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Simulation-Based Analysis of Key Operating Parameters in an Ammonia Synthesis Loop

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ABSTRACT

A steady-state simulation model of the ammonia synthesis loop at the Marsa El-Brega Ammonia Plant was developed using Aspen HYSYS V14 to investigate the effect of selected operating parameters on loop performance. The validated model was based on actual plant operating conditions and was subsequently used to evaluate two practical operating cases: loop pressure and cooling conditions before the high-pressure ammonia separator. The pressure study showed that increasing the loop pressure improved ammonia production, with the best simulated condition reaching 34.490 MT/h, corresponding to an increase of 1.230 MT/h (3.70%) relative to the actual plant-load base case. The cooling study demonstrated that improving cooling before V-501 enhanced ammonia condensation and recovery. Under the combined optimum cooling condition, ammonia production increased to 34.100 MT/h, representing an improvement of 0.840 MT/h (2.53%) over the base case. The results demonstrate that both reaction-side pressure and downstream cooling performance have significant effects on synthesis-loop operation and provide practical directions for improving ammonia production under the current plant operating conditions.

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Keywords: *Ammonia synthesis; Aspen HYSYS; Haber–Bosch process; Loop pressure; Ammonia condensation*

1. Introduction

Ammonia production is one of the most important industrial applications of catalytic synthesis, with the Haber–Bosch process remaining the principal technology for large-scale ammonia production. The synthesis section operates under high pressure and temperature and involves a continuous recycle of unreacted hydrogen and nitrogen together with ammonia separation, purge, and heat-recovery systems. Because of the strong interaction between reaction, heat transfer, gas separation, and recycle, the overall performance of the synthesis loop depends not only on the ammonia converter itself but also on the operating conditions of the surrounding process units [1, 9].

In an industrial ammonia synthesis loop, the operating conditions must be maintained within an appropriate range to achieve high ammonia production while avoiding excessive energy consumption and unfavorable recycle conditions. Pressure is particularly important because ammonia synthesis is associated with a reduction in the total number of gas moles. Consequently, increasing the synthesis pressure generally promotes ammonia formation and can improve converter performance. However, higher pressure also increases the requirements placed on the recycle and compression system and may therefore involve an operational and energy penalty [1, 7]. The practical effect of pressure must therefore be evaluated using the complete synthesis-loop configuration rather than considering the converter independently.

Cooling and ammonia condensation represent another important aspect of synthesis-loop performance. After the synthesis reaction, the process gas is cooled to promote ammonia condensation and separation from the unreacted synthesis gas. The separated gas is subsequently returned to the converter through the recycle system. Inadequate cooling can reduce ammonia condensation, increase the ammonia concentration in the recycle gas, and consequently influence the composition and operating conditions of the converter inlet. The performance of the cooling and separation section is therefore directly connected with both ammonia recovery and the subsequent reaction cycle [1, 9].

Process simulation provides an effective approach for investigating these interactions under industrial operating conditions. Steady-state simulation models can represent the major process units and recycle streams and can be used to evaluate the response of the synthesis loop to changes in selected operating parameters. When validated against actual plant measurements, such models can provide a practical basis for analyzing operating limitations and identifying

potential improvement opportunities without requiring extensive plant experimentation [4, 8, 11].

Several studies have investigated ammonia synthesis through thermodynamic analysis, kinetic modeling, reactor simulation, and process optimization [3, 4, 6, 11]. However, the response of an operating industrial synthesis loop can differ from that of an isolated reactor because the converter is integrated with recycle, cooling, ammonia separation, purge, and compression systems. Therefore, plant-specific simulation and sensitivity analysis are important for identifying which operating variables provide meaningful improvements under actual operating conditions.

Recent studies have further demonstrated the value of process simulation for ammonia synthesis by examining alternative ammonia-recovery systems, flexible reactor operation, process intensification, and integrated energy performance [16–20]. These studies have expanded the understanding of ammonia-process optimization; however, many focus on alternative process configurations, flexible or dynamic operation, or broader energy-integration objectives rather than the diagnosis and optimization of an existing conventional industrial synthesis loop using validated plant operating data. In particular, there remains a practical need for plant-specific studies that link the effects of reaction-side operating conditions with downstream ammonia condensation and recycle behavior under an existing plant-load condition. The present study addresses this gap by developing and validating an Aspen HYSYS model against actual operating data from the Marsa El-Brega Ammonia Plant and using the validated model to investigate two practically adjustable parameters—synthesis-loop pressure and cooling conditions before V-501. The study therefore provides a plant-specific assessment of how reaction-side pressure and downstream cooling jointly influence ammonia production and loop performance without requiring major process modifications.

The present study focuses on the ammonia synthesis loop of the Marsa El-Brega Ammonia Plant, which operates below its original design production capacity. A steady-state Aspen HYSYS V14 model was developed and validated using available plant operating data. The validated model was then applied to investigate two operating parameters that have a direct influence on overall loop performance: synthesis-loop pressure and cooling conditions before the high-pressure ammonia separator V-501. The pressure study evaluates the influence of loop pressure on ammonia production and associated loop performance, while the cooling study examines the relationship between upstream cooling, ammonia condensation, recycle composition, and production recovery. The objective is to identify the effect

of these two parameters and determine practical operating conditions that can improve ammonia production under the current plant operating state.

2. Materials and Methods

2.1 Plant and Synthesis Loop Description

The study was conducted using operating data from the ammonia synthesis loop of the Marsa El-Brega Ammonia Plant operated by the Libyan Fertilizer Company (LIFECO). The plant is based on the Haber–Bosch process and includes the ammonia converter, heat-recovery system, cooling and condensation section, high-pressure ammonia separator, recycle compressor, make-up gas stream, and controlled purge system [1, 9].

Under the operating condition selected for this investigation, the plant was operating at approximately 81% of its nominal design capacity, corresponding to an ammonia production rate of approximately 810 MTPD. The validated plant-load condition was adopted as the reference condition for the two subsequent case studies. The main operating parameters included a loop pressure of 178 kg/cm²(g), a make-up gas flow rate of 108,500 Nm³/h, and a recycle gas flow rate of 441,455 Nm³/h from plant measurements.

The synthesis loop consists of a high-temperature catalytic conversion section followed by heat recovery, successive cooling stages, ammonia condensation and separation, and recycle of the unreacted synthesis gas. Following the converter, the hot reaction products pass through the heat-recovery and feed-effluent heat-exchange sections before entering the cooling train. The gas is subsequently cooled through E-503, E-504, E-505, and E-506, with make-up gas introduced before the final chilling stage. The cooled mixture enters the high-pressure separator V-501, where liquid ammonia is separated from the unreacted gas. The remaining gas is returned through the recycle system to the converter, while a controlled purge is used to limit the accumulation of inert components [1, 7].

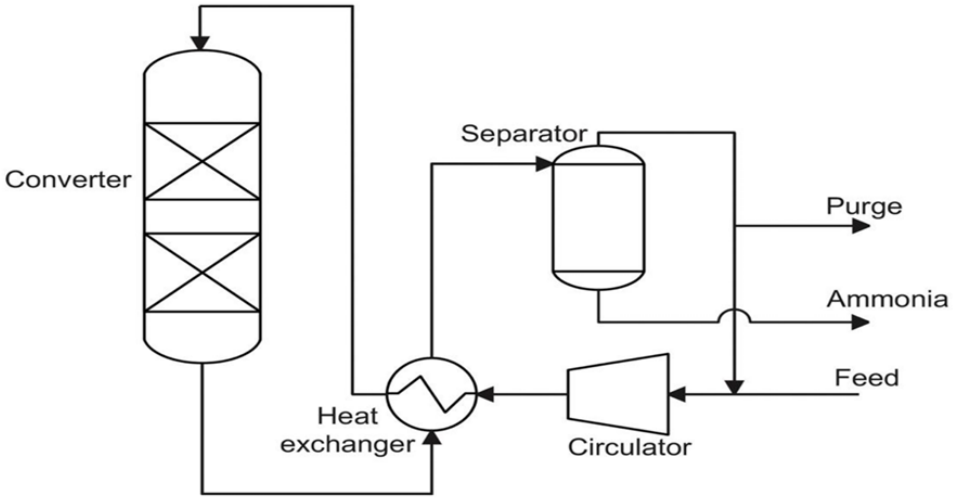


Figure 1: Simplified process flow diagram of the ammonia synthesis loop.

The cooling section preceding V-501 is particularly important to the present study because the final cooling temperature affects ammonia condensation and, consequently, the composition and flow rate of the recycle gas. Therefore, the interaction between cooling performance and recycle conditions was considered when evaluating the second case study.

2.2 Plant Data Collection and Processing

Plant operating data were obtained from several sources to establish a representative basis for model development and validation. The primary source was the plant Distributed Control System (DCS), which provided measurements of process temperatures, pressures, flow rates, and operating conditions. Gas composition data for the make-up, recycle, and purge streams were obtained from laboratory analyses. Design and operating information supplied by the plant technology and equipment licensors was also used to define equipment specifications, catalyst characteristics, reactor configuration, and design performance targets.

The collected DCS measurements were processed using averaged values to minimize the influence of short-term fluctuations. Transient conditions, including start-up, shutdown, and significant process disturbances, were excluded. Additional consistency checks were conducted using mass-balance relationships and expected process trends before the data were used as simulation inputs.

For the actual plant-load reference case, the measured ammonia production rate was 33.75 MT/h, while the corresponding HYSYS prediction was 33.26 MT/h. The measured and simulated recycle gas flow rates were 441,455 and 437,500 Nm^3/h, respectively. These data formed the basis for the validated model used in the subsequent sensitivity studies as shown in Table 1.

Table 1. Main operating conditions of the actual plant-load reference case

Parameter	Unit	Plant data
Plant load	%	≈81
Ammonia production	MTPD	810
Loop pressure	kg/cm²(g)	178
Make-up gas flow	Nm³/h	108,500
Recycle gas flow	Nm³/h	441,455
Purge gas flow	Nm³/h	5,242
Separator inlet temperature	°C	−2.5

2.3 Thermodynamic and Process Simulation Model

The synthesis loop was modeled using Aspen HYSYS V14 under steady-state conditions [2, 8]. The Soave–Redlich–Kwong (SRK) equation of state was selected as the thermodynamic property package because of its applicability to the high-pressure gas-phase conditions prevailing throughout the synthesis loop. The model was used to calculate the thermodynamic properties, phase behavior, material balances, and energy balances required for the process simulation [13].

The simulation represents the principal units affecting synthesis-loop performance, including the ammonia converter, heat-recovery exchangers, cooling train, high-pressure separator, recycle system, make-up gas stream, and purge. The refrigeration system downstream of the ammonia separation section was outside the scope of the model.

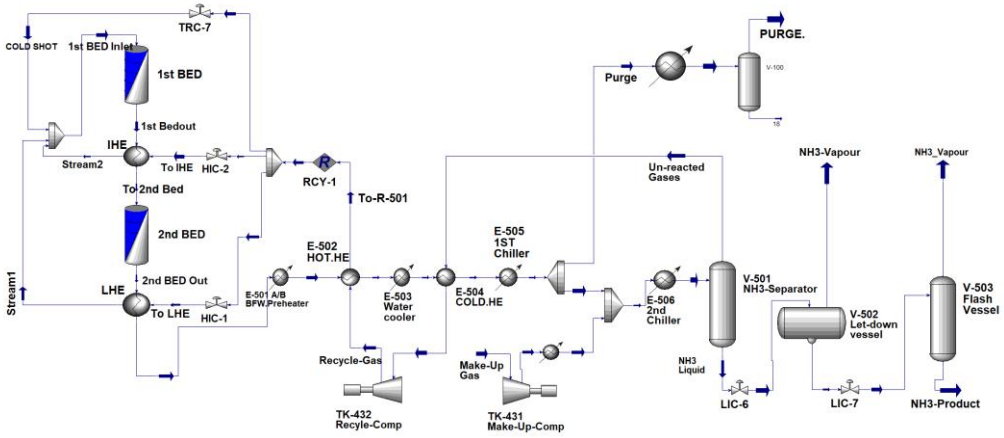


Figure 2: Aspen HYSYS simulation flowsheet of the ammonia synthesis loop.

The ammonia converter was represented using two kinetic plug-flow reactor sections corresponding to the first and second catalyst beds. Each bed was modeled as an adiabatic reactor, while interbed cooling was included between the two beds.

This approach allowed the temperature and composition changes across each catalyst bed to be represented while retaining the essential thermal behavior of the industrial converter.

The ammonia synthesis reaction was represented by the reversible stoichiometric reaction [1, 9]:

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \quad (1)$$

The kinetic formulation was based on the Dyson–Simon modification of the Temkin-type ammonia synthesis rate expression, implemented in HYSYS on an activity basis. The forward and reverse reaction-rate constants were represented using the Arrhenius relationship, while the activity exponents were obtained from the selected kinetic formulation [5, 10, 14].

The converter model incorporated the actual catalyst configuration, with KM1R catalyst in the first bed and KM1 catalyst in the second bed. The catalyst volumes represented in the model were 8.72 and 25.59 m^3 for Beds 1 and 2, respectively, with a bed void fraction of 0.45.

2.4 Model Validation and Case-Study Methodology

Before conducting the parametric studies, the simulation model was calibrated using the available design-condition data and subsequently evaluated against the actual plant-load operating condition. The calibrated kinetic parameters and reactor configuration were retained when the model was transferred from the design case to the approximately 81% plant-load condition. This approach avoided re-fitting the model specifically to the actual operating point and provided a consistent basis for the sensitivity analysis.

The validated actual plant-load model was then used as the base case for the two investigations considered in this paper:

Case Study 1: Effect of synthesis-loop pressure.

Case Study 2: Effect of cooling conditions before V-501.

For each case, the selected operating parameter was varied while the principal reactor, catalyst, kinetic, and process configurations were maintained. The response was evaluated primarily in terms of ammonia production and other process variables relevant to the mechanism being investigated.

This methodology enabled the effects of the two parameters to be evaluated independently using the same validated process model and reference operating condition.

2.5 Model Assumptions and Limitations

Several assumptions were adopted to maintain a practical and computationally manageable representation of the industrial synthesis loop. The model was developed under steady-state conditions; therefore, transient behavior associated with start-up, shutdown, load changes, and process disturbances was not considered. The Soave–Redlich–Kwong equation of state was applied throughout the simulation to represent the thermodynamic behavior of the synthesis-gas mixture under the high-pressure operating conditions. The ammonia converter was represented by two adiabatic kinetic plug-flow reactor sections corresponding to the two catalyst beds, with interbed cooling included between the beds. The kinetic formulation was based on published ammonia-synthesis kinetics and calibrated against the available design-condition data because proprietary kinetic information for the industrial catalyst was not available.

The refrigeration system downstream of the ammonia separation section was outside the model boundary, while its effect was represented through the specified cooling and separator conditions. The upstream synthesis-gas generation section and downstream ammonia storage facilities were also excluded because the objective was to investigate the synthesis loop under the existing plant operating condition. Catalyst deactivation was not explicitly modeled, and the analysis therefore represents the catalyst condition associated with the selected plant-load reference case. These assumptions limit the direct application of the model to long-term catalyst aging, dynamic operation, detailed refrigeration-system optimization, and mechanical equipment design. Accordingly, the simulation results should be interpreted as a validated engineering basis for comparative and sensitivity analysis under the investigated operating range rather than as a substitute for detailed plant testing or final equipment design.

3. Results and Discussion

3.1 Model Validation

Validation of the simulation model was performed before investigating the effects of the selected operating parameters. The purpose of the validation was to determine whether the developed Aspen HYSYS model could adequately reproduce the actual

operating behavior of the Marsa El-Brega ammonia synthesis loop and therefore provide a reliable basis for subsequent case studies.

The comparison was performed using measured plant data and corresponding simulation results for key process variables, including converter temperatures, process-stream compositions, recycle-gas conditions, and ammonia production. The model was developed using the SRK equation of state and the calibrated kinetic representation of the ammonia converter described in Section 2.

The comparison showed good agreement between the measured and simulated values. In particular, the simulated ammonia mole fraction at the converter outlet was 17.07 mol%, compared with the measured plant value of 16.98 mol%, giving an absolute deviation of only 0.09 percentage points. This close agreement indicates that the model adequately represents the reaction and recycle behavior under the actual plant operating condition.

For the recycle system, the specified suction and discharge pressures were maintained at approximately 172 and 182 kg/cm²(g), respectively, to represent the measured plant operating condition. These pressures therefore serve as model boundary conditions rather than independent prediction variables. In contrast, the simulated suction temperature was 30.17 °C compared with the measured value of 30.50 °C, while the calculated recycle-gas flow rate was 437,500 Nm³/h compared with the measured plant value of 441,455 Nm³/h. The close agreement in these calculated and measured variables provides additional support for the representation of the recycle section under the selected plant-load condition.

Table 2. Comparison of selected plant and simulation results

Parameter	Plant	Simulation	Deviation
Converter outlet NH_3, mol%	16.98	17.07	+0.09
Recycle compressor suction pressure, kg/cm²(g)	172	172	0
Recycle compressor discharge pressure, kg/cm²(g)	182	182	0
Suction temperature, °C	30.50	30.17	−0.33
Recycle gas flow, Nm³/h	441,455	437,500	−3,955

As shown in Table 2, the simulation reproduced the principal operating variables with relatively small deviations from the measured plant values, particularly for pressure and temperature conditions.

The agreement between the measured plant values and the corresponding simulation results is further illustrated by the parity plot shown in Figure 3.

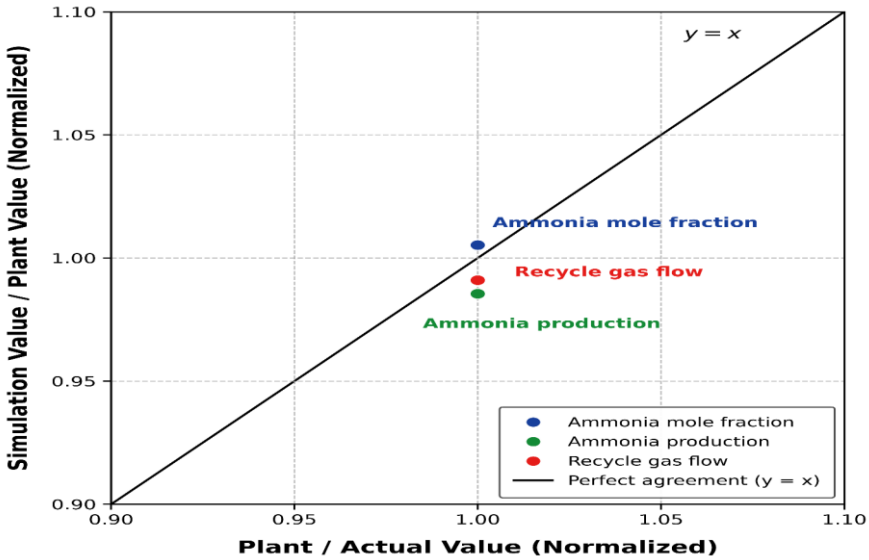


Figure 3: Comparison of measured and simulated key process variables (parity plot).

The results show that the simulated values are distributed close to the parity line, indicating good agreement between the model predictions and the corresponding plant measurements. This agreement provides sufficient confidence in using the validated model for the subsequent operating-parameter investigations.

The small deviations observed between the measured and simulated values indicate that the developed model provides a sufficiently representative description of the actual synthesis-loop operation. The model was therefore considered suitable for investigating the effects of the selected operating parameters.

It should be noted that the plant measurements themselves contain some uncertainty, particularly for ammonia composition. The laboratory analytical instrument used for ammonia analysis was out of service during the relevant period, and the analysis was therefore performed manually. Consequently, the small difference between the measured and simulated ammonia concentration should be interpreted in consideration of the measurement conditions.

3.2 Effect of Synthesis-Loop Pressure

Pressure is one of the principal operating variables governing ammonia synthesis because the reaction $N_2 + 3H_2 \rightleftharpoons 2NH_3$ results in a reduction in the total number of gas moles. Accordingly, increasing pressure favors ammonia formation from a thermodynamic perspective [1, 7, 9]. In an industrial synthesis loop, however, the practical effect of pressure depends on the interaction between the converter, recycle

compressor, gas composition, ammonia separation, and overall loop circulation. Therefore, the validated HYSYS model was used to evaluate the response of the complete synthesis loop to changes in loop pressure.

The actual plant-load condition, corresponding to a loop pressure of 178 kg/cm²(g), was selected as the base case. The pressure was then increased systematically while the remaining principal operating conditions were maintained as consistently as possible. The resulting changes in ammonia production and relevant process variables were evaluated.

The simulation results showed a clear positive relationship between loop pressure and ammonia production over the investigated range. At the highest investigated pressure of 189 kg/cm²(g), the predicted ammonia production reached 34.490 MT/h, compared with 33.260 MT/h for the corresponding base-case simulation. This represents an increase of 1.230 MT/h, equivalent to approximately 3.70%.

Table 3. Effect of synthesis-loop pressure on ammonia production

Loop pressure, kg/cm²(g)	Ammonia production, MT/h	Change from base case, MT/h	Change, %
Base case	33.260	—	—
Increased pressure	34.490	+1.230	+3.70

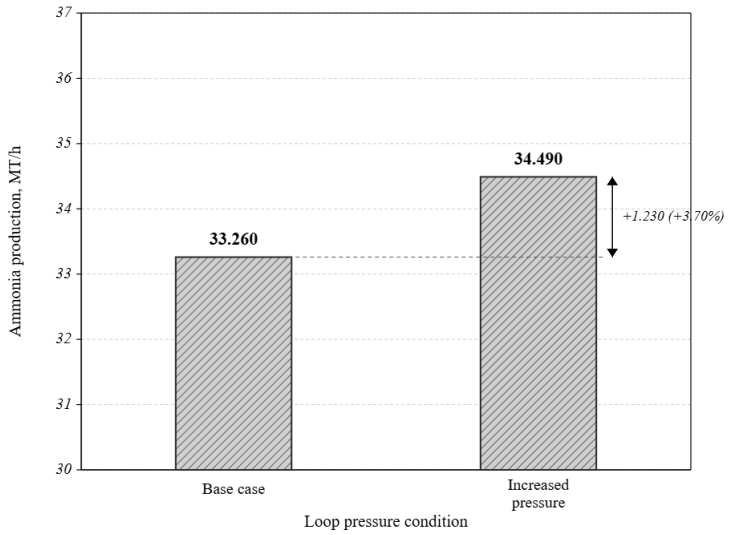


Figure 4: Effect of loop pressure on ammonia production.

The increase in production can be attributed primarily to the favorable influence of pressure on the ammonia synthesis reaction. Higher pressure increases the effective driving force for ammonia formation and can increase the ammonia concentration achieved across the converter. Because the converter is integrated into a recycle loop,

the resulting change in gas composition also affects the downstream separation and recycle streams.

The result is particularly relevant to the current operating condition of the plant because the reference loop pressure is below the design pressure used during converter-model calibration. The sensitivity analysis therefore indicates that part of the lost production capacity may be recovered through appropriate pressure optimization, provided that the compressor, piping, equipment pressure limits, and other operating constraints permit such an increase.

The maximum investigated pressure should not, however, be interpreted as an unconditional operating recommendation. Increasing loop pressure increases the mechanical and compression requirements of the synthesis system. Therefore, the identified production improvement should be considered together with equipment limitations and energy consumption before implementation at plant scale [12, 15].

Overall, the pressure case study demonstrates that loop pressure is a significant operating parameter for the Marsa El-Brega synthesis loop, with the investigated increase producing a measurable improvement in ammonia production. This finding establishes pressure as an important control variable for subsequent operational optimization of the synthesis section.

3.3 Effect of Cooling Conditions Before V-501

The second case study investigated the effect of cooling conditions upstream of the high-pressure ammonia separator V-501. This section is important because ammonia recovery from the synthesis gas depends strongly on the temperature reached before separation [1, 9]. In the modeled loop, E-503 provides the main water-cooling step before the low-temperature cooling section, while E-505 and E-506 provide additional chilling before V-501. The design temperature at the V-501 inlet is approximately −5 °C, at which ammonia condensation is promoted and liquid ammonia can be separated from the unreacted synthesis gas.

The cooling investigation considered two related operating variables: the E-503 outlet gas temperature and the make-up gas temperature. These variables were selected because both influence the thermal load entering the downstream cooling section and consequently affect the final V-501 inlet temperature, ammonia condensation, recycle-gas composition, and ammonia production.

3.3.1 Effect of E-503 Outlet Temperature

The first part of the cooling investigation isolated the effect of E-503 performance by maintaining the make-up gas temperature at its actual value while reducing the E-503 outlet gas temperature. The E-503 outlet temperature was reduced from 38.9 °C to 37.1 °C.

The results demonstrated a clear improvement in downstream cooling performance. The E-506 inlet temperature decreased from 13.315 °C to 11.880 °C, while the V-501 inlet temperature decreased from −2.500 °C to −4.360 °C. Thus, improving E-503 cooling moved the separator inlet condition substantially closer to the design value of −5 °C.

Table 4. Effect of E-503 outlet temperature on synthesis-loop performance

E-503 outlet temperature, °C	V-501 inlet temperature, °C	Recycle flow, Nm³/h	NH_3 production, MT/h	NH_3 in recycle, mol%
38.9	−2.500	437,500	33.263	3.792
38.0	−3.440	436,280	33.495	3.669
37.1	−4.360	435,907	33.804	3.551

The improvement in cooling increased ammonia production from 33.263 to 33.804 MT/h, corresponding to an increase of 0.541 MT/h or 1.63%. At the same time, the ammonia mole fraction in the recycle gas decreased from 3.792 to 3.551 mol%. The recycle flow also decreased by approximately 1,593 Nm³/h.

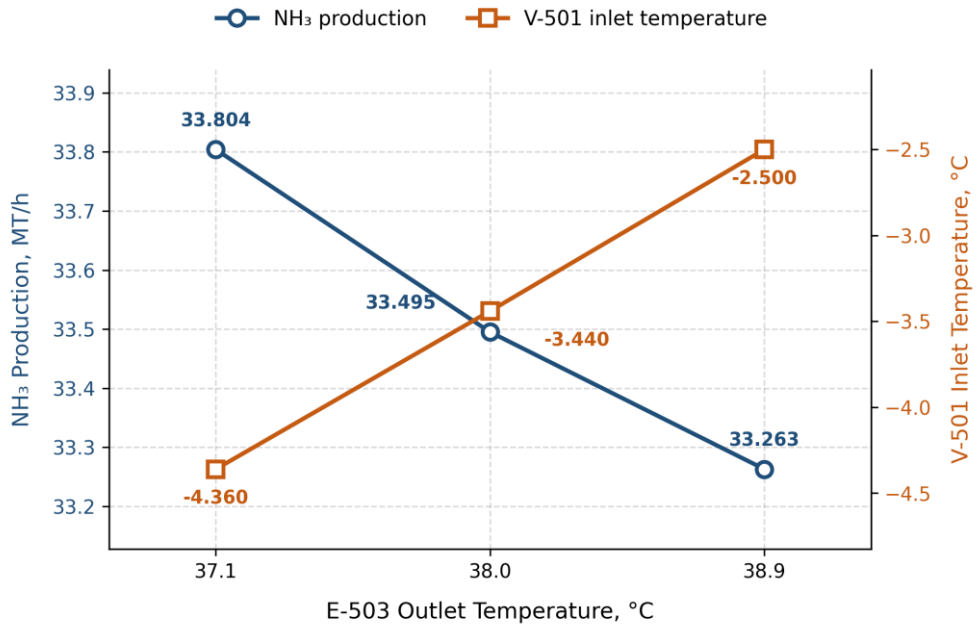


Figure 5: Effect of E-503 outlet temperature on V-501 inlet temperature and ammonia

production.

These changes indicate that improved upstream cooling reduces the thermal load imposed on the low-temperature section, allowing E-506 to achieve a lower outlet temperature. The resulting increase in ammonia condensation improves ammonia recovery in V-501 and reduces the amount of ammonia remaining in the recycle gas. Consequently, the circulating recycle load is also reduced.

3.3.2 Combined Cooling Improvement

Although improving E-503 cooling produced a clear benefit, the complete cooling limitation could not be addressed by this variable alone. The results showed that reducing the make-up gas temperature from 43.6 °C to 37 °C provided an additional production improvement, but the V-501 inlet temperature remained above the design target when this variable was considered alone.

Therefore, the final cooling case combined the two improvements: the E-503 outlet temperature was reduced to 37.1 °C, while the make-up gas temperature was reduced to 37 °C. Under this condition, the V-501 inlet temperature reached −5.150 °C, which is very close to the design value of −5 °C. The NH_3 mole fraction in the recycle gas decreased to 3.450 mol%, compared with the design value of 3.420 mol%.

The resulting ammonia production increased to 34.100 MT/h. Relative to the validated base-case production of approximately 33.260 MT/h, this corresponds to an increase of 0.840 MT/h, or 2.53%. Importantly, this improvement was obtained without increasing the make-up gas flow rate, indicating that the production gain resulted from improved ammonia recovery and loop operation rather than additional fresh-gas consumption.

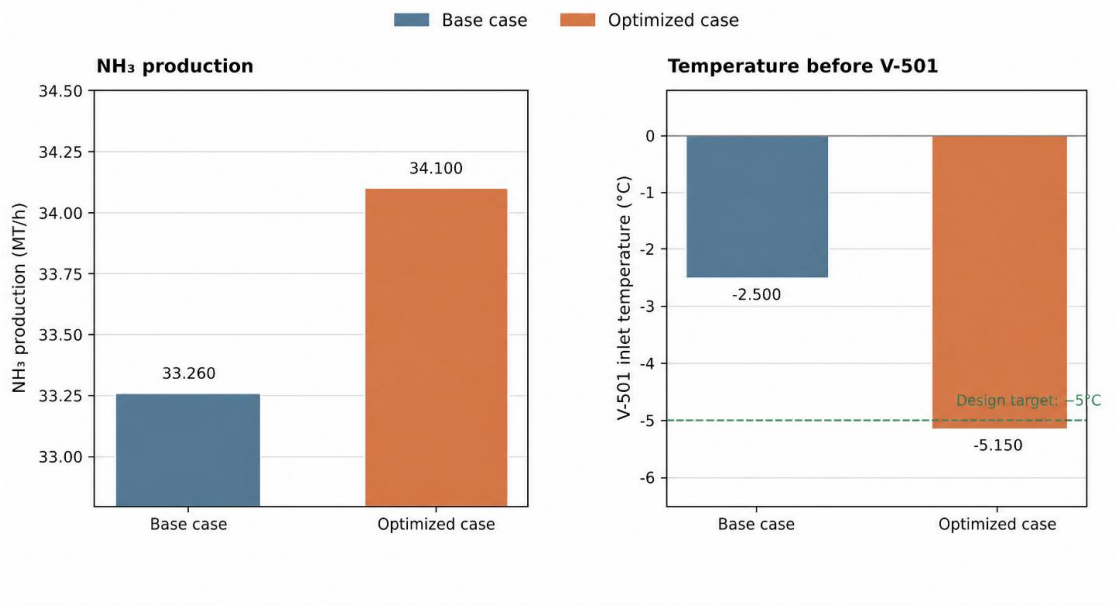


Figure 6: Comparison of base-case and optimized cooling conditions before V-501.

The combined case therefore demonstrates that the cooling limitation before V-501 is an integrated process issue rather than an isolated refrigeration problem. Improvements in E-503 cooling and make-up gas temperature reduce the thermal load on the downstream chilling section, promote ammonia condensation, lower the ammonia concentration in the recycle gas, and reduce recycle circulation. The resulting conditions move the synthesis loop closer to its design operating state.

From an engineering perspective, the cooling improvement represents a particularly practical route for recovering production because it improves ammonia separation without requiring an increase in make-up gas consumption. Nevertheless, implementation should be evaluated against cooling-water availability, E-503 heat-transfer performance, refrigeration capacity, V-501 stability, and recycle-compressor operating limits.

3.4 Comparison of the Two Operating Strategies

The two case studies demonstrate that improvements can be obtained from different parts of the synthesis loop. Increasing loop pressure primarily improves the reaction-side performance, whereas improving cooling before V-501 enhances ammonia condensation and recovery on the separation side.

Table 5. Comparison of the two selected operating strategies

Case study	Best simulated condition	NH_3 production, MT/h	Increase, MT/h	Improvement, %

Loop pressure	189 kg/cm²(g), with first-bed inlet at 385°C	34.490	1.230	3.70
Cooling before V-501	E-503 outlet = 37.1°C; make-up gas = 37°C	34.100	0.840	2.53

The pressure case produced the larger individual improvement, increasing simulated ammonia production by 3.70%, while the cooling case produced a 2.53% improvement. The two improvements should not be added directly because the case studies were evaluated independently; a separate combined optimization would be required to quantify any simultaneous benefit.

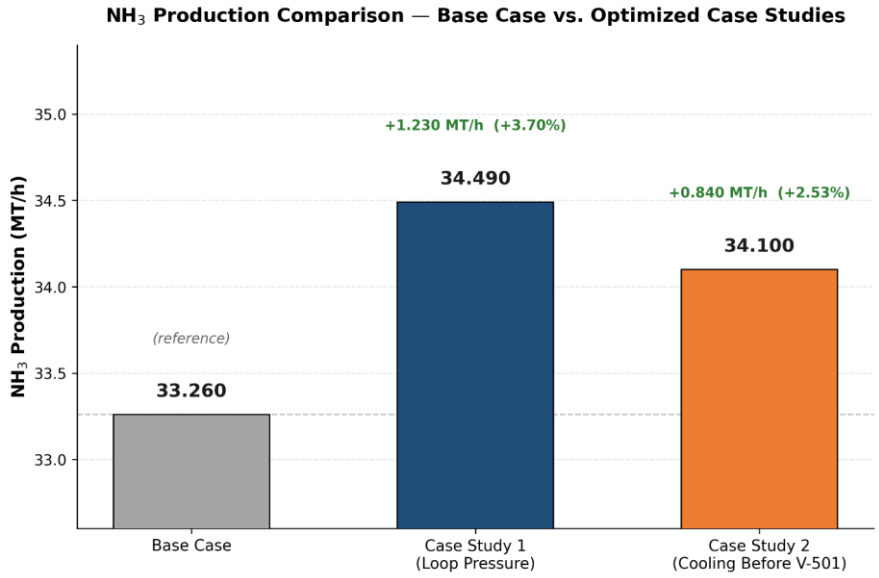


Figure 7: Comparison of ammonia production for the two selected case studies.

Overall, the results show that both operating strategies have practical potential, but they address different limitations within the synthesis loop. Pressure optimization offers the largest simulated production improvement but requires careful consideration of compressor capacity, compression energy, equipment pressure limits, and operating safety [12, 15]. Cooling improvement provides a slightly smaller production gain while directly improving ammonia recovery and moving the separation section closer to its design condition.

4. Conclusions

A steady-state simulation model of the ammonia synthesis loop at the Marsa El-Brega Ammonia Plant was developed using Aspen HYSYS V14 and validated against actual plant operating data. The model showed good agreement with measured process conditions, providing a reliable basis for evaluating the influence of selected operating parameters on loop performance.

Two operating strategies were investigated: synthesis-loop pressure and cooling conditions before the high-pressure ammonia separator V-501. Increasing the loop pressure to 189 kg/cm²(g), with the first-bed inlet temperature maintained at 385 °C, increased the simulated ammonia production to 34.490 MT/h, corresponding to an improvement of 1.230 MT/h (3.70%) relative to the base case. The cooling study demonstrated that reducing the E-503 outlet temperature to 37.1 °C and the make-up gas temperature to 37 °C reduced the V-501 inlet temperature to −5.150 °C, while increasing ammonia production to 34.100 MT/h, an improvement of 0.840 MT/h (2.53%).

The results demonstrate that both pressure optimization and improved cooling before V-501 can enhance synthesis-loop performance. Pressure provided the greater production improvement, whereas cooling offered a practical route for improving ammonia recovery and reducing recycle loading. Implementation of either strategy should consider equipment, compressor, cooling-system, and safety limitations.

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