COST BASED OPTIMIZATION OF INDUSTRIAL BULK COMPRESED NATURAL GAS FILLING FACILITY OPERATIONS

by

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In line with the increase in the world population, natural gas, which has an increasing share in fossil fuels, is nowadays transported throughout pipe-lines in the form of liquefied natural gas and compressed natural gas. Natural gas is preferred to be transported with compressed natural gas in terms of optimum cost. Compressed natural gas is reduced to a volume of 1/250 at 200 bar pressure in filling facilities and is transported to multi-element gas containers or gas tankers where pipe-lines do not reach. Although the highest cost for these plants seems to be gas transportation costs, the design, infrastructure and operational gaps, especially in plant management of the filling facilities constitute the costs that are not significantly visible. In parallel with the costs incurred, in this study, a pre-cooling process was actively applied for cost-based improvement in a bulk compressed natural gas filling facility, while operational optimization was aimed passively. The filling process of the facility in 2016 was examined according to real data and pre-cooling was made in 2017 by adding a "chiller" to the filling process to increase the filling rate to tankers. Thanks to the precooling in 2017, the filling amount made to tankers increased by 7.23%. In 2018, the filling process was analyzed in detail according to the data of 2017 and the factors affecting the filling rate were determined. According to these factors, the filling operation has been optimized on a cost basis. Filling operations in 2018 have been optimized for factors varying from month to month and even day, such as; temperature conditions, filling method, the structure of gas tankers and filling platforms, ie the effect of the material used, personnel effect and the filling rate of machines like chiller, compressor. After optimization, the amount of filling made in 2018 increased by 4.36% compared to 2017.

Key words: *compressed natural gas, filling rates, cost-based optimization, chiller integration*

Introduction

The life of oil, which was once thought to be the only energy source in the world and could change the borders of countries due to political interests, is now at calculable levels. Unlike oil, the fact that the amount of natural gas reserves found every year meets 10% of the world's annual natural gas consumption, drags the world towards the gas age.

Currently, international natural gas supply chain is developing rapidly and encountering an opportunity as well as challenge. Specifically, the natural gas transportation cost accounts for one-third of the total natural gas industry cost [1]. In the industry, while the market

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war is continuing between liquefied natural gas (LNG) and petroleum-derived fuels, natural gas is compressed and natural gas became an alternative to oil in the transportation sector. After the recent commercial approaches, compressed natural gas (CNG) was highly preferred in the industrial market in the world and was born as an alternative to fuels used in the industry. Although the highest cost for CNG filling and selling companies seems to be gas transportation costs, the design, infrastructure and operational gaps in facility management constitute the costs that are not significantly visible. In addition, for industrial bulk CNG filling plants, it was found that, the intercooling of compressors is not enough during the periods that the seasonal temperatures are high. This situation causes additional costs to the facility and at the same time it causes CNG filling to stop.

There are some studies on CNG in the literature. Bielaczyc *et al*. [2] presented a model for the optimization of the CNG fuel station. As a result of the study, it was observed that non-methane HC emissions were much lower when running on CNG, while HC emissions were somewhat higher. Dogan [3] in his study, designed the flow of the high pressure gas compressor which is located in CNG fuel filling stations as 180 Lph and manufactured it. The CNG compressor compresses the natural gas that it receives from the city network line with a pressure of 0.022 bar to 200-250 bar pressure and the compression process takes place in four stages. At the end of his work, he shared the pressure, flow and other tests he performed after manufacturing the compressor required at the stations for the filling of vehicles using CNG. In his study, Dogan [4] produced a four-stage, reciprocating type CNG compressor manufactured as a domestic type. The CNG enters the compressor at 0.022 bar pressure and exits at 200 bar pressure. Due to the high temperature during the compression of natural gas, intermediate cooling step compression was made in the compressor. During the study, the irreversibilities arising from the compressor and the cooling system were found by moving from the Second law of thermodynamics. Efficiency in the compressor was calculated by modelling isentropic, polytropic and isothermal state changes. In addition, the comparison was made by compressing both CNG and air using the same compressor in the study. Farzaneh-Gord *et al*. [5] thermodynamically modeled the fast filling process at CNG fuel filling stations, then aimed to minimize the filling time and finally focused on the optimal volume ratio of the reservoir tanks. Kagiri *et al.* [6], in their study, proposed to optimize the operation at CNG fuel filling stations in order to minimize energy costs and aimed to program the activities of compressors at CNG fuel filling stations in order to manage to minimize the cost of electricity purchased and used in their research. They also suggest that the effect of abrasion and wear will decrease in compressors that will operate at these times. Kagiri *et al*. [7], in their study, stated that the economical operation of CNG fuel filling stations will reduce the cost of fuel delivery and it will benefit consumers and it will be determined that the timing of the compressors in the current CNG fuel filling stations will be optimal and the energy costs will be reduced according to the electricity tariff used. Kagiri *et al*. [8], in their study, proposed optimum energy management strategies for CNG refueling station operations. It is stated that the energy consumption of the compressors is the main item in the total operating costs of the fuel filling stations. It is stated that the developed model reduces the compressor cycle and prolongs its life by providing potential savings of 59.3% in the daily electricity costs of the station. Khadem *et al*. [9] stated that one of the most important parameters in the design of CNG filling stations is a detailed rapid filling process modelling and in their study, they developed new mathematical modelling to analyze the rapid filling process in CNG stations. Beronich *et al*. [10] proposed equations of state for CNG applications. It is stated equations of state for CNG applications is highly dependant on the composition of the gas and the conditions (*e.g*. pressure). Niazmand *et al.* [11] carry out a numerical analysis for reciprocating compressors used in CNG stations is studied thermodynamically for ideal model and real one. Effects of important design factors on entropy generation, isentropic and exergy efficiencies were investigated. Nanthagopal *et al.* [12] examined the hydrogen enriched compressed natural gas (HCNG) usage in case of internal combustion engines. It has been concluded that HCNG fuels pave the road for the use of hydrogen vehicles in the future due to expensive after treatment technologies. Kaleemuddin and Rao [13] in their study, base diesel engine converted into spark-ignition mode to employ gaseous fuels (LPG and CNG). It has been proposed that CO_2 emission is lower with CNG operation and thus can be a eco-friendly operation. Sremec *et al.* [14] examined the effects of excess air ratio and engine speed on the performance and emissions of CNG fuelled spark ignition engine. As a result of the study, due to the reason of the fact that natural gas has higher octane rating than gasoline, it has been possible to use high compression ratios. Saadat-Targhi *et al.* [15] found that reciprocating compressors are the heart of CNG fuel filling stations and the main cost of the station is due to compressor operation. It was stated that the results of the current study were confirmed against previous experimental data and theoretical studies, and the simulation results of the mass-flow rate were compatible with the experimental data. The study revealed that compressor energy consumption for one cycle is 61.86 kWh and the average energy consumption for filling a vehicle is 0.25 kWh/kg.

There are more studies about auto CNG stations that filling vehicles in the literature. Past studies are limited to the perspective of saving money in filling facilities that load gas on vehicles, changing the electricity tariff used and filling in when electricity can be purchased at a lower cost. No studies have been found in the literature for bulk CNG filling facilities that are established or operated to meet industrial needs. With this study, the gap in the literature regarding the optimization of industrial bulk CNG filling plant operations will be eliminated. In this study, pre-cooling was done by adding a chiller to the process to increase the filling rates to tankers in an operated bulk CNG filling facility. In addition, the points that need to be improved in the filling process were determined and the operation was optimized on a cost basis. With this study, the result of active-passive based improvements on a bulk CNG filling facility is expected to be beneficial for operators.

Material and method

When the filling data of 2016 is examined in a bulk CNG filling facility in operation, it is seen that in order to increase the performance of the facility, it is aimed to increase the amount of filling made to tankers. For this purpose, the chiller was added to the process and the filling of 2017 was completed by pre-cooling. The CNG filling facility, which is established and operated on a land of approximately 8000 m^2, was designed in a simple structure, fig. 1. The main equipment of the facility is consists of machinery, equipment, *etc.* necessary for the operation of the energy or facility constitutes infrastructure elements, such as: gas regulation and the metering unit, compressor station, filling platforms, administrative and technical offices, transformer, fire pump, and generator.

The natural gas entering the facility first passes through the regulation and measurement unit of the local gas distribution company with a measurement capacity of 7000 m^3/h. The gas exiting the metering unit enters the compressor station where the compression process is performed. The filling facility has two CNG compressors, with a capacity of 6300 m^3 per hour and 3000 m^3 per hour. These compressors are three-stage, compress the natural gas supplied in the 35-70 bar pressure range up to 200 bar pressure and press it towards the filling platforms as shown in fig. 2 to be filled with tankers.

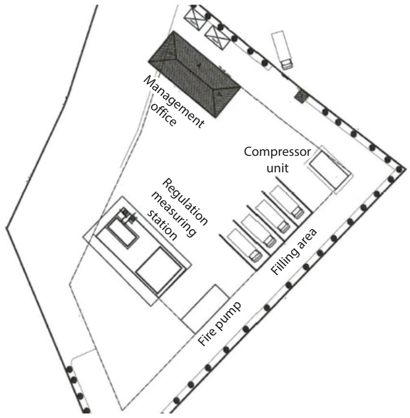

Figure 1. Filling facility lay-out plan [16]

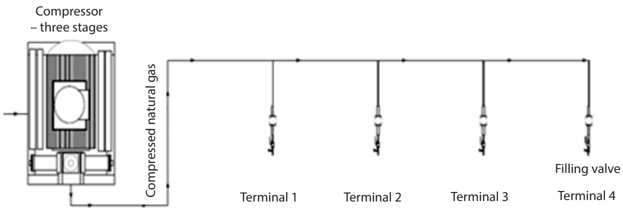

Figure 2. Schematic representation of the precooled filling process [16]

In the CNG filling facility in operation four different capacity tankers as: consisting of 150 L liquid volume tube bundles, 60 units, 120 units and 145 units tube tankers connected in series, and, 108 tubes each of which consists of *90 L liquid volume* tube bundles, connected in series are used. The capacities of the tankers used are 9000 L, 9720 L, 18000 L, and 21750 L, respectively.

The CNG filling facilities have high initial investment costs, so, in order to maintain its profitability and operate efficiently for years, operation costs are very important. The most important of the operational costs in these facilities is the amount of transportation at once. One of the steps that can be taken to increase the amount of transportation at once is to use a higher capacity tanker. Delivering to the point where the gas will be supplied with higher capacity tankers will increase the amount of transportation at once. Another method is to select the working pressures of CNG tubes in tankers from the ones that 250 bar, not 200 bar. Even those with higher working pressure can be selected if possible. In this way, it is possible to load at higher pressure, hence more gas. When CNG facilities are examined, it is seen that high pressure is needed to fill the gas and it is seen that compressors that provide this condition are used. Although the compressors have certain set values, the compressor stops when the compression end pressure of the gas in the compressor reaches the working pressure values of CNG tubes. It is observed that, after a certain period of time, the CNG tanker pressure has decreased slightly compared to the working pressure.

The difference pressure, ΔP, between the compressor outlet pressure and the tanker pressure should be interpreted. One of the reasons why ΔP is high is that gas denseness and pressure losses on the line, such as valves, quick coupling equipment, elbows and reductions, which will narrow the flow or make flow difficult, while gas filling at high flow continues. Another reason is that the temperature of the CNG increases rapidly as the pressure of the tube increases during the filling of the tubes. At this point, it is necessary to lower the temperature of the filled gas to reduce, ΔP. The effect of gas temperature on gas pressure is very high during the CNG filling stage. The most effective solution be done in this regard is to integrate a chiller into the system after the compressor outlet line and to ensure that CNG cools before entering the tanker.

In order to reduce ΔP, purchasing smaller capacity compressors to slow down the flow or having new tankers built to increase the number of simultaneous fillings is difficult to decide in terms of cost for operators. Therefore, the most suitable method to be implemented should be the chiller cooling system, which is relatively less costly than other investments. Schematic view of the pre-cooled CNG filling facility which is shown in fig. 3, added to the filling process within the scope of the study in order to increase the low fillings in hot periods and reduce the fluctuation during the year. The CNG, whose temperature rises at the exit from the compressor, is thought to be cooled before it starts to fill the tankers.

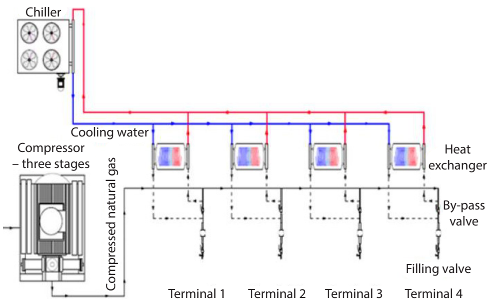

Figure 3. Schematic representation of the pre-cooled filling process [16]

A shell and tube heat exchanger was added to the entrance of each platform and the cooling water added to the process by chiller pulled heat from CNG, allowing the natural gas to cool. In this way, with the decrease in ΔP, there will be more filling and the amount of transportation will increase.

In order to measure the filling performance of the facility, it is necessary to compare the amount of gas filled to tankers of different capacities with reference to the ideal gas equation. In this study, the Redlich-Kwong empirical equation developed by Kwong *et al.* [17], was taken as reference in explaining the behavior of non-ideal gases at critical temperatures. Pressure is calculated:

$$P = \frac{R_u T}{V_m - b} - \frac{a}{\sqrt{T} V_m \left(V + b\right)} \tag{1}$$

where a and b constants are found as:

$$a = \frac{1}{9\left(\sqrt[3]{2} - 1\right)} \frac{R_u^2 \, T_c^{2.5}}{P_c} = 0.42748 \frac{R_u^2 T_c^{2.5}}{P_c} \tag{2}$$

$$b = \frac{\sqrt[3]{2} - 1}{3} \frac{R_u \, T_c}{P_c} = 0.08664 \frac{R_u \, T_c}{P_c} \tag{3}$$

where P [atm] is the gas pressure, R_u [atmLg^{-1}mol^{-1}K^{-1}] – the universal gas constant, T [K] – the gas temperature, V_m [Lg^{-1}mol^{-1}] – the unit mol volume of gas, T_c [K] – the critical temperature of the gas, P_c [atm] – the critical pressure of gas, a – the corrective constant for the bond strength of gas molecules, and b – the volume represents a corrective constant.

These constant values vary depending on the gas analyzed and are calculated according to the critical pressure and critical temperature values of the gas. The reduced pressure and temperature are determined:

$$P_r = \frac{P}{P_c} \quad T_r = \frac{T}{T_c} \tag{4}$$

$$P_r < \frac{T_r}{2} \tag{5}$$

The Redlich-Kwong equation is sufficient to calculate the gas phase properties in cases where the reduced pressure of the gas is less than half of its reduced temperature. The critical pressure and critical temperature values of natural gas vary depending on the type and amount of gases in the composition. For this reason, in order to calculate the critical pressure and critical temperature of the natural gas used in the compression process, it is necessary to know the percentages of the mixed gases contained in the mixture and calculate the effects of the critical pressures and temperatures of each gas on the mixture. For this, the values obtained by multiplying the mix percentages and the critical temperature, critical pressure and molar masses of the gases show the effects of the gases on the mixture. In this way, the average critical temperature of natural gas is calculated as 197.58 K, average critical pressure is 46.10 atm and the average mole weight is 17.38 kg/kmol.

The compressibility factor and constant, h, are expressed:

$$h = \frac{BP}{Z} = \frac{b}{V} \tag{6}$$

$$Z = \frac{1}{1-h} - \frac{A^2 h}{B(1+h)} \tag{7}$$

where variables A^2 and B here are expressed:

$$A^2 = 0.42748 \frac{P_\mathrm{r}}{T_\mathrm{r}^{2.5}} \tag{8}$$

$$B = 0.08664 \frac{P_\mathrm{r}}{T_\mathrm{r}} \tag{9}$$

where A^2 and B [atmL^{-1}] are the refers to variables depending on the reduced pressure and temperature of the gas, h is the volume dependent corrective constant, and Z – the compressibility factor of the gas. The volume of gas filled into the tanker is calculated:

$$V_\mathrm{b} = KV \tag{10}$$

Correction coefficient is calculated:

$$K = \frac{P}{P_\mathrm{b}} + \frac{T}{T_\mathrm{b}} + Z \tag{11}$$

where K is the correction coefficient, V [L] – the filled tanker volume, P [bar] – the measured absolute pressure of the tanker after filling, P_b [1 atm] – the pressure in ideal conditions, T [K] – the measured temperature of the tanker after filling, and T_b [298 K] – the ideal temperature.

In line with the stated equations, if the working pressure of the tankers is resolved according to the reference temperature of 200 bar, that is, 197.378 atm and 298 K. The compressibility factor is calculated as 1.2571 and the average natural gas amount to be filled in 1 liter unit volume is 0.24399 m^3.

In addition the stated natural gas filling amount calculations, the electricity costs related to the motor powers of the compressor and chiller are calculated in comparison the amount that is overfilled in the existing facility:

$$E_\mathrm{consumed} = EL_\mathrm{f}t \tag{12}$$

where E_consumed is the total energy consumed by the chiller and compressor in return for extra filling, E – the total load of the chiller and compressor, L_f – the load factor, and t – the time.

Results and discussion

Cost based optimization of filling facility

The gas coming to the CNG filling facility is compressed by the help of a compressor and delivered to the filling platforms, where CNG is loaded to the tankers with the help of filling valves. The data of the refills made by the facility from 2016-2018 were recorded and were analyzed with MINITAB program. The filling quantity is shown in fig. 4 as annual-average. According to the annual average data of the refills made without precooling in 2016, 0.21365 m^3 per litre filling was made for 9000 litres capacity tankers. Filling was done at the level of 0.23028 m^3 per litre for 9720 litres tankers, 0.23711 m^3 per litre for tankers with 18000 litres capacity and 0.21999 m^3 per litre for 21750 litres tankers.

The overall performance of the plant is 0.22789 m^3 per liter for all fillings. According to the Redlich-Kwong empirical equation, the amount that should be under the reference conditions of 197.38 atm 15 °C is 0.24939 m^3 per litre, and according to this reference value, the overall performance of the facility in 2016 was calculated as 91.38%. In the refills without precooling, the *change of tanker refills on a monthly basis according to the tanker variety* is shown in fig. 5.

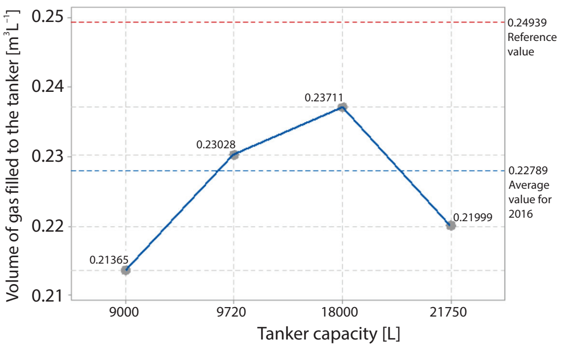

Figure 4. Annual average performance of pre-cooled refills (2016)

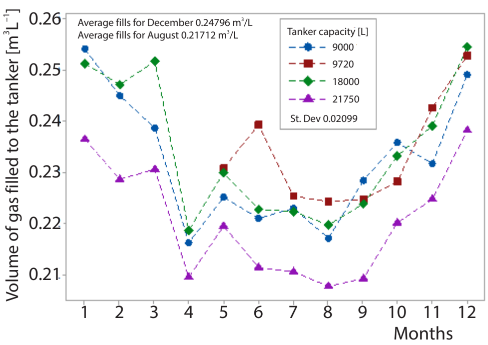

Figure 5. Monthly change of tanker refills in without pre-cooled refills (2016)

Accordingly, the first noticeable thing is that the refills made in the summer months are much less than the winter months. While the average of tanker level was 0.24796 m^3 per litre in December when the fillings were highest, this rate remained at 0.21712 m^3 per litre in August when the fillings were the lowest. It was observed that the difference between 2 months was 14.2%.

In 2017, tanker refills were made by pre-cooling by using a chiller. The annual average performance of the refills made in 2017 after the pre-cooled process is shown in fig. 6. Accordingly, 0.24582 m^3 per litre filling made for 9000 litres capacity tankers, 0.24582 m^3 per litre filling made for tankers with 9720 litre capacity, 0.24606 m^3 per litre filling made for tankers with 18000 litre capacity, and 0.23963 m^3 per litre filling made for tankers with 21750 litres capacity.

The overall performance of the facility is 0.24377 m^3 per liter for all fillings. According to the Redlich-Kwong empirical equation, the overall performance was completed at 97.98% with an increase of 6.6% compared to 2016. The use of chiller also affected the overall distribution of the process. The tanker filling volumes of the pre-cooled filling facility in 2017 are shown in fig. 7, and it has been observed that the filling quantity has improved compared to

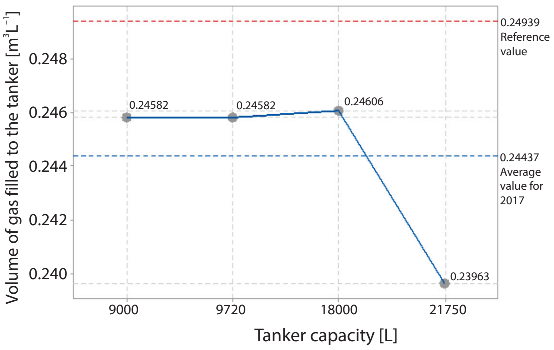

Figure 6. Annual average performance of pre-cooled fillings (2017)

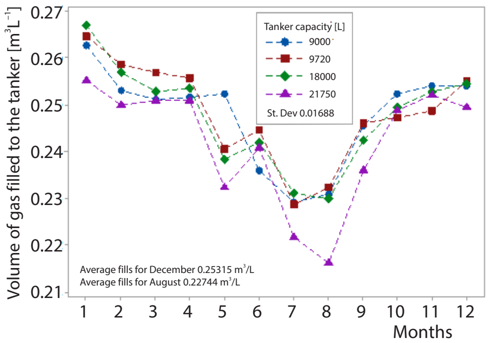

Figure 7. Monthly change of tanker filling in the pre-cooled filling (2017)

2016. While the process standard deviation value of 2016 was 0.02099, this value decreased to 0.01688 in 2017.

According to another data obtained, the tanker level was 0.25315 m³ per litre in December when the filling was high, while this ratio remained at 0.222744 m³ per litre in July when the filling was low. The difference between two months decreased by 2.9 points compared to 2016 and reached 11.30%. Precooling has reduced the distance between the endpoints of the process, that is, reducing the standard deviation, making the process more stable. It also increased refills per liter and reduced operating costs of the facility.

Filling in the facility was made without precooling in 2016 and tankers were loaded with 0.22789 m³ gas per liter. After the chiller was added to the process in 2017, the fillings were precooled and 0.24377 m³ of gas per liter was loaded into the tankers. In 2017, there was a 7.23% increase in efficiency in filling in tankers compared to 2016. Loading more gas on the tankers increased the amount of transportation at once. Therefore, it is seen that less shipping will be needed to sell the same amount throughout the year. The facility data to be used in the reimbursement period calculation is presented in tab. 1 in order to calculate the reimbursement period of the investment according to the savings from the annual shipment and the cost of chillers. In this case the purchase price of chillers is taken from the facility as the first investment cost. Transfer unit charge is also taken from the agreement made between the facility and the transportation company. The electricity cost is taken from the energy market regulatory authority (EMRA).

The average tanker filling in 2016 was calculated as 3910.13 m³. A similar performance would have been achieved in 2017 if the process had not been modified. However, pre-cooling was added to the process in 2017, resulting in an efficiency increase of 7.23%. Based on this increase, the average tanker filling in 2017 was 4192.13 m³. Transporting more gas at one time, that is, increasing the amount of transportation at once will also decrease the number of annual shipments. According to this, according to the data of 2016, 3201 shipments were made, while in 2017, 2985 shipments were made.

One of the important expenses for such businesses is transportation costs. To make the pre-cooled filling with chiller integration the system, the facility has saved 216 shipments per year. Based on this, the annual saving fee can be obtained by multiplying, the number of shipments saved, the average shipping distance (km) of the facility and the price paid for the shipment per km. Thus, with the addition of a chiller to the facility, the annual saving amount was calculated as 18348.44 $ with the pre-cooling process.

Table 1. Facility data to be used for the return on investment

Analysis of data	
Total filling amount (2017)	12516587 m³
Average unit filling amount (2017)	0.24437 m³ per litre
Average tank capacity (2017)	17158 L
Average transfer distance (2017)	197.55 km
Transfer unit fee (2017)	0.43 $/km
Chiller purchase price	34,212 $
Average unit filling amount (2016)	0.22789 m³ per litre
The unit filling amount according to reference conditions	0.24939 m³ per litre
Compressor power	355 kW
Compressor flow	6300 m³ per hour
Chiller power	93 kW
Load factor	75%
Electricity charge including all taxes	0.0656 $/kW

Thanks to pre-cooling, tankers were filled with 7.23% more gas. The filling amount realized with this efficiency increase is 12516587 m³ per year. If there was no pre-cooling process, the filling amount to the tankers would be 11672654 m³. Therefore, it is determined that 843933 m³ of extra filling is made annually. To make this filling, the chiller and compressor were operated more, and it was calculated that the chiller and compressor worked 134 hours more per year. The energy consumed in excess per year was calculated as 45024 kWh according to the eq. (12). Accordingly, annual electricity expense was calculated as 2965.3 $. The pay-back period is calculated as two years and three months by proportioning the chiller purchase price to the annual net savings. Maintenance and repair costs, interest and inflation rates are not included in the calculation of the pay-back period.

Operational optimization of the facility filled with pre-cooling

Optimization according to environmental factors

Environmental factors are temperature-dependent factors. Temperature differences between months, shifts filled and start time of filling are the functions of the temperature. The filling rates that take place depending on the average air temperature taken for Antalya from the web page of the General Directorate of Meteorology are shown in fig. 8. As can be seen from the figure, filling rates decrease when the air temperature is high. It is observed that the filling rates in the cold months are higher than in the hot months.

When the data of the whole year, which is another environmental factor, for the filling effect of the shift is examined. The filling rate was 103.2% in the second shift, namely at night, while the filling rate remained at 101.58% during the day shift. It was determined that the fillings made in the night shift between two shifts yielded 1.62% efficiency compared to the day shift.

To fill the night shift instead of daytime, tanker refills should be delayed by 6-10 hours depending on the situation. Since tankers are one of the most expensive equipment, and they are at a minimum amount in the facilities, it is not possible to plan the filling after approximately

8 hours in order to deliver gas. Instead, it is more feasible to select the time zone that will start filling rather than the shift at the maximum level of filling, and the efficiency will be higher. For this reason, the change of filling rates at the facility according to the filling hours is presented in fig. 9.

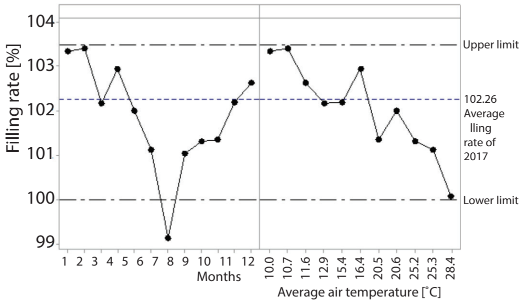

Figure 8. Filling rates depending on the temperature varying from month to month

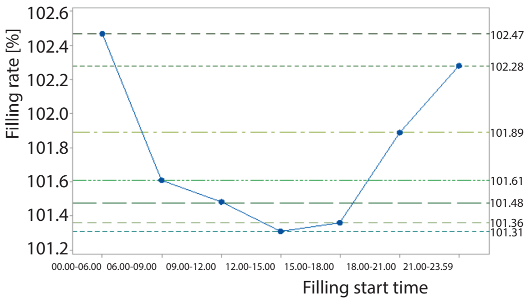

Figure 9. Filling rates varying according to filling start time

In 2018, the highest filling rates were reached in the slice, which started between 21.00 and 06.00, and the lowest filling rate was in the filling between 12.00 and 18.00.

Optimization according to the filling method

Running the compressors by cascade method is called a sequential filling. Tanker filling is started first with a compressor with a capacity of 6300 m³ per hour (large compressor). High flow means high gas temperature, so the sequential filling method is applied to slow down the flow and temperature, and filling continues with a compressor (small compressor) with a capacity of 3000 m³ per hour when the tanker pressure reaches 180 bar. The filling rates according to the ordered filling pressures are shown in fig. 10.

The sequential filling pressure determined by the facility for the process and applied in 2018 was determined as 180 bar. However, according to real data, if the small compressor can be started after at 160 bars or before, instead of after 180 bars, more filling rate can be obtained. It should be remembered that the filling time will increase when switching to lower-order pressurization. In such cases, if the tanker pressure drops below 200 bar, it can be refilled. This method to be applied is an additional filling application.

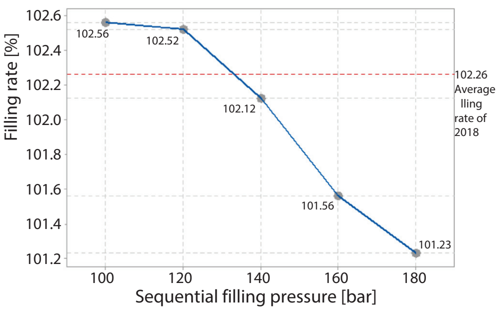

Figure 10. Filling rates varying according to sequential filling

In order to analyze the results of additional filling at the facility, 57 test fillings were made using tankers with the same capacity. After the filling of the tankers has been completed, some of them wait for 1 hour, some for 1.5 hours and the rest for 3 hours, and the effect of holding times on the filling rate is examined. It is possible to provide close to 1% improvement in the filling rate between the tanker waited for 1 hour and the tanker waited for 3 hours. The important point is to be able to create the filling & ordering operation that will enable tankers to be kept waiting.

One of the most important factors that will affect tanker refills is the volume loaded with gas. For this reason, by increasing the volume, ΔP decreases and filling rates will increase. The effect of the number of tankers filled on the filling rate is presented in fig. 11. The rate remained at 100.45% for 1 tanker filling, while the rate reached 102.74% after 4 tankers filling at the same time. As a result, a difference of 2.29% was achieved between the 2 operative options. This increase, compared to the increase in filling rates with the pre-cooling application the CNG filling facility was lower.

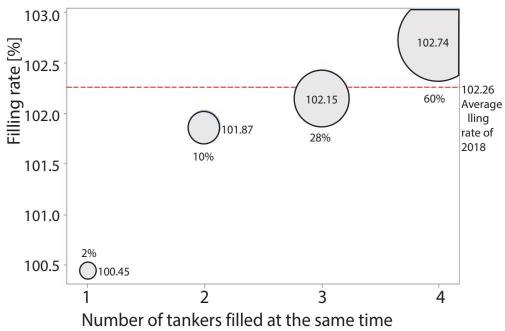

Figure 11. Filling rates varying according to the number of tankers filled at the same time

The filling operation in 2018 was very well optimized. The number of tankers filled at the 4-platform facility at the same time reached 3.45 on average. As can be seen from the graphic, three or four tankers were filled simultaneously in 88% of the fillings. In this way, an increase in filling rates was achieved.

The effect of compressor capacity on filling rates is shown in tab. 2. According to this, it was found that, working with compressors with lower capacity in order to slowing down the flow and decrease the filling temperature, increases the filling rates more.

Table 2. Filling rates according to compressor capacities

Compressor capacities [m^{3}h^{-1}]	Filling rates [%]	End-of-filling temperature [°C]
3000	102.85	14.15
6300	101.14	17.02

While the filling with the small compressor with a capacity of 3000 m^3 per hour of the two compressors used in the facility resulted in a filling rate of 102.85%, the filling with a large compressor with a capacity of 6300 m^3 per hour was completed with a filling rate of 101.14%. While at the filling with large compressor, the end-of-filling temperatures result in 17.02 °C, this value remained at 14.15 °C when the filling made with a small compressor. The fact that the high filling flow increased the temperature at the time of filling, also affected the filling rates.

Apart from the pre-cooling process carried out in 2017, it is thought that approaching the filling and shipment planning more precisely will increase the filling rates. For this reason, awareness of the operation was targeted as passive improvement in 2018. Factors affecting filling performance and root causes were determined and the effect of these factors on filling rate was analyzed. The determining factors are environment (month, shift, filling start time), method (sequential filling, additional filling, multiple filling) and machine (compressor, chiller). The data received from the facility were analyzed with the help of a statistical analysis program. Filling operations in 2018 were carried out with the awareness of eliminating the effect of the identified root causes partially or completely.

Annual average performances of pre-cooled and optimized refills are presented in fig. 12. In 2018, filling was completed at the level of 0.25569 m^3 per litre for 9000 litres capacity tankers, 0.25584 m^3 per litre for 9720 litres capacity tankers, 0.25594 m^3 per litre for 18000 litres tankers, and 0.225267 m^3 per litre for 21750 litres capacity tankers. The overall performance of the facility is 0.25504 m^3 per liter for all fillings. According to the Redlich-Kwong empirical equation, the filling rate was completed by 102.26%, increasing by 4.28% compared to 2017.

The difference between the endpoints of the summer and winter months was calculated as 11.3% in the filling in the facility in 2017. In 2018, the operation was optimized and the difference between the endpoints of the summer and winter months decreased by 3.47% compared to 2017 and reached 7.83%. As a result, the overall distribution of the process in 2018 has improved compared to 2017, and the monthly change of tanker refills at the pre-cooled and optimized CNG facility is presented in fig. 13. While the process standard deviation value of 2017 was 0.01688, this value decreased to 0.00746 in 2018.

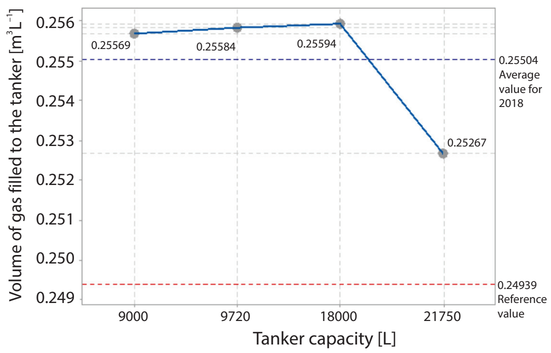

Figure 12. Annual average performance of pre-cooled and optimized refills (2018)

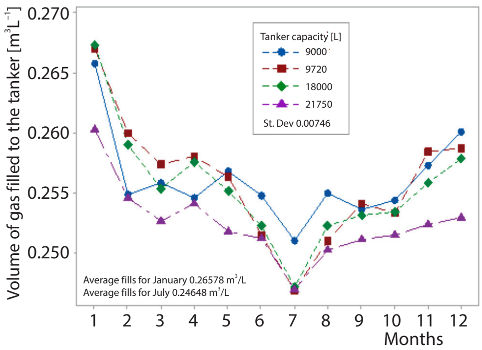

Figure 13. Monthly change of tanker refills in pre-cooled and optimized refills (2018)

Overall evaluation of pre-cooled and no-pre-cooled optimized CNG facility

In addition investing in CNG filling facilities, accurate identification of the process, accurate measurement and detailed analysis of the results also provide opportunities for improving the operation. In order to clarify this situation, the filling was carried out only in July 2018, without precooling. It is aimed to determine the efficiency to be achieved only by optimization of operation without pre-cooling. The variation of the filling volumes made in July 2016 and August of 2018, according to the tanker capacity is shown in fig. 14.

In July 2016, the overall average of the process was 0.22001 m³ per litre, and the performance of the process was 88.22% compared to the reference value. In 2017, the process was actively improved and after adding precooling to the process, the overall average was 0.222744 m³ per litre and overall performance increased to 91.2%. In 2018, pre-cooling was not used in the fillings, only through passive improvement, filling optimization was carried out. The overall average in July 2018 was 0.24648 m³ per litre and the overall performance of the process resulted in 98.83%. In August 2018, the facility was operated both pre-cooled and optimized. Thus, the overall average was 0.25058 m³ per litre and the overall performance of the process was calculated as 100.47%.

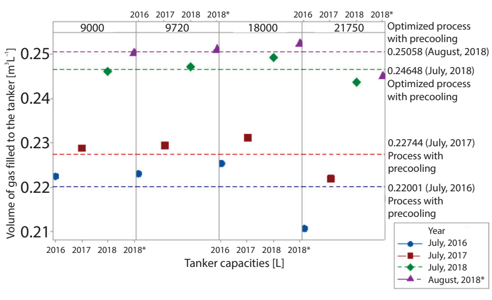

Figure 14. Change of filling quantities made in different processes according to tankers

Conclusion

The results obtained from the study will be very useful for the organizations who want to establish an industrial bulk CNG filling plant and who are operating. In addition, this study will contribute to the gap in the literature regarding the optimization of industrial bulk CNG filling plant operations.

It was found that the industrial bulk CNG filling plant achieved a 91.38% filling rate in 2016, with the pre-cooled process. In order to increase the filling rates of the facility within the scope of the study, the work was started and the chiller was added to the filling process. Chiller was added between the compressor outlet and the tanker filling valve in the process, and all the fillings were pre-cooled using chiller in 2017.

At the end of the 2017 when the datas examined, it was observed that the filling rate was 97.98% after the pre-cooling process. Thus, the facility's volume of transport increased by 7.23%. All these improvements have saved the facility a net savings of 15393.11$ per year, after calculating the electricity costs spent on this business, according to 2017 data. The 34212.3$ investment for chiller repaid itself in about 2 years and 3 months.

Filling operations in 2018 were carried out with the awareness of eliminating the effect of the identified root causes partially or completely. According to this, in 2018 with an increase of 4.28% compared to 2017, the filling rate of the facility was completed by 102.26%. Cost based optimized of the operation giving the facility flexibility in operating costs in response to changing conditions.

Within the scope of the study, the effect of temperature on the filling rate in the environmental factor was examined. Shifting the fillings to the night shift as much as possible or paying attention not to fill at noon at the peak of the Sun will allow tankers to load more gas. There is no option such as not to refill in the summer, but during these periods, approaching the operation more precisely, loading more gas and this will provide the company with cost flexibility.

Increasing the volume filled with gas will decrease the differential pressure of ΔP and the filling rates will be higher. For this reason, instead of filling a single tanker to increase the volume, it is necessary to plan the filling of two tankers or the number of the tanker as much as the number of platforms in the facility at the same time considering the shipment status.

All these methods to be applied are one of the most effective options for increasing the filling rates. Therefore, the goal of the facilities should be to perform filling operations with a low capacity compressor, by predicting critical times when customers can order gas, or to lower the sequential filling pressure. If there is only one compressor in the facility, a sequential pressurization effect can be created by reducing the inlet valve of the compressor and reducing the capacity of the compressor after the appropriate pressure determined, but this time the efficiency of the machine used will be reduced. If there is more than one compressor of the same capacities in the facilities and there is no problem in their operation at the same time, the filling can be done by applying the cascade system. It will be very useful to turn off the compressors in sequence after the appropriate pressures and complete the filling with the last single compressor to increase the filling rate. Cascade application can be done manually or automatically by planning a frequency inverter or a similar automation system.

In addition investing in CNG filling facilities, accurate identification of the process, accurate measurement and detailed analysis of the results also provide opportunities for improving the operation. In order to elaborate on this situation, in July 2018, the refills were made only with operation optimization without pre-cooling. In July 2016, the overall average of the process was 0.22001 m^3 per litre, and the performance of the process was 88.22% compared to the reference value. After adding precooling to the process in July 2017, the general average was 0.22744 m^3 per litre and the overall performance increased to 91.2%. In 2018, the process did not use pre-cooling, only filling optimization was performed. In July 2018, the general average was 0.24648 m^3 per litre, while the overall performance of the process resulted in 98.83%. In 2018, the filling optimization of the pre-cooled process was carried out and in August, the general average was 0.25058 m^3 per litre, while the general performance reached 100.47%.

In 2017, with active improvement by using pre-cooling, 97.98% filling performance was achieved throughout the year. However, in July 2018, without pre-cooling and only through operational optimization, filling performance of 98.83% was achieved. According to these data, it is seen that operational optimization has increased more than the efficiency increase provided by pre-cooling. However, under normal circumstances it will not be possible to provide this operational preciseness. It is considered that it is more convenient to make gas filling with pre-cooling. At the filling plants, providing the gas supply must always be more important than focusing on increasing the efficiency. In terms of the results were obtained and continuing supply, adding chillers to the process seems to be the most appropriate method in bulk CNG filling facilities, to achieve the targeted increase in filling rates. In brief, adding chillers in accordance with the investment plans of the bulk CNG filling facilities planned and operated, will always increase their competitiveness in the sector.

Nomenclature

E – total load of the chiller and compressor, [kW]
E_{consumed} – total energy consumed, [kWh]
K – correction coefficient
L_f – load factor
P – gas pressure, [atm]
P_b – pressure in ideal conditions, [atm]
P_c – critical pressure of gas, [atm]
P_r – reduced pressure
R_u – universal gas constant, [atmlg^{-1}mol^{-1}K^{-1}]
T – gas temperature, [K]
T_b – ideal temperature, [K]
T_c – critical temperature of the gas, [K]
T_r – reduced temperature
t – time, [h]
V_m – unit mol volume of gas, [lg^{-1}mol^{-1}]
V_b – volume of gas filled into the tanker, [l]
V – volume of filled tanker, [l]

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