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Use multistage integrated chilling to increase ammonia production

Ammonia plant operators strive to maximize energy efficiency and ammonia production while minimizing capital cost and downtime, without adding risk or sacrificing operating reliability. However, any significant improvement in energy efficiency without a reasonable increase in ammonia production rarely meets the payout criteria to justify such revamps, which typically require expensive upgrades and downtime to debottleneck compressors and other equipment.

A majority of older ammonia plants have been revamped for higher capacity and improved energy efficiency. Most of them are still relatively inefficient and have been stretched to the maximum operating limits of their equipment, including major compressors, reforming units and steam systems, therefore compromising the operating reliability, risks and ratings.

Increasing ammonia plant capacity with MIC. A new revamp approach uses multistage integrated chilling (MIC). Along with several other proven measures, the MIC scheme provides an option that avoids expensive compressor upgrades for incremental improvements in ammonia production, with energy efficiency improvements up to 15%, depending on the plant and on site-specific constraints. For these types of revamps, the sensitivity analysis demonstrates an economic attractiveness when gas pricing is above $4/MMBtu and ammonia pricing is above $400/metric ton.

The MIC process modification is simply a staged thermal coupling of the ammonia compression system with the process air compressor. This technology can potentially increase the mass throughput of the process air compressor by up to 20% without any compressor or driver modifications, and with practically little or no impact on its compression power or driver steam rate. It also does not require an external refrigeration system.

A comprehensive study was carried out for a large ammonia plant with all three major compressors operating at their maximum speed and the reformer induced draft/forced draft (ID/FD) fans operating at their design limits. With the use of an MIC scheme, along with other proven measures, no changes in the major compressors or ID/FD fans are needed for incremental ammonia production of 12% with an improved energy efficiency of 3 MMBtu/t.

The results of the case study are presented within an overall economics picture, along with changes in key operating parameters and major hardware.

Understanding the MIC process air compressor. Chilling the suction stream prior to entering the compressor systems has long been practiced in various applications to improve compressor performance. A few ammonia plants have implemented suction chilling in the process air compressors, but this provides only a modest increase in air throughput and is typically supplemented with an additional-standalone package refrigeration system.

The process air compressor for a mid- to large-sized, older ammonia plant is usually a multistage centrifugal machine driven by a steam turbine. It is configured in two casings with four stages of compression, with each stage separated by an intercooler, as shown in **FIG. 1.** The low-pressure (LP) compressor is driven by a condensing turbine using superheated medium-pressure (MP) steam, and the high-pressure (HP) compressor is driven through a speed-increasing gear coupled to the LP machine.

Options for upgrading the process air compressor. To upgrade the existing process air compressor system, ammonia plant operators have conventionally used a combination of the following options:

1. Modifications to the existing compressor internals and driver
2. A new compressor and new driver
3. Suction chilling, using an external mechanical refrigeration system
4. Multistage integrated chilling.

Options 1 and 2 require significant downtime and capital and have long delivery schedules. They also require refurbishment of the driver to meet the added power requirement. Option 2, with a supplemental air compressor, requires extra space.
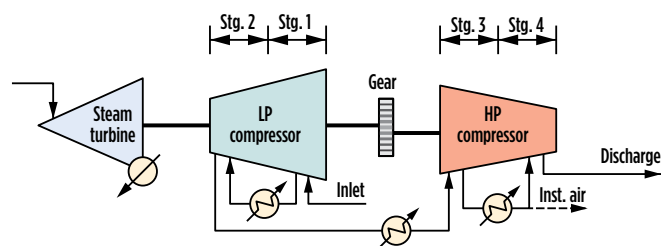

FIG. 1. Diagram of a process air compressor for an older ammonia plant, configured in two casings with four compression stages.

In both of these options, the greater steam demand for the turbine drivers will require an additional surface condenser in the steam system to accommodate the extra steam condensing load, unless an electric option is viable. Both of these options have been implemented in a number of ammonia plants and are economically justified, with significant capacity additions that are typically in excess of 25%.

Option 3, suction chilling, is widely practiced for gas turbines in the power industry, but it is not a very popular option in ammonia plants. A few ammonia plants have implemented this option, using an external refrigeration system that adds power and plot space requirements. This option is much less expensive than the first two options, but it provides only a modest increase in air capacity (approximately 5%) and is rarely economically justified. This is evident from the fact that only a handful of companies have implemented suction chilling in ammonia plants.

Option 4, a new approach using the MIC scheme, provides a cost-effective option to increase the air capacity by up to 20%
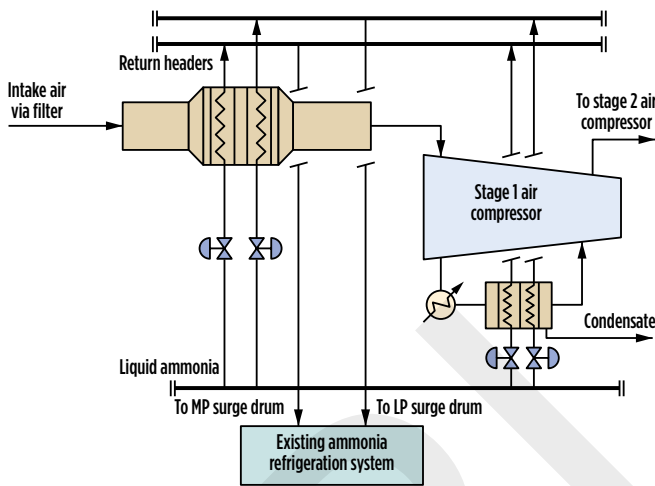

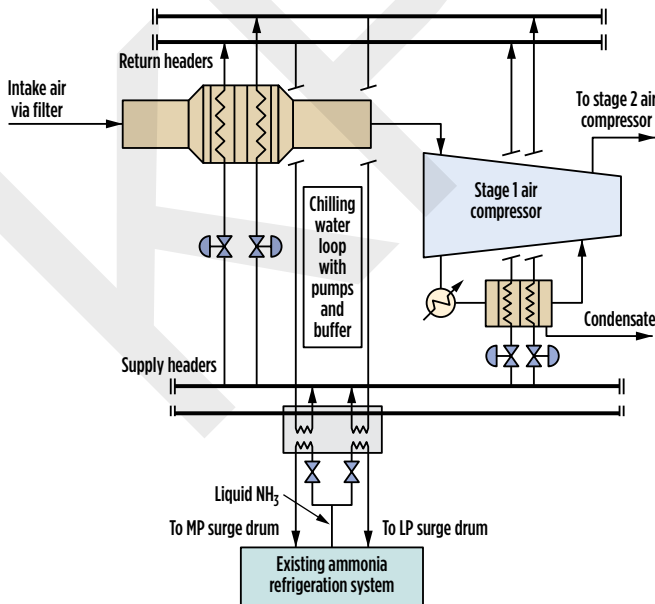**FIG. 2.** Typical direct MIC scheme.

FIG. 3. Typical indirect MIC scheme.

without additional power or the use of an external refrigeration system. However, this option does require additional space.

The MIC solution. The typical MIC scheme shown in **FIG. 2** and **FIG. 3** is a staged thermal coupling of the process air compressor with the ammonia compressor system within the ammonia plant. A direct or indirect chilling scheme, or a combination of the two schemes, can be used, depending on the site constraints. The direct chilling scheme provides the advantage of being the most efficient, with the lowest capital and plot space requirements.

As a part of the ammonia plant revamp for higher capacity, the synthesis loop (synloop) is upgraded with an additional converter bed to suitably increase the single-pass ammonia conversion rate. Higher ammonia conversion results in a reduced gas circulation flowrate and lower refrigeration demand within the synloop.

The freed-up ammonia streams, which are at different temperature levels from the existing ammonia compressor system, are suitably integrated in the staged chilling of the process air compressor, as well as in the makeup syngas compressor. The extent of thermal integration is suitably staged so as to minimize the ammonia compression power to well below its maximum design limits. Furthermore, the extent of the synloop upgrade is suitably synchronized with the upgrade of the front end of the ammonia plant to minimize the additional hardware, downtime and capital requirements.

The higher mass flow of air available is then preheated to higher than the base temperature, using a combination of split flow and an external steam exchanger, as shown in **FIG. 4.** The use of a split flow scheme is plant- and site-specific, and it greatly helps minimize the pressure drop and compression duty with an additional degree of air preheat to maximize the incremental ammonia production.

Benefits of MIC scheme with other measures. The MIC modification, along with other measures, provides the potential to achieve incremental increases in ammonia capacity and energy-efficiency improvements up to 15%, with the following key benefits:
- No modifications are needed for any of the following major compressors, with only a small change in additional steam consumption:
  o Process air compressors
  o Syngas compressor
  o Ammonia compressor
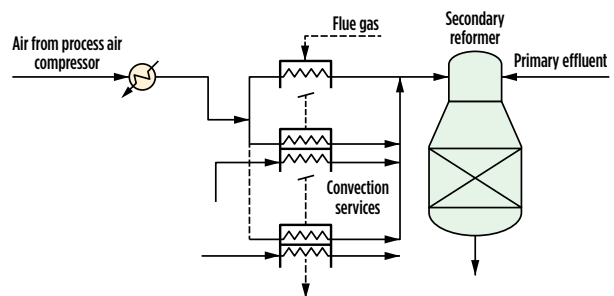- No potential change in the pressure of the main surface condenser for steam turbines

FIG. 4. Scheme showing a combination of split flow and an external steam exchanger.

- Proportionately reduced steam demand at all levels improves energy efficiency
- Reconfiguration and integration allows the temperature to be increased for the following streams, despite space constraints in the convection section:
  - Process air
  - Mixed feed
  - Superheated steam
- Increases in the process air flow and temperature allow the outlet temperature of the secondary reforming unit to be raised, resulting in reduced methane slip and improved H_2/N_2 ratio for better synloop efficiency
- The combination of a higher degree of preheat of mixed feed coupled with process air easily permits shifting the reforming load from the primary reformer to the secondary reformer
- The steam-to-carbon (S:C) ratio in the primary reformer can also be decreased, despite a reduction in the overall methane slip, resulting in:
  - Reduced arch firing, which could be indirectly used to raise reformer tube outlet temperature for the same tube metal temperature
  - Reduced load on ID/FD fans, which could be further reduced by replacing a leak-prone rotary air preheater
  - Reduced mass flowrate of syngas to the cooling train, for improved hydraulics and pressure profile for higher capacity
- Higher steam superheat temperature coupled with lower condensing pressure helps to reduce the steam rates for the same power demand.

Key bottlenecks in old ammonia plants.
A majority of the old ammonia plants are still relatively inefficient, and most of them are operated close to the design limits of the major equipment. Some of the key bottlenecks in the old ammonia plants are listed below:

- **Limits of ID/FD fans in the primary reformer:**
  - Excessive air leakage from the old rotary-type air preheaters
  - Higher-than-design excess air for burners
  - Proportionately high firing load on arch burners due to limiting mixed feed preheat temperature, limiting air preheat temperature and higher-than-design S:C ratio
- **Higher inerts in makeup gas (MUG):**
  - Higher-than-expected methane slip in reforming due to lower temperature at the outlet of the secondary reformer, as a result of limited process air compressor capacity and limited preheat temperature of process air
  - Higher-than-expected CO_2 slip due to:
    - Limited solvent circulation rate
    - Limited cooling of lean solvent due to limited cooling water (CW) or heat transfer surface

- Higher-than-expected loading of the lean solvent
- Non-optimal solvent concentration
- Mass transfer and hydraulic limitations of absorber and stripper internals
- **Major compressors:**
  - Reached maximum volumetric limit at maximum design speed
  - Actual operational efficiency is lower than design
  - Higher-than-design suction temperature (percent of relative humidity for air compressors)
  - Limited intercooling
  - Unfavorable plant hydraulics (lower-than-design suction pressure)
- **Plant throughput limitations:**
  - Higher-than-design S:C ratio
  - Higher-than-design level of inerts in MUG
  - Inefficient synloop and poor feed efficiency
  - Higher-than-expected system pressure drop
- **Excessive steam venting from the deaerator:**
  - Excessive reboil load in CO_2 strippers
  - Excessive temperature in the main surface condenser
- **Higher temperature in the main surface condenser of turbines:**
  - Excessive backpressure due to higher-than-design load
  - Limiting heat transfer surface
  - Efficiency loss in condensing turbines due to lower steam superheat temperature and higher-than-expected steam rates.

Case study. A case study of a large ammonia plant is outlined. The referenced ammonia plant had been stretched to its operating limits, with the following constraints:
- Process air compressor near its maximum design speed
- ID/FD fans of the primary reformer at full open conditions
- Syngas compressor near its maximum design speed
- Ammonia compressor near its maximum design speed
- No extra space in the convection section to add coils
- High inerts in MUG due to high methane and CO_2 slippage
- Excess venting of steam from the deaerator
- High energy consumption.

This revamp study posed a major challenge to provide viable capacity and energy improvements without expensive compressor upgrades.
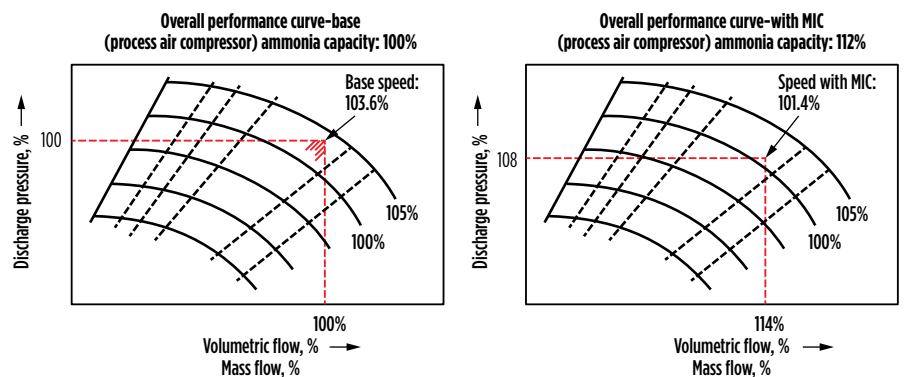

FIG. 5. The mass flowrate of the process air compressor is increased, with reduced speed and without any increase in its power requirement.
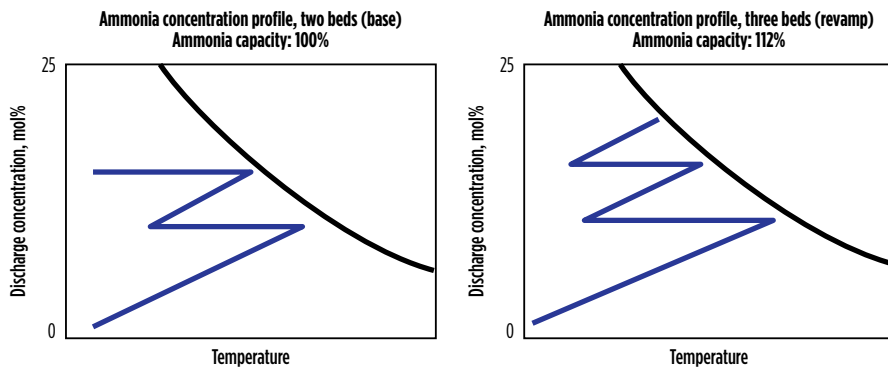
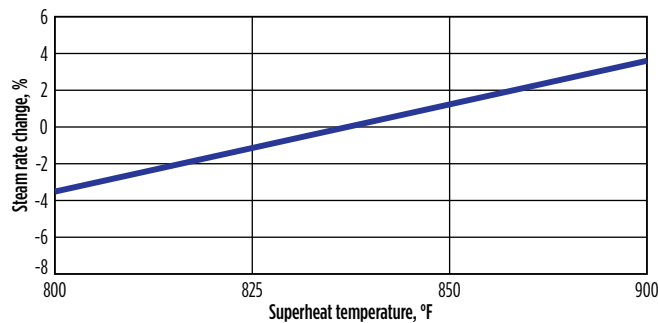**FIG. 6.** The ammonia loop is upgraded with an additional single-bed converter.

FIG. 7. MP steam temperature vs. steam rate.

TABLE 1. Key performance parameters

Parameter	Base case	Revamp
Ammonia capacity	Base	112%
Energy consumption, MMBtu/t	Base	–3
Mixed feed preheat temp., °F	Base	+40
S:C ratio, mol %	3.5	3.15
Process air preheat temp., °F	Base	105
Steam superheat temp., °F	Base	+35
Secondary outlet temp., °F	Base	+50
MUG suction pressure, psi	Base	+15
Inerts in MUG, mol%	Base	65%
MUG H_2/N_2 ratio, mol%	3.06	3
Loop H_2/N_2 ratio, mol %	3.65	3
NH_3 in converter effluent	Base	+5% mol
Purge rate, mass rate	Base	88%

List of major modifications. Based on a comprehensive study using the MIC scheme, no upgrades were required in any of the major compressors for a capacity increase of 12%, along with energy savings of 3 MMBtu/t. The following major changes were required as a part of the revamp:

- MIC system
- Replacement of rotary air preheater with plate-type preheater
- Minor modifications of feed preheat coil
- LP flash column system in CO_2 removal

- Additional single-bed converter
- Few parallel exchangers for additional duty
- Larger impellers for pumps.

Key performance parameters for the base case and the MIC revamp are shown in **TABLE 1.**

Process air compressor. Using the MIC scheme, including the two intermediate stages, the mass flowrate of the process air compressor is increased to 114% with reduced speed and without any increase in its power requirement, as indicated in **FIG. 5.**

All of the chilling duty is internally supplied, without any need for an external refrigeration package. No modifications of the air compressor or its driver are required. Each stage of the air compressor is rated for its limitations and any cooling requirement for the target capacity. The MIC scheme is suitably staged and optimized to minimize the compression requirements of both ammonia and air compressors, along with some additional modifications for size, space and capital requirements.

The speed of the makeup syngas compressor is also reduced for the revamp case. It is accomplished by slightly raising its suction pressure and by lowering the suction temperature.

With a balanced upgrade of the synloop and the front end, the speed of the ammonia compressor is marginally reduced.

Reforming area. Reconfiguration and integration allow the temperature of the following streams in the reforming area to be increased, despite space constraints in the convection section:

- Process air
- Mixed feed
- Superheated steam.

Increases in the process air flow and temperature permit a rise in the outlet temperature of the secondary reforming, resulting in reduced methane slip and an improved H_2/N_2 ratio for better synloop efficiency.

A combination of a higher degree of preheat of mixed feed coupled with higher temperature of the process air easily permits shifting of the reforming load from the primary reformer to the secondary reformer. In addition, the S:C ratio in the primary reformer is also reduced, despite a decrease in the overall methane slip that results in reduced arch firing, which could be indirectly used to raise the reformer tube outlet temperature without affecting the tube metal temperature. It also helps reduce the load on the ID/FD fans, which could be even further improved by replacing the leak-prone rotary air preheater with a plate-type preheater.

A reduced mass flowrate of syngas (due to a lower S:C ratio) to the cooling train also helps the hydraulics and the pressure profile for higher capacity. A higher steam superheat temperature coupled with lower condensing pressure helps reduce the steam rates for the same power demand.

CO_2-removal area. The CO_2-removal system scheme is a conventional, single-stage MDEA and piperazine.

To overcome the mass-transfer and hydraulics limitations in the CO_2-removal sections, several schemes were simulated

and further reviewed based on a cost-benefit analysis. Several changes were made in the revamp scheme:

1. Optimization of the MDEA and piperazine concentration in the solvent
2. Inclusion of an LP flash tower to offload the stripper reboiler duties by 16%
3. Replacement of existing packing with more efficient, lower-pressure drop packing
4. Replacement of the pump impellers, along with the supplemental exchanger area
5. Addition of the hydraulic turbine in the rich solvent stream.

A two-stage scheme was also considered and simulated, but was discontinued based on the cost-benefit analysis.

The cooler lean solvent, coupled with a slight increase in lean solvent flow, helped to significantly reduce the CO_2 slip, thereby lowering the total inerts to the loop.

Reducing the CO_2 stripper duty by approximately 16% offloaded the stripper internals without any modification required, and completely eliminated the large continuous steam vent from the deaerator, resulting in energy savings.

Ammonia synloop. The ammonia loop is suitably upgraded with an additional single-bed converter, as shown in **FIG. 6,** with a relative ammonia concentration profile. The upgraded ammonia conversion is carefully chosen to balance the capacity increase in the front end for minimum modifications and capital requirements.
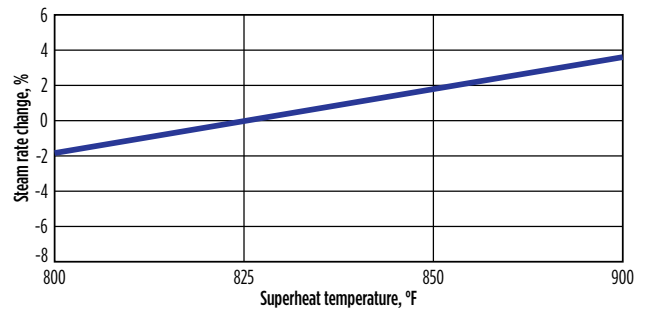

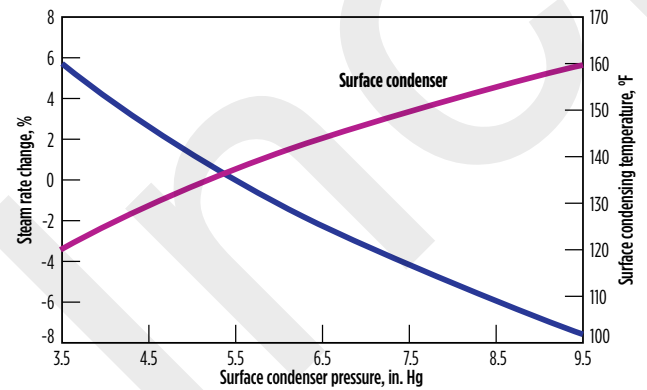**FIG. 8.** HP steam temperature vs. steam rate.

FIG. 9. Condensing pressure vs. steam rate.

FIG. 10. IRR for ammonia pricing of $400/metric ton.

FIG. 11. IRR for ammonia pricing of $500/metric ton.

Economics. The economics of the case study, in terms of internal rate of return (IRR) for ammonia pricing of $400/metric ton and $500/metric ton, are shown in **FIG. 10** and **FIG. 11**. IRR estimation also considers varying gas prices of $4/MMBtu to $10/MMBtu in step changes of $2/MMBtu, along with the capital sensitivity from −10% to +20%. This estimation provides a reasonable representation of various global locations for the assessment of the MIC scheme.

The following assumptions are used in the economic evaluation:

- CAPEX: total installed cost, including owner's costs
- Project completion: 36 months
- Operating rate: 100%
- Utility rates: typical of US Gulf Coast
- Financing: internally funded (no debt)
- Lifecycle: 15 years
- Discount rate: 10%
- Loan interest: 8%
- Tax rate: 25%
- New catalyst life: 15 years
- Ammonia prices: $400/metric ton and $500/metric ton.

As expected, the IRR greatly improves with higher ammonia and gas prices. Interestingly, the estimated IRR is higher than the typical minimum of 15%, even with the lowest gas price of $4/MMBtu and a 20% higher CAPEX than estimated. The IRR improves with higher ammonia and gas prices.

Takeaway. The MIC scheme, in conjunction with other process improvement measures, provides a cost-effective option to ammonia plant operators for incremental improvements in capacity and energy efficiency up to 15%, while avoiding expensive upgrades of major compressors.

The sensitivity analysis demonstrates an economic attractiveness for gas prices above $4/MMBtu and ammonia prices above $400/metric ton, mainly for revamps. The ammonia plant locations with higher feed gas prices will provide higher economic returns.

The opportunity to use these incremental improvements in ammonia plants is most promising in situations where capital and/or additional feed gas availability is limited. **HP**

With an increase of ammonia conversion in the synloop, the refrigeration duty requirement from the ammonia compressor is significantly reduced. The spare load from the ammonia compressor is used to provide the chilling duty of the process air compressor and the makeup syngas compressor without any modifications or power increases in the ammonia compressor.

With a higher ammonia conversion, the outlet temperature will increase beyond the design temperature of the existing boiler feedwater (BFW) preheater. For this reason, a new exchanger is added before the existing BFW preheater. In addition, a parallel CW exchanger is added for more ammonia condensation at the CW level.

Steam system. The steam system is suitably optimized and balanced for higher ammonia capacity. It takes advantage of a higher degree of steam superheat at the HP and MP levels, and it also reduces the steam rates to minimize the surface condenser pressure and load.

Furthermore, by reducing the stripper reboil duty, the LP vent from the deaerator or excess LP steam can be significantly minimized, resulting in improved energy efficiency.

For every 50°F temperature rise in the degree of superheat, the condensing steam turbine steam demand will decrease by about 3.5%, as shown in **FIG. 7** and **FIG. 8**.

Most of the surface condensers in ammonia plants are overloaded with as high as 9 in. of mercury (Hg) pressure, as opposed to a typical Hg pressure of 3.5 in. to 4.5 in. for normal operation. For a reduction of every 1 in. of Hg in backpressure in the main surface condenser, there is an approximate rise in condensing turbine efficiency of about 3%, as indicated in **FIG. 9.**

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