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CONSIDER KRES FOR FUEL COST SAVINGS AND INCREASING CAPACITY IN THE AMMONIA PLANT (a)

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1. Abstract

In October 1994, the KBR Reforming Exchanger System - KRES and Autothermal Reforming - ATR, a simple heat exchanger based steam reforming process used for generation of ammonia synthesis gas was commissioned in Pacific Ammonia Incorporated's ammonia plant at Kitimat, British Columbia, Canada.

KBR has further optimized and improved the design of KRES and ATR for synthesis gas generation for large capacity ammonia plants. In 2001 KBR was awarded a contract to supply a 1070 metric tons/day KRES as part of an ammonia revamp project in China. In this project KRES replaces an existing fired reformer to reduce the natural gas fuel requirement. This unit is scheduled for commissioning in 2003.

The KRES system can also be used for increasing the capacity of the front-end of ammonia plant, while at the same time reducing the natural gas fuel requirement. The purpose of this paper is to provide an overview of the various flow schemes where incorporating KRES unit can effectively reduce the fuel cost and increase the capacity of the ammonia plant. The paper also highlights the cost, environmental, reliability and operability benefits KRES provides to the ammonia producer.

2. Introduction

KBR's Reforming Exchanger System – KRES is a simple heat exchanger based steam reforming process used for the generation of synthesis gas for the manufacture of ammonia, methanol, hydrogen or gas to liquid application. KRES went into commercial operation in Pacific Ammonia's (PAI) ammonia plant in Canada in October 1994. It produces synthesis gas that is converted into 350 metric tons/day of ammonia. The KRES system at PAI has proven highly successful.

In 2001 KBR was awarded a project to supply technology for a revamp of Liaohe's ammonia plant in China. Part of this project includes the supply of a KRES unit. Capacity is 1070 metric tons/day and the unit is scheduled to start up in the first half of 2003. In this project KRES unit replaces the primary reformer. Most of the natural gas fuel requirement is eliminated with steam import from a coal fired off-site boiler.

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The scale-up of KRES by a factor of three represents a significant step forward in this technology. KBR believes reforming exchangers will ultimately replace fired steam-methane reformers for production of synthesis gas. As discussed in other papers,(2,3) we have made KRES part of our KAAPplusTM flow sheet. This paper reviews the performance of KRES since its start up at PAI and discusses some of the differences between the PAI design and the design for Liaohe. The paper also discusses how KRES can be used to reduce fuel cost and increase the capacity of the front-end of an existing ammonia plant. We also describe the design for KRES for a single-train 4500 MTPD ammonia plant.

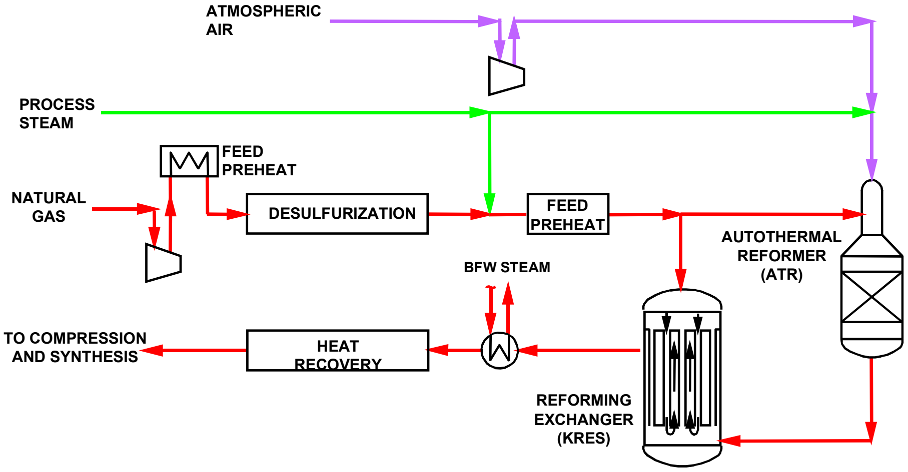
Fig.1: KRES at plant in Canada, with autothermal reformer on the left and reforming exchanger on the right.

3. **KRES Flow Scheme**

The KRES process is illustrated in Figure 2. The preheated mixed feed consisting of hydrocarbon feed plus steam flows in parallel to both the reforming exchanger and autothermal reformer. The oxidant is introduced as a separate feed to the ATR. Air is used as an oxidant in KBR ammonia plants where the Purifier is incorporated downstream as in the KAAPplusTM process. KAAPplusTM has eliminated the need for an air separation plant to produce oxygen.

The effluent from the ATR, typically at about 940~960°C, flows to the shell side of the KRES exchanger. The remaining portion of the hydrocarbon feed and steam enters the tube side of the KRES exchanger. As the hydrocarbon-steam mixture flows inside the tubes, it comes in contact with steam reforming catalyst, which is used to promote the endothermic reaction. The heat required for this reaction is provided from the shell side gases, which consist of the combined effluent from the ATR and the tube side of the KRES exchanger. The shell side gases, after heat exchange with the reacting tube gases, exit the shell side of the exchanger for further downstream processing.

Fig 2: KRES flow scheme with reforming exchanger in parallel with the autothermal reformer



KBR’s KRES reforming exchanger operates in parallel with the autothermal reformer, as illustrated in Figure 2. Parallel operation has several advantages. System pressure drop is lower than in series operation. More importantly, the single train capacity limit is much higher as only part of the hydrocarbon feed flows through the reforming exchanger.

Fig 3: KRES–Open Tube Reforming Exchanger

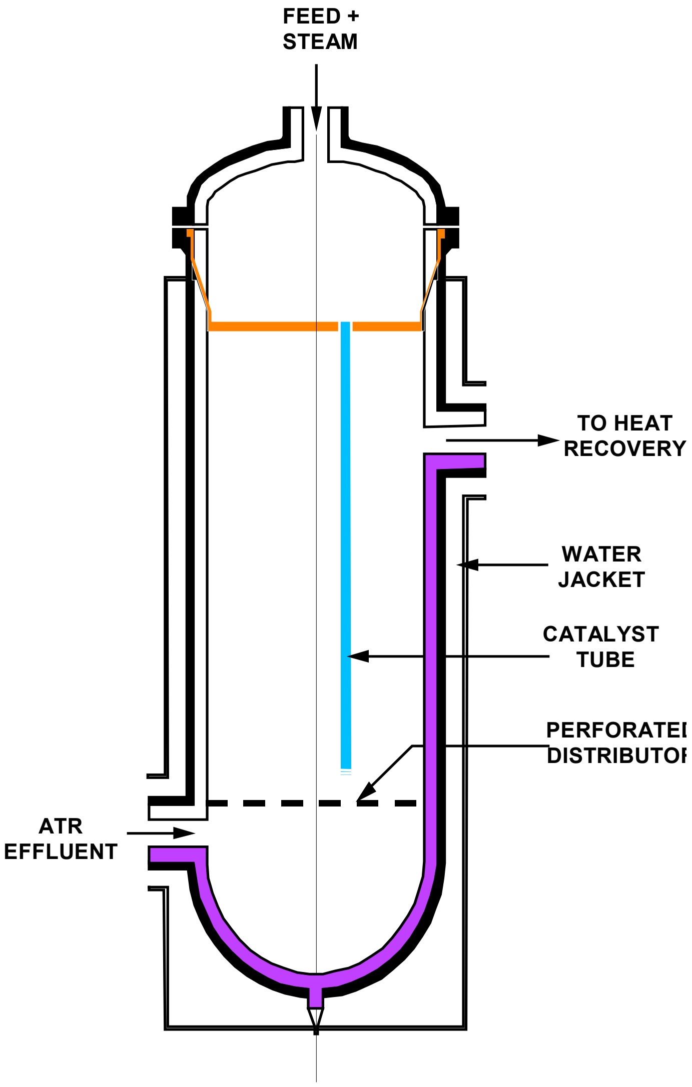


Fig 4: KRES Exchanger Bundle Arrangement

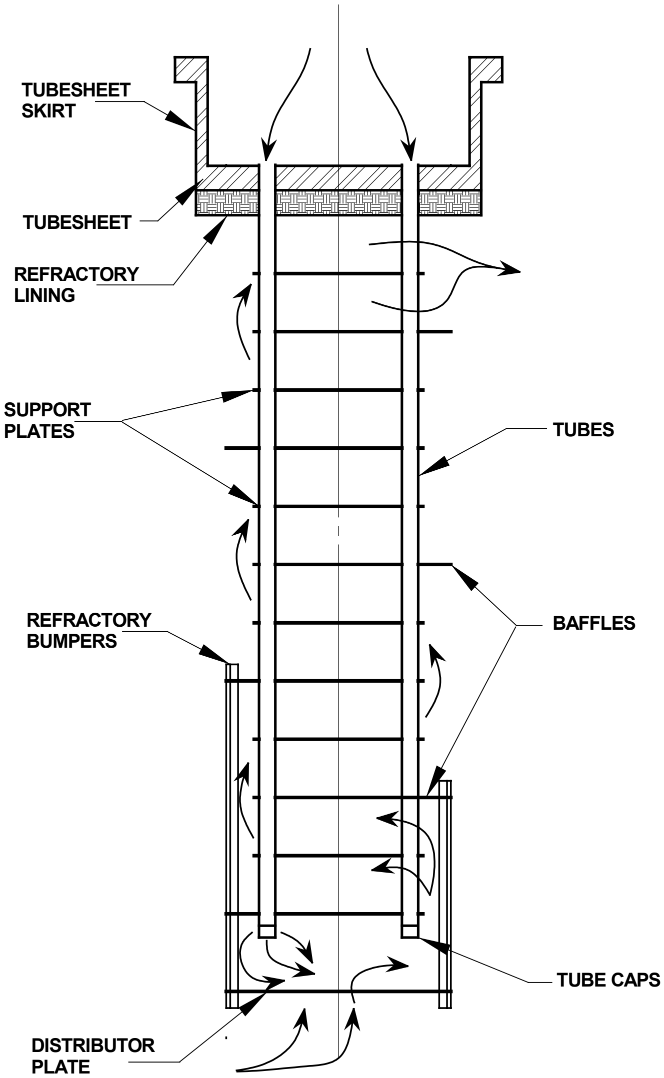


Figure 3 and 4 are sketches of the KBR’s open tube reforming exchanger. It has the following unique design features.

Simple open tube arrangement that allows each tube to expand individually. This results in a very low stress on the tube sheet since only the weight of the bundle is present. In addition, the presence of a single tube sheet and open tube arrangement eliminates any thermal stresses which result from differential tube to shell temperatures.

The bundle is completely removable to allow easy inspection or replacement with a minimum of facility downtime.

The tube sheet is located at the cold end of the exchanger, which results in higher allowable material stresses.

The tube sheet is a hanging type, which allows the flanged joint to operate at a uniform and practical temperature.

The shell is refractory lined with a proven dual layer internal refractory. In addition, the shell is externally water jacketed to assure uniform lower operating temperature and an added protection to allow an orderly shutdown in the event of a refractory failure.

The ATR effluent is uniformly distributed across the bundle field by use of a perforated distributor. This design has been optimized by the use of computational fluid dynamic (CFD) analysis. The reformed gas exiting the open tubes is mixed with the ATR effluent by use of a perforated end cap, which is designed specifically to promote mixing with the shell side fluid.

The bundle arrangement is illustrated on Figure 4. Design features of the bundle are as follows:

The bundle uses a no-tube-in-the-window segmented baffle design which results in true cross flow of the shell side fluid. This assures uniform heat input along the tube length in each cross pass and to each individual tube.

Additional supports are added between each baffled cross pass, which provides a stiff bundle design free of any potential vibration.

4. PAI Experience

All of the above mentioned unique design features were provided in the 350 MTPD KRES unit at Pacific Ammonia Incorporated's ammonia plant in Kitimat, British Columbia, Canada. In October of 1994, KRES was put into operation at PAI. (5) These unique features have been primarily responsible for a long, sustained, and successful run of the KRES exchanger at PAI. All these features are scalable to larger capacity units. An inspection was performed in October 1996 by pulling the bundle and removing and reloading the catalyst in three tubes. All elements of the reforming exchanger were in a new-like condition. There was no evidence of metal dusting. The catalyst was found to be in good condition. Details of this inspection are discussed in the literature. (4)

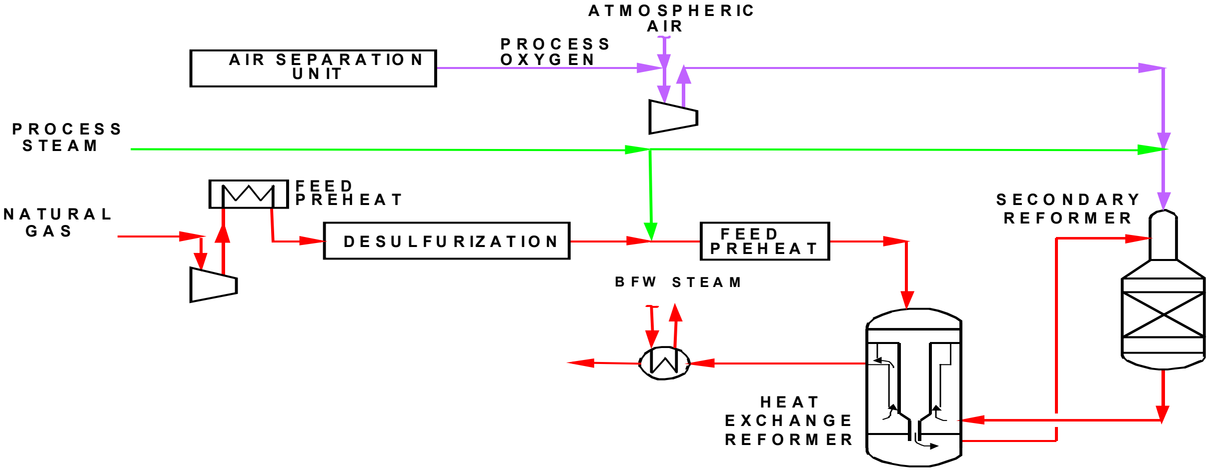
In late 1999 the pressure drop across the tube side of the reforming exchanger began to rise. The decision was made to change the catalyst. During a scheduled turnaround in May 2000, PAI replaced the five-year old catalyst with a new loading. It was noted that some of the original load of catalyst had crushed over time leading to the high pressure drop across the tubes.

The KRES system at PAI has proven highly successful and makes up the front-end of KBR's most advanced ammonia technology, KAAPplusTM. In seven plus years of operation, the reforming exchanger has been 100% available. In other words, the KRES unit has never caused a plant outage.

5. Reforming Heat Exchanger Schemes

Two proven reforming exchanger schemes are available in the industry for the production of synthesis gas. The first is the parallel scheme, which is described in Figure 2. The parallel scheme is licensed only by KBR. The other is a series scheme, as shown in Figure 5.

Fig. 5: Series Scheme for Reforming Exchanger



In the parallel scheme used by KBR, the mixed feed is split into two parallel streams with 25~ 50 % going to KRES tube side and the rest going to the ATR. This split is set to achieve optimum cost and energy consumption. For example the KRES design for KAAPplusTM flow sheet has about 40% of the mixed feed going to the tube side of the KRES exchanger. In the enriched air style PAI Kitimat plant, the split is 25~30% going to the tube side of the KRES exchanger. The flexibility inherent in the parallel design permits the optimization of the temperature and methane content of the gas exit the tubes of the KRES exchanger to match the requirements of the downstream processing scheme. In the case of PAI, actual temperature and methane content of the gas exit the tube side of KRES is 955°C and less than 0.2 dry mole % respectively. Whereas in the case of the KAAPplusTM flow sheet, the tube side temperature is lower and therefore the methane content is higher. However, the KAAPplusTM flow sheet includes a Purifier to remove this extra methane in the feed stream.

In the series scheme, all the mixed feed enters the reforming tube exchanger tube side, where it is reformed. Effluent is sent to the secondary reformer, where oxidant is added. The oxidant in all the cases is enriched air or oxygen and not ambient air. The synthesis gas produced in the secondary reformer is then sent to the shell side of the reforming exchanger to provide the endothermic heat of reaction. The shell side gases, after heat exchange with the reacting tube gases, exit the exchanger for further downstream processing.

For the same capacity plant, the size of the reforming exchanger is much larger than in a parallel design since all the mixed feed is sent to it. The series scheme also requires a complicated double tube sheet design on the cold end. On the hot end of the exchanger, either a complicated gas collection system with pigtails and collection headers or a sealing system is used. Both are difficult to maintain. Since the diameter of the shell is much larger in the series scheme, the designers use double pipes with fins in order to improve the heat transfer coefficient on the shell side.

The KRES system uses a parallel scheme for the following reasons:

- Mechanically simple exchanger design
- No complicated double fin tubes and multiple tube sheets
- No complicated seal system or pigtails/collection headers
- Catalyst filled tubes, suspended from single tube sheet, located at cold end
- Unit pressure drop is minimized
- Unit stresses are minimized
- Smaller exchanger for same capacity plant

6. KRES Application for Fuel Cost Savings

KRES system can be used to reduce “fuel gas” cost by replacing with cheaper energy produced by a coal-fired boiler or other lower cost energy sources. This scheme is very attractive for locations where natural gas is expensive or unavailable but has coal or oil fired boiler at site.

This concept has helped KBR win its second license of a KRES unit. In the fall of 2001, KBR was awarded a contract to supply KRES technology for Shenzhen Liaohe Tongda Chemical Co. Ltd.'s 1070 MTPD ammonia plant revamp project at Liaohe, China. Liaohe operates a nameplate 1000 MTPD plant at its site in Liaoning Province. Liaohe is facing a shortage of the natural gas.

In order to overcome the shortage of natural gas, Liaohe is installing KRES to reduce their natural gas fuel requirement. Existing primary reformer along with convection section and secondary reformer will be replaced with KRES exchanger, ATR and process heater. The heat previously used to generate high pressure steam will now be used to heat the reforming exchanger. The lost steam production will be made up by generating steam in a coal-fired boiler.

Table 1: Comparison of Feed & Fuel Gcal/MT for a typical KRES Revamp Project

	Before Revamp	KRES Revamp
Feed	5.7	6.2
Fuel	3.8	0.3
Total Natural Gas	9.5	6.5
Steam/BFW Export	-0.4	-0.2
Coal Fired Boiler	0.0	2.3
Total (ex ASU)	9.1	8.6

Table 1 indicates the benefit of a typical KRES project in this type of application. Natural gas consumption is reduced from 9.5 Gcal/MT to 6.5 Gcal/MT. Coal fired boiler provides another 2.3 Gcal/MT energy, which is far cheaper than the energy from natural gas. In this way KRES system helps ammonia producer to:

- Reduce natural gas consumption by 30%. Considering natural gas cost of 3 US$ per mmBTU this results in about 36 $/MT lower natural gas cost.
- Supplement with the cheaper energy produced by coal
- Lower NOx and CO2 emissions
- Ease of operation
- Higher reliability

The design of the KRES exchanger for Liaohe is very much optimized as compared to the design of PAI. These optimized features, which are described in detail in the later part of this paper, have resulted in lowering the cost of the reforming exchanger while retaining all the reliability features of the design of PAI.

It is expected to be on-line in 2003. Some of the key dimensions of the Liaohe reforming exchanger are:

Shell ID = ~ 2050mm
Tube ID = ~ 25mm
Number of tubes = ~ 1400

7. KRES System For Increasing Capacity of the Front End

In case the fired primary reformer of an existing ammonia plant is a bottleneck to increase capacity, the KRES can be used to increase the reforming capacity. Such an example is shown in Figure 6. Preheated mixed feed is split into two parallel streams. One goes to the primary reformer and other is sent to the tube side of the new KRES exchanger. Gas exit the secondary reformer is mixed with the tube side exit gas from KRES exchanger. This combined gas then provides heat required for reforming in the KRES exchanger.

Fig. 6: KRES For Increasing Reforming Capacity

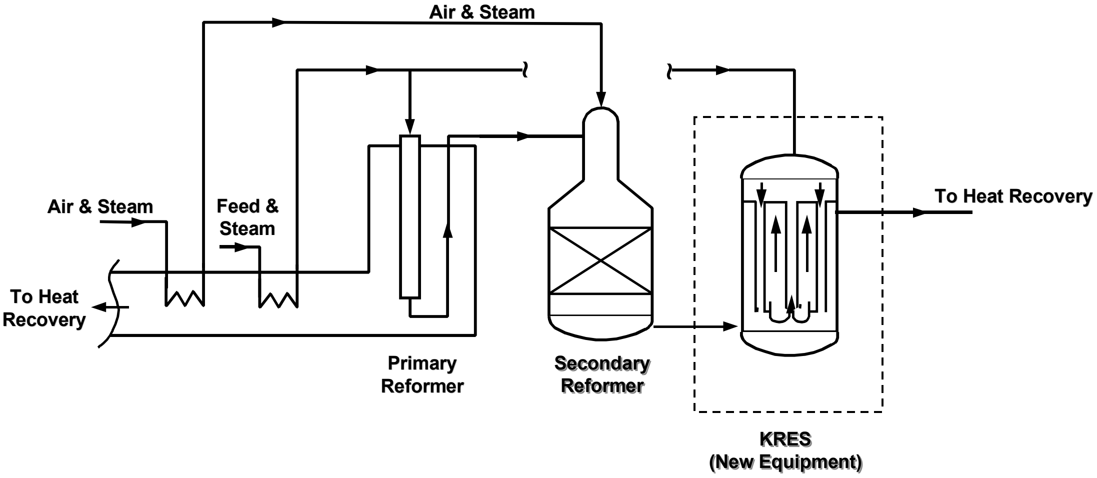


Table 2: Comparison of Process Parameters

	1000 mtpd Original Ammonia Plant	1500 mtpd Conventional Revamp	1500 mtpd KRES Revamp
Duty Gcal/hr			
Primary Reformer	51.5	77.2	46.8
KRES	-	-	29.9
WHB	46.9	70.3	46.1
Temperature °C			
Exit Pr. Ref.	802	798	776
Exit KRES Tube	-	-	985
Inlet WHB	1001	1001	798
% Methane Exit			
Pr. Reformer	13.0	13.0	15.5
KRES	-	-	1.2
Inlet WHB	0.31	0.31	0.31

Table 2 indicates process parameters for 1000 MTPD ammonia plant (base case), 1500 MTPD conventional revamp (retrofit radiant section) and 1500 MTPD revamp using KRES exchanger.

Advantages of KRES Revamp are:

Possible to increase reforming capacity by 50%
No need for oxygen or enriched air
Reduced unit energy consumption
Simple revamp.
Radiant duty of the primary reformer is lower than the base case. No modification to the radiant section of the primary reformer.
Lower natural gas consumption and possibility to use other source for steam requirement
Temperature of the gas exit the primary reformer is lower by 25~30 °C thereby increasing the tube life.
No modification to the existing burners of the primary reformer
Lower NOx and CO2 emission
Ease of operation
No increased pressure drop through the reforming section due to parallel operation of KRES

8. Designing KRES for Large Ammonia and Syngas Plants

KBR has developed designs for a single stream KRES system for large ammonia or synthesis gas plants. The design concepts used are the same as used when designing the unit for PAI Kitimat, but some of the details are different. In arriving at the design for large-scale reforming exchangers, KBR considered the process parameters, mechanical limitations, and catalyst shapes.

9. Optimization of Process Parameters

Selection of process parameters is of great significance for achieving optimum design of the KRES exchanger. Details of these process parameters are discussed in the literature. (1) Some of the important process parameters are:

- Mixed Feed Inlet Temperature to KRES:
- Hot-end Temperature Approach:
- Fraction of Feed Gas Flow to KRES Exchanger:
- Table of Optimized Parameters

	Enriched Air	KAAPplusTM
Tube Inlet Temp °C	500 ~ 575	600 ~ 640
Tube Exit Temp °C	940 ~ 960	840 ~ 860
ATR exit Temp °C	~ 1000	940 ~ 960
Fraction to KRES	0.25 ~ 0.30	0.40 ~ 0.45

10. Limitation of the Diameter of the Tube Sheet

Based on KBR's experience in the design of the reforming exchanger for large capacity facilities, the maximum practical diameter of a high alloy tube sheet is about 3000mm. This is based on the use of an Inconel 601 tube sheet about 150mm thick. While this limitation is considered practical, it will normally result in the tube sheet being the critical path component in the reactor manufacture. It will also add cost to assure the quality.

Therefore, KBR has optimized the reactor inlet conditions, as indicated above, and provided additional design details to eliminate this potential critical path problem. These include reducing the mixed feed inlet temperature to ~ 580 to 610 °C and adding refractory (refer Figure 4) to the shell side face of the tube sheet. This assures a uniform temperature that is close to the temperature of the tube-side inlet fluid. The resulting design uses a lower grade material and has a thickness of about 110mm for the tube sheet. This design approach resulted in the tube sheet no longer being on the critical path for the reactor fabrication. Consequently, the maximum practical diameter of the tube sheet can be more than 3550mm. In other words, a major obstacle was removed to design single stream KRES exchanger for large capacity plants.

11. Further Optimization & Cost Reduction

KBR investigated the following items to further optimize design and reduce cost for KRES units for large-scale ammonia or synthesis gas plants.

Tube Size
The size of the reforming exchanger reactor is normally "heat transfer limited." In other words, the size of the reactor is set by the heat transfer rate, which can be achieved with the target design pressure drop. Typically, there is more than adequate catalyst volume for the kinetic reaction. Therefore the designer must pay particular attention to maximizing the heat transfer coefficients within the allowable pressure drop to achieve a low cost design. Based on previously established guidelines for catalyst/tube diameter ratio, reactors for large capacity facilities can become quite large in terms of exchanger designs. Therefore for reducing the cost of the equipment and for large capacity KRES units, KBR investigated smaller diameter tubes.

Catalyst Shapes, Size, and Testing
In 1998, KBR entered a collaborative agreement with Sud Chemie to investigate catalyst, which can enhance heat transfer, lower pressure drop, and result in lower reactor costs. Based on this collaborative effort, several catalysts types were identified which provide the necessary surface to volume ratio and shape that promotes turbulence and higher heat transfer coefficients. This effort lead to experimental testing at the KBR Technology Center located in Houston, Texas.

Three different shapes of catalyst were examined in detail. These included raschig rings of the same size as presently used in the PAI's reforming exchanger and two other catalyst types which bench scale testing demonstrated improved heat transfer performance. These catalyst types were tested to determine heat transfer and hydraulic performance. The test unit consisted of three different reactor tubes with IDs ranging from 25mm to 50mm and materials similar to a KBR commercial sized reforming reactor exchanger.

Results Of Tests and Optimization

Based on KBR's experimental results, correlations were developed for each catalyst type. In summary, we found the following:

- Tube side heat transfer coefficients for a target design pressure drop can be increased by 20 to 40% or even higher by using catalysts shaped specifically to enhance thermal performance.
- Improved heat transfer performance, use of the optimized process parameters and the use of smaller diameter tubes resulted in a KRES cost, which is 40 to 60% less than a PAI type of KRES design with 50mm tubes.
- This also results in a smaller diameter reactor shell and will allow practical designs well within the realm of fabrication experience for larger capacity facilities.

12. KRES Design For Mega-Ammonia Plant

In the last year, ammonia licensors are touting so-called "mega" ammonia plants--plants above 3,000 MTPD. KBR has concluded that its KAAP*plus*™ flow sheet is ideally suited for these extremely large-scale plants. Accordingly, we have put together designs for several capacities of single-train ammonia plants.

We started with a design for a 2,000 MTPD ammonia plant based on our KAAP*plus*™ process. ATR uses ambient air and the front-end is based on our Purifier design. Overall dimensions of the KRES exchanger in this plant are:

ID Shell = 2184 mm
Number of tubes = ~ 2070
ID of tubes = ~ 25 mm

As explained earlier, the maximum practical limit of diameter for the modified tube sheet design is 3550mm. Therefore, KBR can design single stream KRES units for much higher than 2,000 MTPD ammonia plant using proven features. Accordingly, KBR developed a preliminary design for a reforming exchanger for a 4500 MTPD ammonia plant. We determined that the size is within the capacity of several qualified fabrication shops. Some of the dimensions are as follows.

Shell ID = 3280 mm
Number of tubes = 5670
Tube ID = 25 mm

13. Single Train Capacity Limit

So what is the maximum capacity possible with KRES? Prorating the capacity from 4500 MTPD up to the maximum diameter of 3550mm implies a single-train design of about 5270 MTPD. If a pre-reformer is added to the flow scheme, the radiant duty can be reduced by 10 to 15 percent. This opens up the eventual possibility of 6000+ MTPD capacities.

14. Summary

- An enriched air KRES unit is in operation since October 1994 at PAI at capacities up to 350 MTPD
- KBR has highly optimized the design of KRES unit. This has resulted in a KRES cost, which are 40 to 60% less than a PAI type of KRES design.
- In the fall of 2001, KBR was awarded a contract to supply KRES technology for Shenzhen Liaohe Tongda Chemical Co. Ltd.'s 1070 MTPD ammonia plant revamp project, Liaohe, China. In this project KRES will reduce the natural gas consumption by 30 % and replace the energy with steam produced by a coal fired boiler.
- KRES system can be effectively used to increase capacity up to 50% and reduce energy consumption of the reforming section in an existing ammonia plant.
- KBR can design a single stream KRES system about 5000 MTPD ammonia plant.

15. References

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