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Research Article

Function of cascade compressors and power consumption optimization in ammonia liquefaction process: A system evaluation with a 6 sigma approach

Ahmet Ozan GEZERMAN[1*] Ali YETGİN[1]

[1] *Toros Agri Industry, Research & Development Center, Mersin, Turkey*

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*Corresponding author e-mail: ozan.gezerman@toros.com.tr

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ABSTRACT

Ammonia is stored as a liquefied raw material as it is used in the fertilizer and cooling industries. The use of multistage compressors during storage is essential, as the boiling point is very low (-33°C) due to a typical petroleum derivative. Because pressure-temperature optimization with a typical single-stage compressor does not allow ammonia to be stored under atmospheric conditions. The use of condenser and throttling valves used in cooling systems together with multi-stage compressors for storage in atmospheric conditions allows ammonia to be stored in liquid form during storage. In this study, a method has been developed to optimize the energy consumption by calculating the power consumption for the pressure and temperature conditions determined for the liquefaction of anhydrous ammonia, to improve the liquefaction conditions and to minimize the energy consumption.

Keywords: Ammonia, multi-stage compressor, power consumption, consumption optimization, compressor liquefaction capacity.

Amonyak sıvılaştırma işleminde kademeli kompresörlerin fonksiyonu ve güç tüketim optimizasyonu

ÖZ

Amonyak, gübre ve soğutma endüstrilerinde kullanıldığı şekli ile hammadde olarak sıvılaştırılarak depolanmaktadır. Kaynama noktasının tipik bir petrol türevi olması sebebiyle çok düşük (-33 °C) olmasından ötürü, depolama sırasında çok kademeli kompresörlerin kullanılması elzemdir. Zira, tipik bir tek kademeli kompresör ile basınç- sıcaklık optimizasyonu amonyağın atmosferik şartlarda depolanmasına izin vermez. Atmosferik şartlarda depolanması amacıyla, soğutma sistemlerinde kullanılan kondenser ve kısılma vanalarının çok kademeli kompresörler ile birlikte kullanımı amonyağın depolama esnasında sıvı halde depolanabilmesine olanak verir. Bu çalışmada, susuz amonyağın sıvılaştırılması için belirlenen basınç ve sıcaklık şartları için güç tüketim hesabı yapılarak enerji tüketiminin optimize edilerek, sıvılaştırma şartlarını iyileştirilmesi ve enerji tüketiminin minimize edilmesi için bir yöntem geliştirilmiştir.

Anahtar Kelimeler: Amonyak, çok kademeli kompresör, güç tüketimi, tüketim optimizasyonu, kompresör sıvılaştırma kapasitesi.

1. INTRODUCTION

Multistage compressors are used in many production sectors due to the number of cylinders they contain. Two-stage and two-cylinder compressors are the most widely used among multi-stage compressors.[1] However, the design of multistage compressors may differ according to the industry in which the pressurization will be performed.[2] Although multistage compressors are used for liquefaction processes, they are used with condensers, throttling and expansion valves, apart from compressors, for the storage of liquefied gases.[3] Therefore, many models have been developed for the design of compressors and other pressurization equipment.[4] These are formulated on the enthalpy changes and flow rate during the movement of the refrigerant in the liquefaction process.[5]

Another model developed for compressor design is the enthalpy differences caused by temperature differences and the mathematical model put forward due to these differences.[6] The dimensionless mass flow parameter

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defined in this model allows real results to be obtained under liquefaction conditions in measurements made in multistage compressors.[7] It forms the basis of another mathematical model in which enthalpy changes are calculated to determine the power consumption of multistage compressors.[8] “Mach number” is determined as an important parameter in the design of multistage compressors for ammonia liquefaction.[9] The Mach number is used to plot performance curves during the pressurization process [10]

Multi-stage compressors can provide a higher flow rate than single-stage compressors in ammonia pressurization – liquefaction process, thus providing a more efficient operating performance.[11] Multistage compressors consist of three parts. These sections are; The induction mechanism where the gas to be pressurized/liquefied enters can be expressed as the impeller system where the kinetic energy of the gas is increased during liquefaction and the discharge point after liquefaction.[12] A cooling system that allows storage at the discharge point can be used. Energy consumption in multistage compressors depends on the number of cylinders that compress. As the number of cylinders increases, the compression ratio will increase, so an increase in energy consumption is expected. The Mach dimensionless number approaches 1 depending on the increase in the number of cylinders, which means an increase in the performance value. In two-stage compressors, the temperatures reached during the compression process to the desired pressure, the enthalpy change in the compressor design, are among the parameters that determine the energy consumption of the compressors during the operating period.[13]

In this study, the compressor conditions that provide the ambient conditions for the storage of anhydrous ammonia under atmospheric conditions and the resulting energy consumption increase, and the results obtained are optimized. Because, with the optimization study here, it is aimed to prevent the energy consumption of the facility that performs the compression (pressurization) / liquefaction process and the system loss, leakage and unpredictable consumption of the raw material (ammonia).

2. MATERIALS AND METHODS

2.1. Materials

The power consumption in the ammonia liquefaction process by means of a two-stage two-cylinder Compressor can be expressed mathematically as follows.

$$P = \sqrt{3}.V.I.\cos\varphi$$ [14]

Here, V is the voltage in volts, I is the current in amperes, and cos ϕ is the phase difference between the current and voltage, and the cosine of this angle is the power factor. The most ideal situation is that the angle is close to 0, that is, the power factor is close to 1.

Here, when it is desired to calculate the amount of energy consumed for its operation at pressures for a two-stage two-cylinder compressor; Ampere value, 41 A, 6.3 kVolt, for a compressor operating at 100% capacity, the cos φ value measured at this amperage and voltage value is 0.88. The power consumed in this case

$$P = \sqrt{3} \times 6.3\ \text{kV} \times 41\ \text{A}.0.88 = 393\ \text{kW}$$

can be calculated as

In case the compressor capacity drops to 75%, the amperage value is 35 A, 6.3 kV. and the cos φ value measured at this amperage and voltage value was measured as 0.77. In this case, the power consumed for this process can be calculated as

$$P = \sqrt{3} \times 6.3\ \text{kV} \times 35\ \text{A}.0.77 = 291\ \text{kW}$$

In case the compressor capacity is reduced to 50%, the amperage value is 29 A, 6.3 kVolt, the cos φ value measured at this amperage and voltage value was measured as 0.75. Accordingly, when the expressed numerical values are substituted in the formulation, a calculation as follows can be made;

$$P = \sqrt{3} \times 6.3\ \text{kV} \times 29\ \text{A}.0.75 = 237.3\ \text{kW}$$

However, when the obtained consumption amounts are associated with the pressure value of the ammonia gassed in the ammonia tanks, it is necessary to express each ammonia pressure value mathematically by relating it to the electricity consumption. The energy consumption corresponding to each pressure value can be expressed mathematically by making typical interpolation between the measured pressure values in the ammonia tanks and the energy consumed by the compressors for pressurization. In this case, any instantaneous pressure change can be represented as follows.

P_1: Pressure value in ammonia tanks at 50% compressor operating capacity
P_2: Pressure value in ammonia tanks at 75% compressor operating capacity
P_3 : Pressure value in ammonia tanks at the compressor working capacity to be calculated
W_1: Amount of energy consumed to pressurize in ammonia compressor at 50% compressor operating capacity
W_2: The amount of energy consumed to pressurize the ammonia compressor at 75% compressor operating capacity
W_3: Pressure value in ammonia tanks at the compressor operating capacity to be calculated;

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$$\frac{(P_1 - P_2)}{(P_1 - P_3)} = \frac{(W_1 - W_2)}{(W_1 - W_3)}$$

Accordingly, in the optimization study carried out with reference to the amount of energy consumed for 50%, 75% and 100% capacities, it is the case that a single compressor consumes the least energy when it operates at 75% capacity. Because for such a case, when high tank pressures are taken as reference, at least 75% of energy was used for liquefaction.

3. RESULTS AND DISCUSSION

Ammonia is the most widely used industrial raw material. Storing ammonia in the industry where it is used requires the use of various equipment such as compressors. Maintaining the pressure-temperature balance with expansion and throttling valves in the refrigeration cycle of ammonia used with its refrigerant feature is an absorber system requirement. For a refrigeration system, ammonia is not stored under atmospheric conditions. Because ammonia consumption is not realized for such a system. However, due to production conditions, in systems where ammonia is used as raw material, ammonia consumption causes the steam pressure to vary in storage conditions.

Various mechanisms have been developed for the storage of ammonia for consumption. All the developed mechanisms require cryogenic conditions and include condenser, compressor and expansion valves (Figure 1). Depending on the climatic conditions in which the ammonia storage facility is built, the number of all equipment forming the storage mechanisms may differ. This number of equipment is a system requirement to be able to maintain ammonia at its solidification point under atmospheric conditions.

In ammonia storage systems, the amount of liquefied ammonia is directly related to the system pressure. System pressure is the most important parameter that determines the power consumption in the ammonia storage system. In the literature, the number of studies related to the liquefaction of ammonia and, accordingly, power consumption is very limited. Because parameters such as the type and number of compressors used during ammonia liquefaction directly affect the liquefaction capacity. The power consumption of the cascade compressors used to store ammonia at its boiling point also determines the energy costs of the ammonia storage facility. Studies of ammonia liquefaction and its energy cost so far are limited to single-stage compressors. In this respect, calculating the power consumption of multistage compressors and optimizing the day consumption for different pressure values will significantly affect the energy costs in ammonia storage facilities.

In this study, the amount of energy required during the liquefaction of ammonia needed in a facility using 75 mtons of anhydrous ammonia per hour was calculated. The use of multistage compressors during the Liquefaction of Ammonia process requires an optimization study in terms of energy consumed.

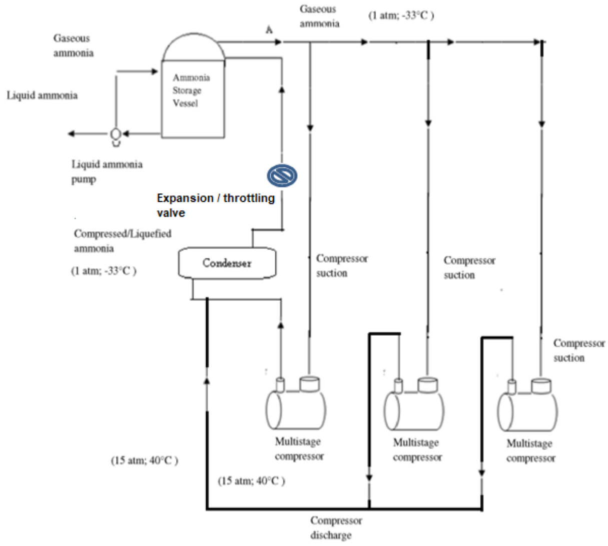

Figure 1. Ammonium liquefaction / storage system with 2-stage compressor system.

3.1. Energy consumed in the ammonia liquefaction process and optimization from a 6 sigma perspective

In order to optimize energy consumption for the ammonia liquefaction process according to the number of compressors and their capacities, the data shown in Table 1 were taken as reference and a "Box Plot" analysis, which is a 6 Sigma statistical analysis form, was performed over these values.

In the "Box Plot" analysis as an evaluation method that can be applied within the 6 Sigma quality management system, the Median and mode values show the most frequently observed energy consumption levels for the number and capacity of compressors used in the liquefaction system (Figure 2).

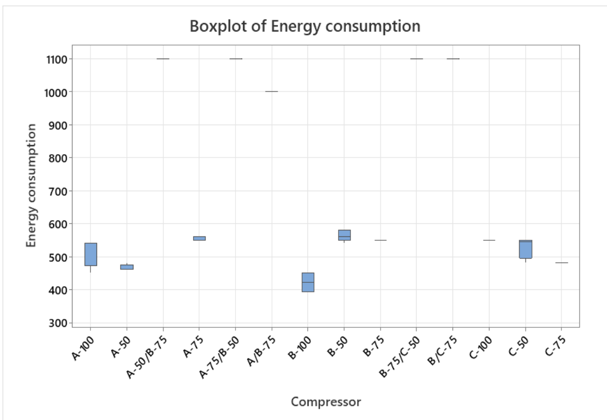

Figure 2. Box plot of compressor (number) and energy consumption (kWh).

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These findings can provide insights into the energy efficiency and performance characteristics of compressors, allowing for further analysis and optimization in terms of energy consumption.

Table 1. Number/capacity of compressors used and amount of energy consumed for the ammonia liquefaction process.

Compressor Number(A,B,C) and Capacity(%)	Energy consumption (kWh)
A(75)+B(75)	1000.0
A(75)+B(75)	1000.0
A(50)	470.0
C(50)	480.0
C(50)	480.0
A(50)	480.0
A(50)	460.0
A(50)	460.0
A(50)	460.0
C(50)	550.0
C(50)	550.0
C(50)	540.0
C(50)	540.0
B(50)	540.0
B(50)	580.0
B(50)	580.0
B(50)	550.0
C(50)	550.0
C(50)	550.0
C(75)	480.0
A(100)	450.0
B(100)	450.0
B(100)	393.7
A(75)	560.0
B(50)	560.0
B(50)	560.0
B(50)	560.0
B(75)	550.0
B(75)	550.0
A(100)	540.0
A(75)	550.0
C(100)	550.0
B(75)+C(75)	1100.0
B(75)+C (75)	1100.0
A(50)+B(75)	1100.0
A(50)+B(75)	1100.0
A(75)+B(50)	1100.0
A(75)+B(50)	1100.0
A(75)+B(50)	1100.0
A (75)+B(50)	1100.0
A(75)+B(50)	1100.0
A(75)+B(50)	1100.0
B(75)+C(50)	1100.0
A(100)	540.0
A(100)	540.0
A(75)	560.0

Statistical evaluation of the number of Compressors used during liquefaction and their energy consumption patterns provides valuable information for evaluating energy efficiency and identifying potential areas for optimization. Analysis of the mean, median, mode, standard deviation, range and count provides a comprehensive understanding of the energy consumption characteristics of each compressor. This information can be used to make informed decisions and develop strategies for energy optimization, leading to more efficient, sustainable compressor operations.

4. CONCLUSIONS

Due to its low boiling point (33°C), ammonia cannot be stored under atmospheric conditions. Compressors used to store ammonia in liquid form alone will not be sufficient to keep ammonia at its boiling point. Condenser and throttling valve are used to achieve this. In this study, liquefaction process was carried out with three two-stage two-cylinder ammonia compressors in three different pressurization capacities as 50%, 75% and 100% in ammonia pressurization process and energy consumption and compressor outlet temperatures were monitored during this pressurization process. When the compression pressure data obtained were examined, although the amount of liquefied ammonia increased as the pressurization capacity of a single compressor increased, the change in the pressure value did not change linearly in parallel with the increase in the capacity value. Therefore, in the interpolation study between pressure and energy consumption values, a predictable energy consumption model is presented for all pressure values according to the modeling process carried out throughout this study. It is seen that the pressure values caused by the amount of liquefied ammonia versus the amount of energy consumed by more than one compressor during compression during operation do not change significantly compared to 75% capacity, but energy consumption increases when more than one compressor is used. In this research study, a similar optimization study was carried out using the 6 sigma statistical analysis method and the compressor capacity needed in energy consumption was determined. In such a calculation model, considering the working capacity of the compressor and the amount of energy consumed, the amount of energy consumed versus the amount of liquefied ammonia is approximately 531.4 kWh, if a single compressor operates at 75% capacity, a plant that produces 2000 tons/day of fertilizer produces its own energy. It can be said that ammonia meets its own needs for the liquefaction process.

Conflict of interests

I declares that there is no a conflict of interest with any person, institute, company, etc.

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