (14)) is presented. Reactor pressures (absolute) of 1 bar, 0.9 bar, 0.5 bar, and 0.1 bar are considered. As illustrated in Fig. 3, small reductions in the system pressure have only a limited effect on the minimum steam requirement. Furthermore, reducing the reactor pressure to levels significantly below atmospheric pressure can lead to major parasitic loss, thus reducing the efficiency of the Cu-Cl cycle.

The interpolated data in Fig. 4, from tabular data in Ref. [10], reports experimentally determined saturation pressures at 10°C intervals. The experimental data points are calculated by Eq. (1), with measured data of the temperature of the gaseous flow exiting the humidifier.

To compare the horizontal and vertical reactor experiments, the data is selected based on the time of minimum steam requirements. As presented in Table 1, the time during which the test

reaches a minimum steam requirement is selected and the cumulative data up to this point is maintained for further calculations of the effects of an inert gas on the conversion efficiency.

In Fig. 5, the experimental reaction quotient is presented and compared with the theoretical equilibrium constant based on the Gibbs reaction energy. The reaction quotient from the horizontal reactor's Run 1 is closer to the calculated equilibrium constant, compared to Run 2, suggesting that physical resistances develop quickly in this design and reduce the conversion extent. The figure illustrates that the theoretical steam conversion efficiency can be approached in a hydrolysis reactor. However, as physical resistances to the reaction develop, the reaction quotient is continuously reduced and so too the steam conversion efficiency.

The horizontal reactor design provided several orders of magnitude of more residence time and an excess H_2O - CuCl_2 ratio compared to the vertical design. However, as illustrated in Fig. 5, the vertical reactor achieves similar or better conversion efficiencies. The lower partial pressure of H_2O in the vertical design (caused by the ambient humidifier, compared to the heated humidifier) is likely a major contributor to the higher conversion efficiency.

In Fig. 6, the theoretical maximum conversion, as predicted by Eq. (13), is presented for various values of β and compared with experimental data. The results from the horizontal reactor, for Run 1 and 2, are presented with the filled circles and squares ($\beta = 5$ and $\beta = 10$), respectively. The low H_2O partial pressure from the ambient humidifier causes a high value of β , namely $\beta = 49 - 50$, for the vertical reactor (with an ambient humidifier). As illustrated in Fig. 6, Eq. (13) predicts how changes in the amount of inert gas will influence the conversion extent of H_2O . This provides important utility to better design future hydrolysis reactors and to successfully integrate the reactor with other unit operations of the Cu-Cl cycle.

In Fig. 7, the experimental results are standardized to $\beta = 0$ to compare various partial pressures of H₂O with a single parameter (Eq. (15)). The experimental data follows the trends of the correlation well, although consistently higher. This can be explained by the reaction quotients (see Fig. 5), which show how close the results came to chemical equilibrium in each test. As presented in Figure 8, a significant portion of the energy input to the hydrolysis reactor is used to convert water to steam, particularly when the steam requirement is high. Figure 8 highlights the importance of maintaining a low steam requirement in the hydrolysis reactor since higher steam requirements need a significantly higher energy input. This paper provides details on the theoretical minimum steam requirement and the effects of reactor pressure on steam conversion to enable designs that improve the energy efficiency by limiting the inputs of heat energy and pumping power.

The measurement accuracy, bias (B) and precision (P) errors, as well as the uncertainty (U) propagation in the calculations are determined for the experimental results [12], by combining the bias and precision errors with $U_i = \sqrt{B_i^2 + P_i^2}$. In the Appendix, the experimental uncertainties and errors associated with the measuring devices in the experiments are presented in Table A1. Equations (A1) - (A4) are used to calculate the propagation of bias error. Equilibrium conditions are maintained for the precision error calculations and double the standard deviation of a sample of 50 measurements [12]. Equations (A5) - (A8) are used to calculate the propagation of precision error, as presented in the Appendix. The relative bias error is taken to be the ratio of bias error to the corresponding reference value (Table A1). The calculations of steam requirements of the CuCl₂ hydrolysis reactors have a net overall uncertainty of $\pm 8\%$. The propagation of uncertainties in the calculations is presented in Table 2.

5. Conclusions

In this paper, the effects of H₂O vapor pressure on the theoretical minimum steam requirement were presented for a hydrolysis reactor in the Cu-Cl cycle of hydrogen production. Effectively minimizing the steam requirements of the hydrolysis reactor and maximizing the solid conversion rate are crucial for effective integration of the Cu-Cl cycle. The results showed that the steam to copper chloride ratio can be significantly reduced by introducing an inert carrier gas into the reactor, thus shifting the equilibrium of the reaction towards more hydrogen chloride production. A new predictive formulation was also developed to analyze the maximum conversion of reactants with various fractions of steam in an inert gas.

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Appendix - Experimental Errors and Measurement Uncertainties

The Appendix presents the analysis of the propagation of uncertainty in the experimental results. Equations (A1) - (A4) and (A5) - (A8) represent the propagation of bias and precision errors, respectively. The individual variables are defined in the nomenclature. Results of the analysis are presented in Table A1.

$$B_{\dot{N}_{Cl_2}}^2 = \dot{N}_{Cl_2}^2 \left(\frac{B_{\dot{N}_{N_2}}^2}{\dot{N}_{N_2}} + \frac{B_{\dot{M}_{Cl_2}}^2}{\dot{M}_{Cl_2}} \right) \quad (A1)$$

$$B_{\dot{N}_{H_2O,in}}^2 = \dot{N}_{H_2O,in}^2 \left(3 \left(\frac{B_{T_H}}{T_H} \right)^2 + \left(\frac{B_{RH}}{RH} \right)^2 + \left(\frac{B_{\dot{N}_{N_2}}}{\dot{N}_{N_2}} \right)^2 \right) \quad (A2)$$

$$B_{\dot{N}_{HCl,out}}^2 = \dot{N}_{HCl,out}^2 \left(\left(\frac{B_{\dot{M}_{Cl_2}}}{\dot{M}_{Cl_2}} \right)^2 + \left(\frac{B_{V_s}}{V_s} \right)^2 + \left(\frac{B_t}{t} \right)^2 + 2 \left(\frac{B_{\dot{N}_{Cl_2}}}{\dot{N}_{Cl_2}} \right)^2 \right) \quad (A3)$$

$$B_{\xi}^2 = \xi^2 \left(\left(\frac{B_{\dot{N}_{H_2O,in}}}{\dot{N}_{H_2O,in}} \right)^2 + \left(\frac{B_{\dot{N}_{HCl,out}}}{\dot{N}_{HCl,out}} \right)^2 \right) \quad (A4)$$

$$P_{\dot{N}_{Cl_2}}^2 = \dot{N}_{Cl_2}^2 \left(\left(\frac{P_{\dot{N}_{N_2}}}{\dot{N}_{N_2}} \right)^2 + \left(\frac{P_{\dot{M}_{Cl_2}}}{\dot{M}_{Cl_2}} \right)^2 \right) \quad (A5)$$

$$P_{\dot{N}_{H_2O,in}}^2 = \dot{N}_{H_2O,in}^2 \left(3 \left(\frac{P_{T_H}}{T_H} \right)^2 + \left(\frac{P_{RH}}{RH} \right)^2 + \left(\frac{P_{\dot{N}_{N_2}}}{\dot{N}_{N_2}} \right)^2 \right) \quad (A6)$$

$$P_{\dot{N}_{HCl,out}}^2 = \dot{N}_{HCl,out}^2 \left(\left(\frac{P_{\dot{M}_{Cl_2}}}{\dot{M}_{Cl_2}} \right)^2 + \left(\frac{P_{V_s}}{V_s} \right)^2 + \left(\frac{P_t}{t} \right)^2 + 2 \left(\frac{P_{\dot{N}_{Cl_2}}}{\dot{N}_{Cl_2}} \right)^2 \right) \quad (A7)$$

$$P_{\xi}^2 = \dot{N}_{\xi}^2 \left(\left(\frac{P_{\dot{N}_{H_2O,in}}}{\dot{N}_{H_2O,in}} \right)^2 + \left(\frac{P_{\dot{N}_{HCl,out}}}{\dot{N}_{HCl,out}} \right)^2 \right) \quad (A8)$$

Table 1: Experimental parameters with the vertical reactor connected to a humidifier

Test number	Test time (min)	Temperature (°C)	H ₂ O density (g/m ³)	β	Steam requirement	Reaction quotient
Horizontal reactor						
1 - (Run 1)	10	373	153	5.55	2.8	0.067
2 - (Run 1)	5	374	152	5.57	1.5	0.113
3 - (Run 1)	5	375	131	5.78	2.2	0.054
4 - (Run 2)	5	369	85	9.70	2.8	0.019
5 - (Run 2)	6	364	84	9.84	2.4	0.030
6 - (Run 2)	5	369	78	10.49	2.4	0.023
7 - (Run 2)	5	378	78	11.26	1.8	0.037
8 - (Run 2)	5	379	72	11.84	2.2	0.025
Vertical reactor						
1	30	400	17	48.53	0.51	0.27
2	25	365	16	49.03	4.8	0.0024
3	30	390	17	48.60	3.3	0.016
4	61	390	17	50.28	0.57	0.28

Table 2: Propagation of experimental uncertainty

Variable	Equation numbers	Bias error	Precision error	Uncertainty
\dot{N}_{Cl_2}	A1 and A5	0.025	0.003	0.029
$\dot{N}_{H_2O,in}$	A2 and A6	0.025	0.017	0.043
$\dot{N}_{HCl,out}$	A3 and A7	0.036	0.68	0.050
ξ	A4 and A8	0.057	0.96	0.083

Table A1: Bias and precision errors associated with the measurement devices

Variable	Measurement device	Accuracy	Device range	Reference value	Relative bias error	Relative precision error
\dot{N}_{N_2}	Omega FVL-2600A volumetric flow controller	± 0.15	0 to 50 LPM	6 LPM	0.025	5.7×10^{-9}
M_{Cl_2}	Optima continuous gas analyzer AQ2020	$\pm 0.025\%$	0 to 10%	10%	0.0025	0.0024
M_{Cl}	Geneq MKII chloride analyzer 926	± 3 mg/l	0 to 999 mg/l	999 mg/l	0.003	0.0081
RH	Hydroflex5-series humidity transmitter	± 0.08 RH	0 to 100 RH	98 RH	0.00082	0.0019
T_H	Hydroflex5-series temperature transmitter	$\pm 0.1^\circ\text{C}$	0 to 200°C	100°C	0.001	0.01
V	Eppendorf Research plus pipette	± 2 μl	100 to 1000 μl	500 μl	0.004	-
M_{Cu}	Hach pocket colorimeter II	± 0.04 mg/l	0.04 to 5 mg/l	5 mg/l	0.008	-
t	Fisher Scientific traceable stopwatch	-	300 s	5 s	-	0.011
V_s	Mettler Toledo ML3002E	± 0.01 g	100 to 3200 g	2500 g	4.0×10^{-6}	-
T	Omega Type-K Thermocouple	$\pm 2.2^\circ\text{C}$	-200 to 1250°C	400°C	0.0055	0.00063
P	Burkert Pressure Transmitter 8311	± 0.04 bar	0 to 4 bar	1.2 bar	0.033	0.024
pH	Omega PHH-103A pH meter	± 0.02 pH	0 to 14 pH	14 pH	0.0014	-

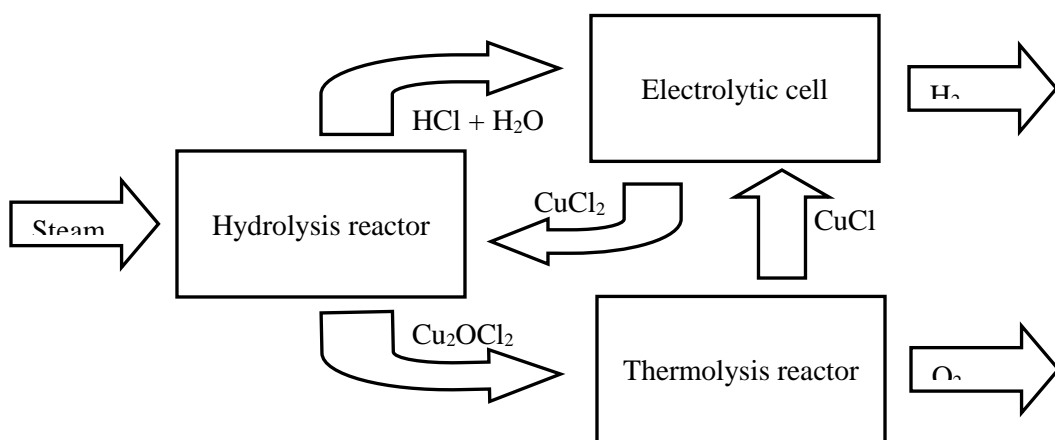
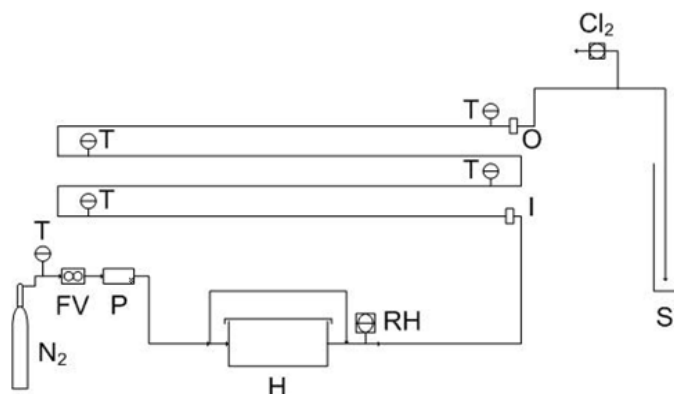
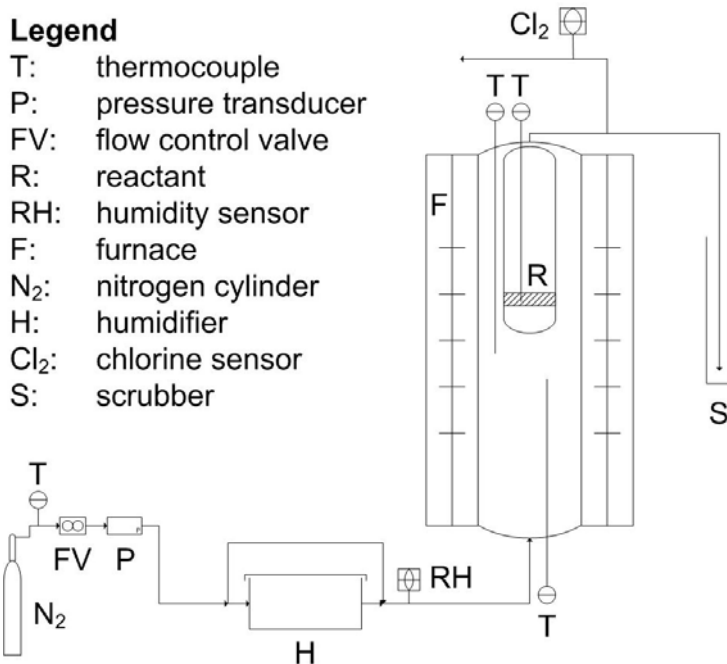


Figure 1: Schematic of the Cu-Cl cycle for thermochemical hydrogen production



(a)



(b)

Figure 2: Schematic of the hydrolysis reactor with humidified nitrogen: (a) horizontal and (b) vertical configurations

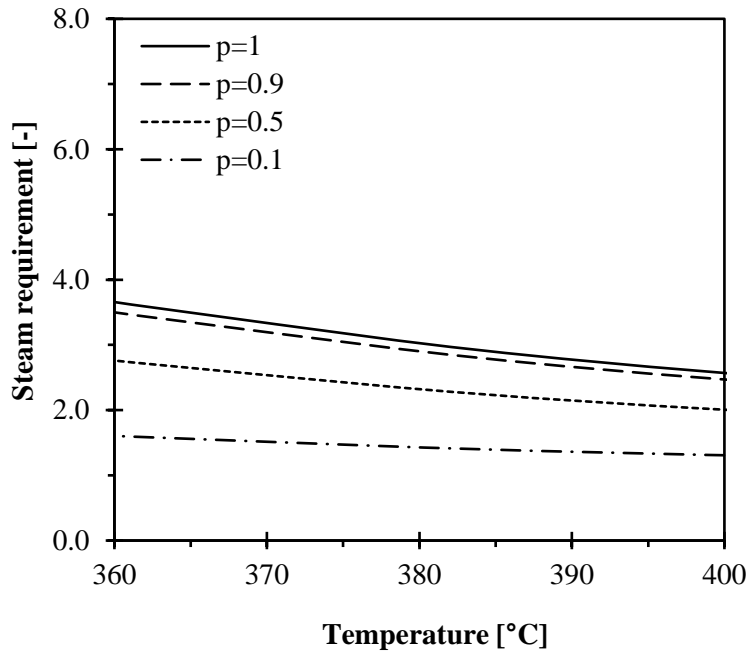


Figure 3: Pressure effect on theoretical minimum steam requirement in hydrolysis reactor

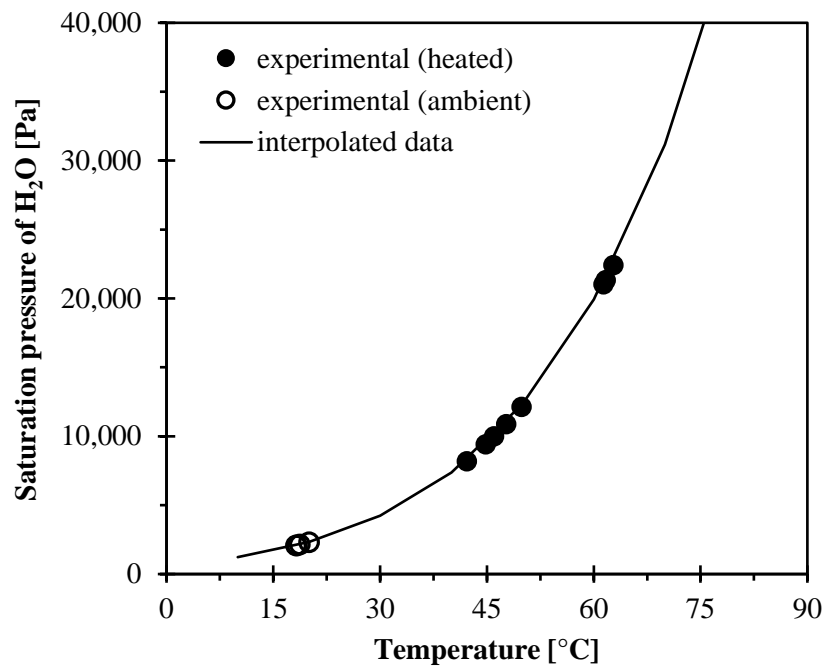


Figure 4: Saturation pressure of H₂O vapour in heated humidifier

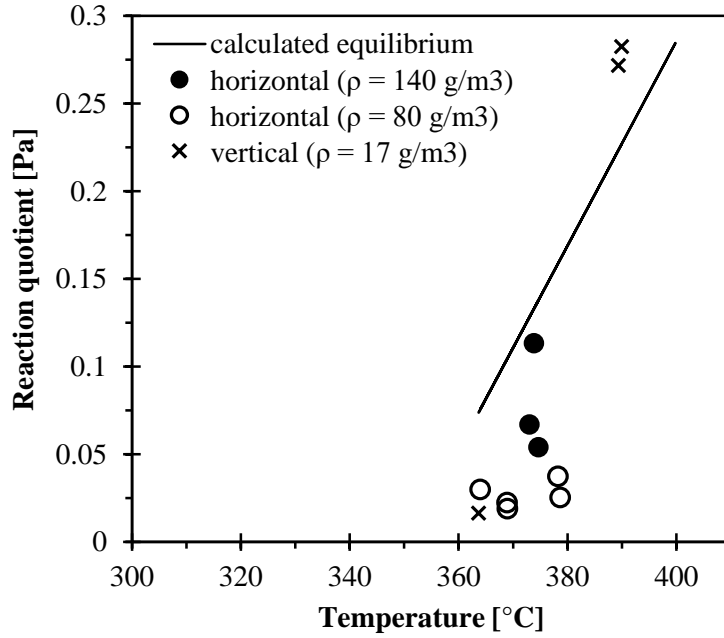


Figure 5: Experimental reaction quotient of hydrolysis reaction at various temperatures

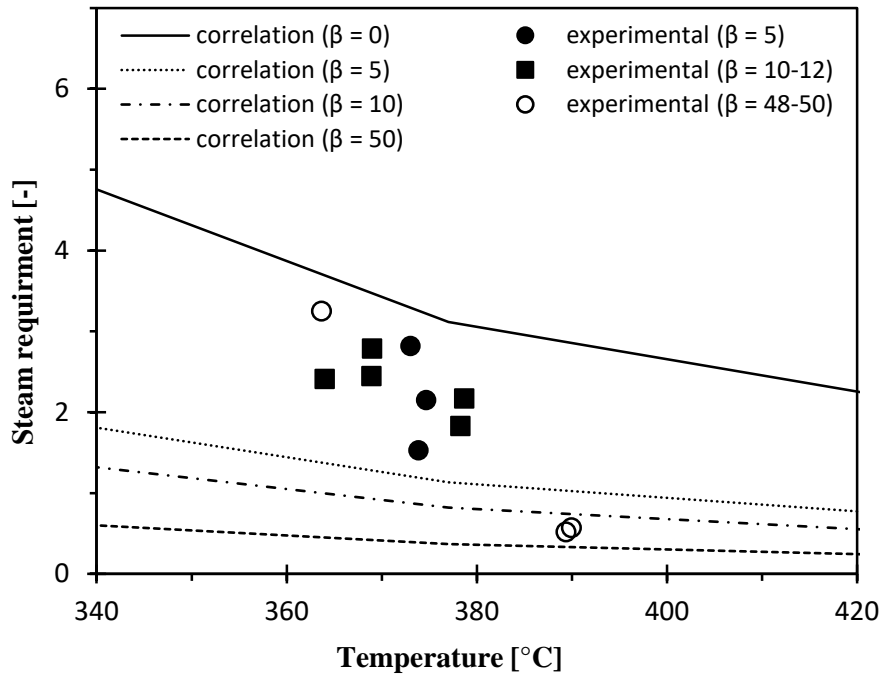


Figure 6: Steam requirement for a hydrolysis reactor at various steam partial pressures

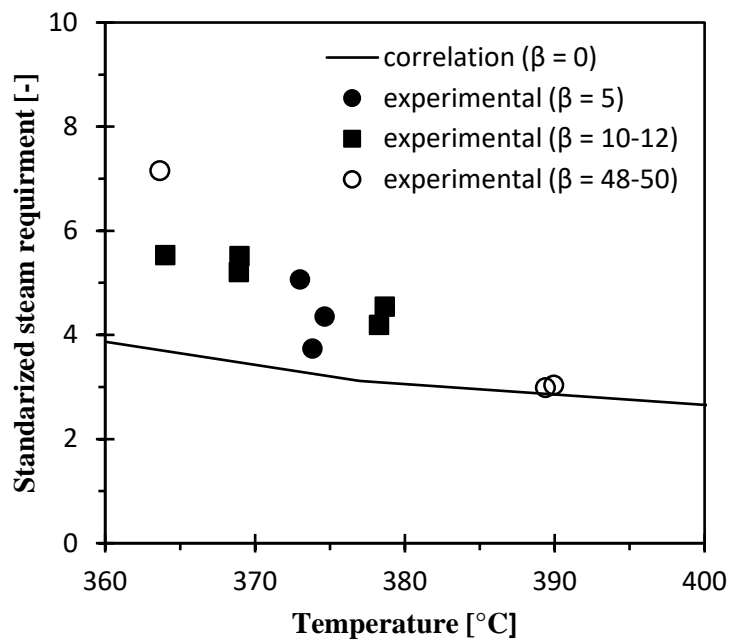


Figure 7: Steam requirements in a hydrolysis reactor standardized to $\beta = 0$

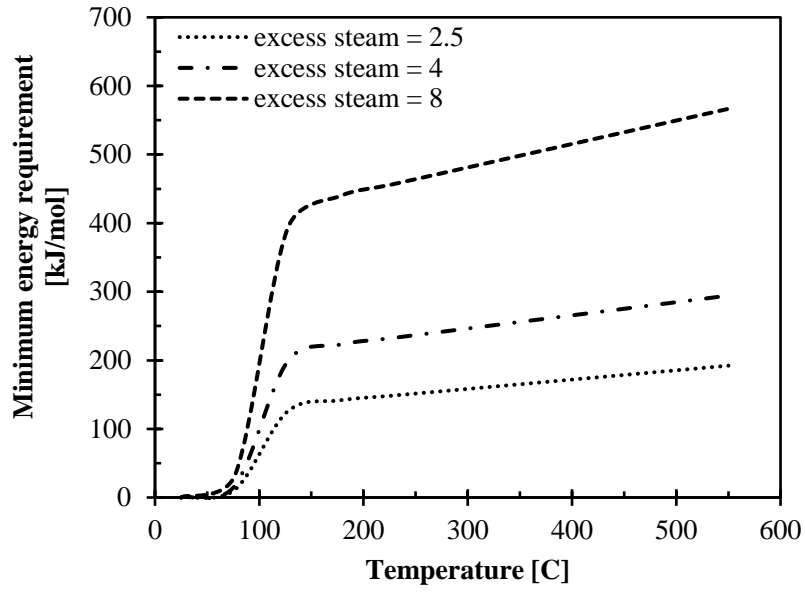


Figure 8: Minimum energy input of a CuCl₂ hydrolysis reactor