

Selective catalytic oxidation of ammonia in synthesis/producer gas streams from ammonia based hydrogen production

A performance evaluation under reducing conditions

by

Carl Graneskog

Department of Process and Life science

Lund University

&

Hulteberg Chemistry & Engineering AB

June 2026

Version 2

Supervisor: Christian Hulteberg

Supervisor Hulteberg Chemistry & Engineering AB: Josefina Ekelund

Examiner: Sara Blomberg

Postal address

P.O. Box 124
SE-221 00 Lund, Sweden

Web address

www.ple.lth.se

Visiting address

Naturvetarvägen 22, Lund

Telephone

+46 46-222 82 85

+46 46-222 00 00

Telefax

+46 46-222 45 26

Preface

This thesis marks the final project of my masters and five amazing years here in Lund. I would like to thank my supervisor Christian Hulteberg for getting me this interesting thesis so fast when I needed it and for being a great supervisor during the project. I would also like to thank Josefina Ekelund and Per Tunå at Hulteberg for being incredibly helpful with my project and for answering any my questions. A thank you to Alex, who have helped me with lots of little things during the experimental phase and showed me around the lab. A big thank you to all of the wonderful people at Hulteberg who have helped me during my time at the company and for welcoming me into the wonderful social culture.

I would also like to thank my partner, family, and friends for being supportive during my years of study, student engagements and this thesis. Without you, it would not have been possible to do everything I've done.

Thank you!

Abstract

Selective catalytic oxidation (SCO) of ammonia is a interesting field of research and is becoming increasingly more popular due to ammonias role as a hydrogen carrier for ammonia based hydrogen production. With the rise of ammonia based hydrogen, focus now lies on finding cheap and efficient ways to remove unreacted ammonia from the final gas stream. This to be done, without burning or destroying the hydrogen by converting the ammonia and some of the hydrogen into nitrogen and water using oxygen and a catalyst.

This thesis aims to investigate and evaluate the performance of five different catalysts, four of which are zeolite based, for SCO of ammonia and to see if they work under reducing conditions when they have been proven to work under oxidizing conditions. It also aims to find a zeolite based catalyst capable of SCO of ammonia in a reducing environment.

The results shows that the catalysts do not perform well in the hydrogen rich reducing environment and the selectivity for ammonia was at most 40% and at worst 0% with it being close to zero to be the more reasonable assumption. The reason for the low selectivity could be attributed to multiple factors but the biggest is most definitely the hydrogen. The hydrogen outcompeted the ammonia for the active sites on the catalysts due to its greater affinity towards metallic copper and silver compared to ammonia, resulting in almost no conversion of ammonia into nitrogen. The hydrogen most likely reacted with the majority of the oxygen before the ammonia could, leading to mostly water forming in the reactor.

The conclusion drawn from the tests was that the catalysts were not selective towards ammonia in the reducing environment. Using catalysts for SCO in oxidizing environments in reducing ones does not work. This was not surprising, however, since so little research on SCO in hydrogen rich environments could be found this was the next best option. Further research is needed on the topic if a zeolite based catalyst for SCO of ammonia that work under reducing conditions is to be found and synthesised.

Populärvetenskaplig Sammanfattning

Vätgas är en av de påtänkta lösningarna när vi rör oss mot en fossilfri värld. Problemet är att vätgas är otroligt knepigt att flytta i stora mängder billigt och effektivt. Istället brukar man ta hjälp av en så kallad vätgasbärare som då ska vara enklare och billigare att transportera utan att man förlorar speciellt mycket vätgas. En sådan bärare som börjar få mer uppmärksamhet är ammoniak. Att omvandla ammoniak till väte är relativt enkelt men kommer inte utan besvär. Reaktionen kan aldrig gå fullt åt vätgas och kväve hållet vilket innebär att det alltid kommer finnas lite ammoniak kvar och den vill man inte släppa ut.

Syftet med detta arbete har varit att ta fram fem selektiva katalysatorer som ska kunna förstöra ammoniaken utan att påverkar vätgasen i strömmen speciellt mycket och utvärdera hur de presterade med det ändamålet. Eftersom detta är ett relativt nytt forskningsområde baseras mycket på forskning gjort i andra sammanhang och ska testas att översättas till detta arbetes betingelser.

Resultatet visade tyvärr att ingen av de fem katalysatorer som tillverkades var selektiva nog för ammoniaken och lyckades inte förstöra något. Vätgasen som fanns i strömmen var mer reaktiv till metallerna i katalysatorerna än vad ammoniaken var och konkurrerade ut den om platser på katalysatorerna. Resultatet blev att ingen eller väldigt lite ammoniak förstördes och mest omvandlades vätet som reagerade till vatten.

Slutsatsen är att katalysatorerna som testades inte är selektiva för ammoniak när det finns vätgas i strömmen. Mer tid och forskning behövs för att hitta en katalysator som fungerar under dessa betingelser.

Contents

1	Introduction	1
1.1	Aim	1
2	Background	2
2.1	Selective catalytic oxidation of Ammonia in oxidizing environments .	2
2.2	Zeolites	2
2.3	SCO catalysts	3
3	Materials and Method	4
3.1	Catalyst synthesis	4
3.2	Setup	5
3.3	Start-up and Testing	7
4	Results	8
4.1	Catalyst synthesis	8
4.2	Catalytic testing	8
5	Discussion	11
5.1	Reasons for non-selectivity	11
6	Conclusion	12
7	References	13

List of abbreviations

Abbreviations	Full name
wt%	Weight Percent
GHSV	Gas Hour Space Velocity
SCO	Selective catalytic Oxidation
Cu/Y	Copper/Zeolite Y
Cu/Mor	Copper/Mordenite
Ag/Y	Silver/Zeolite Y
Ag/MOR	Silver/Mordenite
Ag/Al₂O₃	Silver/Alumina
MFC	Mass Flow Controller
OD	Outer diameter
ID	Inner diameter
SS	Steady state

1 Introduction

Ammonia (NH_3) is one of the largest and widely used industrial chemicals in the world, and the industry continues to innovate and find new uses for it in all types of applications. About 2% of the world's energy is used in ammonia synthesis [7]. Ammonia has many applications and is used in everything from agriculture and fertilizers to reduce NO_x emissions in industry through selective catalytic reduction. The use of ammonia as a hydrogen carrier is becoming an increasingly common way to transport large amounts of hydrogen because gaseous hydrogen is expensive and difficult to transport efficiently, and hydrogen liquification is energy intense. Ammonia has a hydrogen density of about 17.7 wt% which is high relative to many other carriers. Hydrogen has many uses in chemical reactions and has also become very popular for use as an energy vector in energy production. Hydrogen-based fuel cells emit no direct carbon dioxide or other greenhouse gases, making them an excellent way of producing green energy in a world that wants to de-fossilize.

Cracking ammonia into hydrogen and nitrogen is becoming an increasingly viable option and the technology is continually improved and innovated upon [10]. The reaction of ammonia cracking into hydrogen and nitrogen is an equilibrium reaction which means that some ammonia will always remain in the outgoing gas. Ammonia is a toxic, corrosive and dangerous compound, and emissions should be limited in any way possible. There are different methods for removing ammonia from gas streams, all with their own advantages and disadvantages, but the most efficient ones, both in energy requirement and yield wise, are catalyst based [4, 6]. With cracking ammonia into hydrogen increasing in popularity, a good solution for ammonia oxidation in hydrogen rich environments, without burning the hydrogen, is sought after, but is a very new topic and as of writing this, the author could not find any publications on SCO of ammonia in a reducing environment. This thesis will dive into different catalytic solutions for selective ammonia oxidation, provide experimental results from five different catalysts, and discuss their performance in hydrogen free and hydrogen dense gas streams.

1.1 Aim

The aim of this thesis is to synthesise and evaluate the performance of five different catalysts for low temperature SCO (Selective Catalytic Oxidation) of ammonia in hydrogen synthesis/producer gas streams. The results will be compared with literature findings of SCO of ammonia in hydrogen free environments and recommended future endeavours will be discussed. The following research questions will be examined:

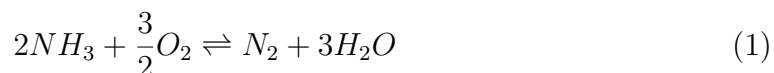
- Is there a good selective zeolite based catalyst for SCO of ammonia in hydrogen rich environments?
- Do SCO catalysts designed for oxidizing environments work under reducing conditions?
- Do they work in the temperatures range of 200-300°C?

2 Background

Oxidation of ammonia is a well researched area since it is one of the worlds largest industrial chemicals. Much of today’s research focus on achieving a high selectivity for ammonia at as low temperatures as possible. Almost all research focus on ammonia oxidation in atmospheric gas composition, meaning the gas mostly contain nitrogen and some oxygen and then the trace amounts of ammonia. With increasing interest in hydrogen production from ammonia, more research on ammonia oxidation in hydrogen rich environments is starting to appear but since it is still relatively new, not much have been published yet. Traditionally, if a catalyst isn’t used for ammonia removal or oxidation, membranes have be used [2].

2.1 Selective catalytic oxidation of Ammonia in oxidizing environments

One method of removing ammonia from gas streams is to oxidize it into water and nitrogen gas using heat and a catalyst. This method is called selective catalytic oxidation (SCO) of ammonia, selective since you only want to oxidize the ammonia, not the hydrogen. The reaction can be seen in equation 1 below.



Different types of catalysts can be used for oxidation, Gang found promising results when testing copper/zeolite (Cu/Y) based catalysts as well as silver/aluminium oxide (Ag/Al₂O₃). Specifically, copper and zeolite Y with a copper content of 3.7 and 8.4 wt%, respectively were tested. For the Al₂O₃ catalyst, the silver loading was 10 wt% [4]. Wang et al. tested multiple copper-based zeolites, specifically ZSM-5, beta, Y, mordenite and MCM-49, all with a 3 wt% of copper [14]. It is very important that the catalyst has a high selectivity for only ammonia to minimize the creation of N₂O and NO_x gases. N₂O is a very potent greenhouse gas and NO_x contributes to acidification of the environment when released into the atmosphere. They can also hinder the catalyst and lower its efficiency. The catalyst metal used determines the selectivity, efficiency and by-product formation of the operation and the correct choice is very important for a successful catalyst [4, 8, 12].

2.2 Zeolites

Zeolites are a class of crystalline aluminosilicate nanoporous materials with large specific surface areas, that are widely used in various industrial applications, showing excellent catalytic activities and product selectivity. In recent years, researchers have become increasingly interested in zeolite-supported metal catalysts because of their superior activity and stability in diverse heterogeneous catalytic processes. Compared to other metal-based catalysts, zeolite-supported catalysts possess many advantages such as high thermal stability during catalytic reactions, the ability to withstand harsh conditions, and shape selectivity in catalysis. Depending on size and properties of the metal and zeolite, the location of the metal can be in different positions on the zeolite. For example, on the surface or encapsulated inside [6, 11].

Different techniques can be utilized to create a zeolite-supported metal catalyst but the most common are ion exchange or incipient wetness impregnation which are then followed by calcination of the complex [9].

2.3 SCO catalysts

SCO of ammonia can be achieved with a wide variety of catalyst but depending on the desired parameters, the chosen catalyst will differ. Gang screened multiple different catalyst materials to find a suitable catalyst for low temperature SCO of ammonia in an oxidizing environment, meaning no hydrogen was present. CuO, V₂O₅ and MoO₃ are all metal based catalyst and performed well at high temperatures. However at 300°C and below the performance dropped below what would be useful in industrial applications. The catalysts that did show promise were Cu/Y and Ag/Al₂O₃. The 3.7 wt% copper/zeolite catalyst performed decently at 300°C, achieving good N₂ selectivity of about 98% but only 54% NH₃ conversion. The experiments with the Al₂O₃ catalyst showed great performance, achieving a good N₂ selectivity of about 82% and a 100% conversion of NH₃ at 160°C [4]. The reaction conditions of both the Cu/Y and Ag/Al₂O₃ catalysts can be found in table 1 and 2.

Table 1: Reaction conditions for 3.7wt% Cu/Y at 300°C

Gas properties	Reactor	Catalyst
NH ₃ = 1.14 vol%	Internal reactor d = 4mm	Amount = 0.2 g
O ₂ = 8.21 %	Flow rate = 74.7 Nml/min	Particle size = 250-425 μ m

Table 2: Reaction conditions for 10wt% Ag/Al₂O₃ at 160°C

Gas properties	Reactor	Catalyst
NH ₃ = 1000 ppm	Internal reactor d = 4mm	Amount = 0.1 g
O ₂ = 10 %	Flow rate = 50 Nml/min	Particle size = 250-425 μ m

Noble metals, such as Au, Pd and Pt, are often used as the active phase in catalyst but in the case of ammonia oxidation they show low N₂ selectivity resulting in NO_x formation. Researchers have found that Ag based catalyst show a very high selectivity for N₂ and at low temperatures in the 100-200°C range [13]. Copper/Zeolite catalysts in general show great promise in the SCO of ammonia. Wang et al. screened multiple different 3 wt% Cu/Zeolite catalysts and analysed their NH₃ conversion and N₂ yield. At 300°C Cu/ZSM-5, Cu/Beta and Cu/MCM-49 all showed ammonia conversion of around 98% while Cu/Y and Cu/Mordenite achieved around 95%. The nitrogen gas yield was greater than 90% for all the catalysts with Cu/ZSM-5 reaching the highest of about 95% [14]. The reaction conditions can be found in table 3.

All of the catalysts mentioned above are developed and evaluated in oxidizing environments since this has been the areas where SCO of ammonia has been necessary until now. In real life applications of SCO of ammonia, like diesel engines, burning the H₂ has been considered fine since not much has been present and it has

Table 3: Reaction conditions for the Cu/Zeolite catalysts 300°C

Gas properties	Reactor	Catalyst
NH ₃ = 1000 ppm	Internal reactor d = 3cm	Amount = 0.2 g
O ₂ = 10 %	Flow rate = 350 Nml/min	Particle size = 250-425 μ m

not been the main product. The purpose has been on reducing ammonia to water and nitrogen without creating NO_x and N₂O [1].

In this report, the following five catalysts seen in table 4 were tested. These catalysts were of interest as some of them preformed well in SCO of ammonia in the oxidizing environment and some are new for this thesis.

Table 4: The five catalyst that were tested

Cu/Y	Cu/Mor	Ag/Y	Ag/Mor	Ag/Al ₂ O ₃
------	--------	------	--------	-----------------------------------

3 Materials and Method

Multiple different things needed to be completed for the tests to be able to be conducted, such as synthesising the catalysts and build the reactor. All the catalyst material, testing equipment, and reactor setup was provided by Hulteberg and conducted in their lab. The method presented below for catalytic synthesis and testing is common in the industry and at Hulteberg.

3.1 Catalyst synthesis

Zeolite Y, mordenite, and alumina were crushed and then sieved with 10-20 mesh sieves for a particle size of 1-2 mm. Before adding the metal salts of copper and silver to the supports, water absorption tests were done to calculate the pore volume which in turn was used to determine the amount of metal solution needed for the desired wt% of active phase. The tests were conducted by weighing the support and then adding small amounts of water until it was saturated and then weighing the support again. Four tests per support were conducted, and an average was used for further calculations. Equations 2 - 5 were used to calculate the water absorptivity, salt and metal weight and the required amount of water for the salts to be dissolved in.

$$ABS_{water} = \frac{g_{sup,wet} - g_{sup,dry}}{g_{sup,dry}} \quad (2)$$

$$g_{metal} = wt\% \cdot g_{tot} \quad (3)$$

$$g_{salt} = g_{metal} \cdot \frac{M_{salt}}{M_{metal}} \quad (4)$$

$$g_{water} = g_{support} \cdot ABS_{water} \quad (5)$$

Copper nitrate ($\text{Cu(II)(NO}_3)_2 \cdot 3 \text{H}_2\text{O}$) and silver nitrate (AgNO_3) were used as precursors for the metal. The five catalysts were prepared using the incipient wetness impregnation method, a common standard for catalyst synthesis. The impregnation solutions were prepared with the calculated amounts of salts and water required for 3wt% metal loading and then added to the support. The catalysts were then calcined for 2 h at 120 °C and then 4 h at 400°C [5]. Before each catalyst run, the catalyst was reduced over night at 220°C with a flow of 5% H_2 and 95% N_2 to remove oxygen and convert the metal oxides into pure metal and to not burn the catalyst when a large flow of H_2 is added during testing.

3.2 Setup

The catalytic measurements were carried out in a 1" (25.4 mm) OD, 10 cm long steel pipe reactor. An internal diameter of about 2 cm was used, as a width of about 10 particle diameters is desired for good reaction conditions. A preheater filled with quartz wool for better heat distribution was installed before the reactor. Two thermocouples, one before the reactor and one after, were installed to monitor the temperature inside the reactor as well as add the possibility to log the temperature during testing. A bypass valve was installed before the preheater to divert the gas if needed. The entire reactor was then mounted inside a two chamber oven. The reactor was loaded with a mix of 2 ml of catalyst and 8 ml of inert alumina for each test. The gas mix consisted mainly of hydrogen and nitrogen, with small amounts of ammonia and synthetic air. The ratio between ammonia and oxygen ($\text{NH}_3:\text{O}_2$) was chosen to be 1:3 to ensure good oxidation of ammonia. Higher ratios yield better oxidation but also lead to more hydrogen turning into water, which is not favourable. The total flow rate of the gas mixture was 20 nL/h, which corresponds to a GHSV of about 10000 h^{-1} . Each catalyst was evaluated at temperatures of 200, 250, and 300°C. To analyse the outgoing ammonia content in the gas stream, a simple Dräger tube and pump setup was used. Tubes with detection range of 5-100 ppm and 5-600 ppm ammonia were used [3]. The complete list of reaction parameters can be found in table 5 below as well as a schematic view of the setup in figure 1 and a picture of the reactor in figure 2.

Table 5: Reaction parameters for catalytic testing

Gas mixture	Reactor	Catalyst
$\text{H}_2 = 75\%$	OD = 25.4 mm (1")	Active = 2 ml
$\text{N}_2 = 23.8\%$	ID = 21 mm	Inert = 8 ml
$\text{NH}_3 = 0.1\%$	Flow rate = 20 nL/h	Particle size = 1-2 mm (10-20 mesh)
Synthetic Air = 1.1%	GHSV = 10000 h^{-1}	

The Dräger tube was inserted into a silicone tube which was connected to the main system and only separated by a valve. When testing was to be done, the tube was inserted into the silicone and the valve was turned to allow gas to be pumped

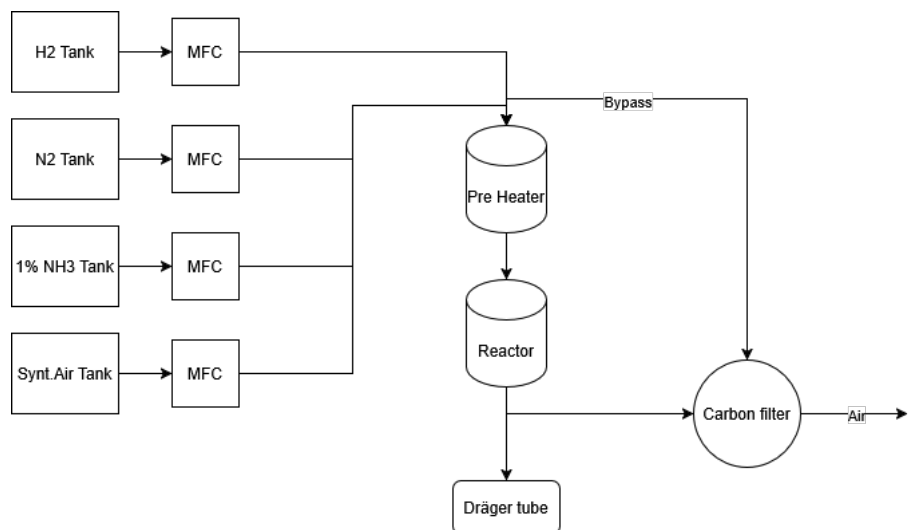


Figure 1: Schematic view of the reactor setup

into the detection tube by the Dräger system. A picture of the system can be seen in figure 3.

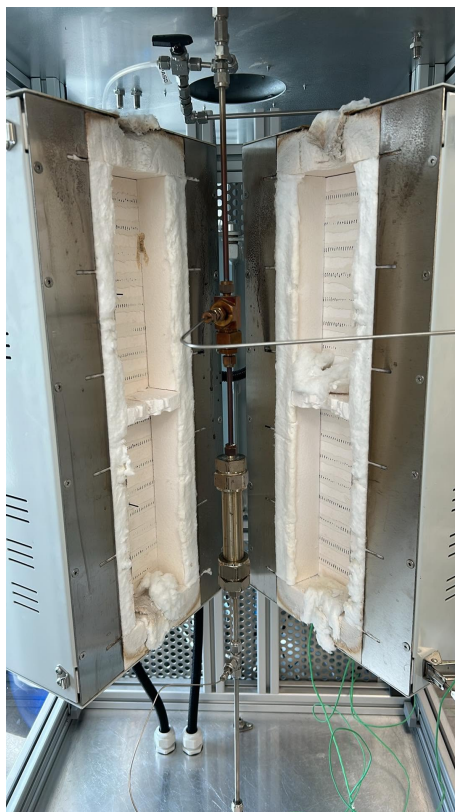


Figure 2: Picture of the reactor and oven

3.3 Start-up and Testing

Before the tests the MFCs were calibrated and adjusted to the right flow rate using a flow meter. The entire system was then filled with N_2 to check for leaks. Thereafter, the reactor was loaded with the catalyst/inert mixture and brought up to temperature with a steady flow of N_2 . After the desired temperature was reached, the calculated gas mixture was turned on and pumped through until steady state was reached. After steady state was reached, gas was pumped into the Dräger tube where the results were analysed and noted. The gas mix was then turned off and N_2 was once again pumped through the system until the temperature reached the new target and steady state was achieved, then next test was began. This was done for all the catalysts. Between catalysts, N_2 was also pumped through while the system cooled to room temperature so that the catalyst could be exchanged for a new one.



Figure 3: Silicone tube setup for the Dräger tubes to be inserted into

4 Results

The results from the catalytic testing will be presented in this section and discussed in the next section. The data used to calculate everything for the impregnation of the catalysts will also be presented here. The performance of all five catalysts will be presented together since they performed similarly. Since the thesis main focus is on the catalytic performance of the catalysts in terms of ammonia selectivity, the result section will be rather short.

4.1 Catalyst synthesis

For the three different supports, four water tests were conducted and an average was calculated and later used. A theoretical table of the catalysts properties was calculated and later used for the real impregnation as a guide. Table 6 below shows the theoretical, calculated values and table 7 shows the actual results. The numbers were very close.

4.2 Catalytic testing

Before each sample of gas was taken, the reactor ran for 30 minutes after the targeted temperature was reached to ensure steady state and that the system was saturated with gas. As mentioned before, Dräger tubes with the detection range of 5-600 ppm ammonia were used. 1-3 tubes were used for each test to ensure the measured value

Table 6: Tabel of calculated values for catalyst impregnations based on the support water tests

Catalyst	wt%	Tot weight [g]	Support [g]	Metal [g]	Salt [g]	Water [g]
Cu/Y	3.00	5.00	4.85	0.15	0.57	3.69
Cu/Mor	3.00	5.00	4.85	0.15	0.57	2.71
Ag/Y	3.00	5.00	4.85	0.15	0.236	3.69
Ag/Mor	3.00	5.00	4.85	0.15	0.236	2.71
Ag/Al ₂ O ₃	3.00	5.00	4.85	0.15	0.236	4.69

Table 7: Tabel of real measured values for the catalyst impregnations

Catalyst	wt%	Tot weight [g]	Support [g]	Metal [g]	Salt [g]	Water [g]
Cu/Y	3.02	5.01	4.86	0.15	0.57	3.7
Cu/Mor	3.01	5.00	4.85	0.15	0.57	2.7
Ag/Y	3.04	5.01	4.86	0.15	0.24	3.7
Ag/Mor	3.05	5.00	4.85	0.15	0.24	2.7
Ag/Al ₂ O ₃	3.04	5.01	4.86	0.15	0.24	4.7

was accurate, but for most of the tests, one tube was enough. None of the five catalysts performed well enough to go below the 600 ppm limit of the Dräger tube. Since it is impossible to know how far above 600 ppm the ammonia was, the result was written as 600+. Only one compression of the Dräger pump was necessary to completely saturate the tube. With a ppm of 600 or above it means that the conversion of ammonia was at best 40% and at worst 0%. The complete results can be seen in table 8 below.

Table 8: Experimental results from catalyst testing

Catalyst	Temperature [°C]	Outgoing Ammonia [ppm]
Cu/Y	200	600+
	250	600+
	300	600+
Cu/Mor	200	600+
	250	600+
	300	600+
Ag/Y	200	600+
	250	600+
	300	600+
Ag/Mor	200	600+
	250	600+
	300	600+
Ag/Al ₂ O ₃	200	600+
	250	600+
	300	600+



Figure 4: Picture of a fully saturated Dräger tube after one of the tests (left) and a new unused one (right)

5 Discussion

The results from the tests were disappointing, but not surprising. From the results, it can clearly be stated that none of the five catalysts were selective enough for ammonia in the reducing environment. As the Dräger tubes maxed out at 600 ppm NH_3 it is possible that some of the catalysts performed better than others but without better analysing equipment it was impossible to know and even then the results would not have been satisfactory. The conversion was between 40% at best and 0% at worst, which is significantly worse than what other papers reported when running tests without hydrogen. As mentioned previously, oxidization of ammonia in a hydrogen rich environment is a very new area of research and not much has been published on the topic as of yet. Therefore, the catalysts in this project were based on articles that successfully managed to achieve SCO of ammonia in an oxidizing environment. This came with the risk of the catalysts not working as intended, but since no other papers were found that suggested anything else, it was the best thing to go of. There are multiple possible reasons why the catalysts did not perform well but the major ones are almost certainly because of the hydrogen.

5.1 Reasons for non-selectivity

For the catalyst to be selective towards ammonia, multiple things need to work in its favour. Both hydrogen and ammonia are competing for the oxygen in the gas mixture, as well as the active sites on the catalyst. It is very likely that the hydrogen easily outcompeted the ammonia for the active sites due to its much stronger adsorption power towards elemental copper and silver compared to ammonia, and then reacted with almost all the oxygen, converting it into water, leaving very little for the ammonia. Adding more oxygen could increase the ammonia consumption but would mostly just burn more hydrogen, which is wasteful and not viable since that is the desired gas. Advanced analysis of the catalysts could tell us more about active sites, selectivity and structure of the catalyst, but would take time, money, and effort not really worth it for a thesis like this.

The temperature of which these tests were done were also partly based on prior research of SCO in oxidizing environments. But when switching to an hydrogen rich, reducing environment, the selectivity window can change. It is possible that these catalysts were tested at too high or too low of a temperature with these new conditions. It is, however, not very likely that this would have increased the selectivity but is a possibility that it would have had some impact. It is also possible that this new reducing environment led to the formation of more by-products such as NO_x and N_2O since the catalyst wasn't selective towards the ammonia any more, but since no gas analysis except for ammonia was conducted, it can be concluded for sure.

6 Conclusion

The catalysts were not selective towards ammonia in a hydrogen rich environment. The final selectivity for ammonia landed between 0 and 40% with it being most likely closer to 0 than 40. The hydrogen outcompeted the ammonia for active sites on the catalysts and for the oxygen in the gas. Hydrogens adsorption power towards metallic copper and silver was much greater than that of the ammonia, resulting in an almost non-exciting selectivity under the conditions. Basing the tests on catalysts made for SCO of ammonia in oxidizing environments meant that there was a high chance for the catalysts to not work or not work as intended, which was confirmed during the testing. It can be concluded that the catalysts made for oxidizing environments cannot be translated to reducing environments as they do not work. The experiments did not find a good zeolite based catalyst for SCO of ammonia and more research into the subject needs to be conducted in order to determine if it is possible to synthesize such catalysts. Selective catalytic oxidization of ammonia in a reducing environment is an area of research that needs to be expanded if the use of ammonia as hydrogen carrier in hydrogen production continues to rise in popularity.

7 References

References

- [1] Maria U. Alzueta et al. “Flow Reactor Oxidation of Ammonia–Hydrogen Fuel Mixtures”. In: *Energy & Fuels* 38.4 (Feb. 2024), pp. 3369–3381. ISSN: 0887-0624. DOI: 10.1021/acs.energyfuels.3c03929. URL: <https://doi.org/10.1021/acs.energyfuels.3c03929> (visited on 06/03/2026).
- [2] George. C. Bandlamudi et al. “Fine Gas Purification Approaches for High Purity Hydrogen Production from Ammonia”. en. In: *Energy Technology* 13.2 (2025). eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/ente.202301023>, p. 2301023. ISSN: 2194-4296. DOI: 10.1002/ente.202301023. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ente.202301023> (visited on 06/03/2026).
- [3] Dräger Nederland BV. *Dräger tube: Ammonia 5/a, CH20501*. en-US. URL: <http://www.draeger-mo.com/en/artnr/ch20501/draeger-tube-ammonia-5-a> (visited on 05/05/2026).
- [4] L. (Lu) Gang. *Catalytic oxidation of ammonia to nitrogen*. en. 2002. DOI: 10.6100/IR551135. URL: [https://research.tue.nl/en/publications/catalytic-oxidation-of-ammonia-to-nitrogen\(9ed55678-9b96-4d3c-b9c9-e60ee7c52b30\).html](https://research.tue.nl/en/publications/catalytic-oxidation-of-ammonia-to-nitrogen(9ed55678-9b96-4d3c-b9c9-e60ee7c52b30).html) (visited on 02/18/2026).
- [5] S Haukka, E-L Lakomaa, and T Suntola. “Adsorption controlled preparation of heterogeneous catalysts”. en. In: *Studies in Surface Science and Catalysis*. Vol. 120. Elsevier, 1999, pp. 715–750. ISBN: 978-0-444-50165-3. DOI: 10.1016/S0167-2991(99)80570-9. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0167299199805709> (visited on 04/13/2026).
- [6] Magdalena Jabłońska. “Progress on Selective Catalytic Ammonia Oxidation (NH₃-SCO) over CuContaining Zeolite-Based Catalysts”. In: *ChemCatChem* 12.18 (Sept. 2020), pp. 4490–4500. ISSN: 1867-3880. DOI: 10.1002/cctc.202000649. URL: <https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/cctc.202000649> (visited on 02/18/2026).
- [7] Patricia Mayer et al. “Blue and green ammonia production: A techno-economic and life cycle assessment perspective”. In: *iScience* 26.8 (Aug. 2023), p. 107389. ISSN: 2589-0042. DOI: 10.1016/j.isci.2023.107389. URL: <https://www.sciencedirect.com/science/article/pii/S2589004223014669> (visited on 05/26/2026).
- [8] Mingchu Ran et al. “Unraveling the Mechanistic Origin of High N₂ Selectivity in Ammonia Selective Catalytic Oxidation on CuO-Based Catalyst”. In: *Environmental Science & Technology* 58.27 (July 2024), pp. 12249–12259. ISSN: 0013-936X. DOI: 10.1021/acs.est.4c02656. URL: <https://doi.org/10.1021/acs.est.4c02656> (visited on 02/23/2026).

- [9] W.M.H. Sachtler. “Zeolite-supported transition metal catalysts by design”. en. In: *Catalysis Today* 15.3-4 (Oct. 1992), pp. 419–429. ISSN: 09205861. DOI: 10.1016/0920-5861(92)85007-9. URL: <https://linkinghub.elsevier.com/retrieve/pii/0920586192850079> (visited on 03/26/2026).
- [10] Elvira Spatolisano et al. “Ammonia as a Carbon-Free Energy Carrier: NH₃ Cracking to H₂”. In: *Industrial & Engineering Chemistry Research* 62.28 (July 2023), pp. 10813–10827. ISSN: 0888-5885. DOI: 10.1021/acs.iecr.3c01419. URL: <https://doi.org/10.1021/acs.iecr.3c01419> (visited on 03/16/2026).
- [11] Qiming Sun, Ning Wang, and Jihong Yu. “Advances in Catalytic Applications of Zeolite-Supported Metal Catalysts”. en. In: *Advanced Materials* 33.51 (2021). eprint: <https://advanced.onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202104442>, p. 2104442. ISSN: 1521-4095. DOI: 10.1002/adma.202104442. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.202104442> (visited on 03/26/2026).
- [12] Minoru Suzuki et al. “Preparation of small nickel-oxide cluster by hydrolysis of NiY and activity for CO oxidation”. In: *Zeolites* 8.4 (July 1988), pp. 284–291. ISSN: 0144-2449. DOI: 10.1016/S0144-2449(88)80124-6. URL: <https://www.sciencedirect.com/science/article/pii/S0144244988801246> (visited on 03/05/2026).
- [13] Haifeng Wang et al. “The Development of the Regenerable Catalytic System in Selective Catalytic Oxidation of Ammonia with High N₂ Selectivity”. In: *ACS Applied Materials & Interfaces* 16.15 (Apr. 2024), pp. 18693–18702. ISSN: 1944-8244. DOI: 10.1021/acsami.3c17138. URL: <https://doi.org/10.1021/acsami.3c17138> (visited on 02/24/2026).
- [14] Hao Wang et al. “Selective catalytic oxidation of ammonia over nano Cu/zeolites with different topologies”. en. In: *Environmental Science: Nano* 7.5 (2020), pp. 1399–1414. ISSN: 2051-8153, 2051-8161. DOI: 10.1039/D0EN00007H. URL: <https://xlink.rsc.org/?DOI=D0EN00007H> (visited on 03/11/2026).