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Investigation of Energy Performance Improvement in a Natural Gas Compressor Stations via Reduce Compressed Gas Temperature through Heat Pipes

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Abstract: Natural gas compressor stations in gas transmission industries cause to increase gas pressure and discharge to gas transmission pipeline. Air coolers in compressor station, have high electrical energy consumption and pressure drop. In this investigation, the application of heat pipe heat exchangers (HPHE) in a case study of the gas compressor station is evaluated to use instead of air coolers. The result of the investigation shows that applying 620 heat pipes with a 50% filling ratio, working fluid R134 and arranged triangularly, can reduce the compressed natural gas temperature. Energy performance analysis shows that using this method improves total, thermal, and electrical energy performance indicators (3%, 2.4 %, and 78%, respectively). Also simulating process demonstrate that using HPHE cause to save 1,115,000 SCM fuel in gas turbine and 3,800 MWh electrical saving in air coolers. In addition, results show with using HPHE 2,615,000 $ cost saving is available and project payback period value less than 1 year evaluated, and avoiding 1652 ton CO2 emission estimated annually.

keywords: Energy performance; Natural gas Cooling; Heat pipe.

1. Introduction

In recent years, the use of natural gas for power generation and industrial purposes has increased significantly (Cascio, Borelli, Devia, & Schenone, 2018). Natural gas compressor stations are used along transmission pipelines to create the pressure needed to move natural gas in pipelines. On the other hand, due to the pressure drop in the gas transmission network, several gas compressor stations are required (Bianchi, et al., 2019). The location and pressure required for natural gas compressor stations are determined by permissible pressures, available power, and geographical and environmental factors because the pressure drop is highly dependent on elevation conditions and reduces the pressure drop along pipelines. (Diao, Wang, Guo, & Feng, 2018).

Natural gas compressor station consists of several scrubbers to filter inlet gas, a gas compressor to increase pressure, and an air cooler to reduce the compressed gas temperature. The inlet gas to the natural gas compressor station enters to the scrubber and then enters the gas compressor. The power of the gas compressor is supplied by the gas turbine cycle. Naturally increasing gas pressure by the compressor lead to increase gas temperature. Air coolers are a type of heat exchanger that reduces temperature through produced air by electro fans. The cost of generating pressure at a natural gas compressor station can be up to 50% of total

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gas transmission costs (Bianchi, et al., 2019), so pressure loss is really important. On the other hand, applying air coolers in gas pressure boosting stations has some disadvantages, such as relatively high-pressure drop and significant electrical consumption due to the use of electro fans (Davarpanah et al. 2019, Kwon, Kim, and Sohn 2018, Abdel Rahman and Mokheimer 2018).

Nowadays, heat pipes are used to heat transfer for commercial purposes. Using heat pipes as economizers, air pre-heaters and electronic cooling had been common in the recent decade. Heat pipe heat exchangers have the ability to recover and motivate heat during various industrial and constructional parts (Burlaco, Sosoi, Stefan, Barbuta, & Dora, 2018). It is the most taken as an organized means of heat recovering system. High Efficiency and low volume are two key desirable properties that can mention for heat pipes. In addition, not polluting the environment can be also the unique characteristic for this equipment (Shafii, Ahmad, & Faegh, 2017).

According to the literature, so many contributions have a significant role to improve efficiency and heat transfer; such as the use of heat pipes in various parts of the industry, ventilation systems in buildings, and the electronics industry (Hagens, Ganzevles, Vandergeld, & Grooten, 2007).

The heat pipe can be made of materials such as copper, aluminum, and stainless steel that are suitable for all kinds of applications (Faghri, 1995; Hilpert, 1993; Kröger, 2004). Heat pipes need neither the input energy, except the transferred heat, nor any mechanical moving parts. Therefore, they do not need any repair and maintenance (Sun, et al., 2018). In the heat pipe, the propulsion force is the local differential vapor pressure between the evaporator (the hot end of the tube) and the condenser (the cold end of the tube) (Jian & Luo, 2018). When the liquid in the evaporator is heated, the main vapor pressure increases and the fluid moves along the device towards the condenser part with low vapor pressure. After condensation, because of capillary and gravity effects, the fluid changes into liquid and then returns to the evaporator (Cao, Luan, & Wang, 2018). The heat absorbed in the evaporator is transferred in the tube to change the operating fluid from the liquid to the vapor, and when the fluid changes back to the liquid phase, this heat is lost in the condenser (Li & Zhang, 2018; Ma, et al., 2016; Shafii, Ahmad, & Faegh, 2017; Sudakov, Maidanik, & Ershinin, 2000).

Ma et al. studied the thermal performance of heat pipe heat exchangers based on heat transfer rate, heat transfer coefficient, energy efficiency, and NTU method. The results showed that energy and thermal efficiency were improved, also energy performance increased from 34 to 41%. The heat transfer rate, heat transfer coefficient, and system efficiency were improved by heat pipes 6, 10, and 7%, respectively, using this system (Ma, et al., 2016).

In another research, Noei analyzed an empirical sample for the design of a heat pipe for heat recovery (Noei, 2006). In this research, ε.NTU method was used for designing a heat pipe converter sample for energy recovery. Research has shown that in the design of the converter, with an increase in Ce/Cc ratio, the heat transfer rate increased. They also described the method to measure pressure drop inside the heat pipe. The fundamental and practical part of their research was designing the part of the heat exchanger with ε.NTU method and measuring the pressure drop (Noei, 2006).

In a review article, Vasiliev studied different types of heat pipes. It is very unlikely to combine these devices with mechanisms such as the formation and destruction of the bubble, the operation of bubble accumulation and pumping, changes in flow regime, pressure/temperature turbulence, dynamic instability, low-stable non-equilibrium conditions, or the distribution of thermal performance in general (Vasiliev & Luikov, 2005). Finally, this author pointed out that choosing and designing heat pipes requires considering some important issues. Vasiliev emphasized taking into account the exact conditions and limitations of the system because of various advantages of heat pipes such as high conductivity, high heat transmission, low repair and maintenance costs (Vasiliev & Luikov, 2005).

Also, Yang et al could significantly improve energy efficiency in the air conditioning system of a building; it was done by designing and using heat pipes in a constructional exchanger (Honghai & Wang, 2019).

In this study, the use of heat pipes in natural gas compressor outlet has been investigated. Heat pipes are investigated in three different situations and after selecting one of the appropriate conditions, heat pipe for a natural gas compressor station in IRAN as a case study is evaluated and designed. In addition, reducing outlet gas temperature in the gas compressor and the effects of this change on energy performance through simulation are evaluated.

In a similar study, Mosleh et al. investigated the use of pulsating heat pipes in the exchanger structure through laboratory works. The results proved that utilizing pulse heating pipes can improve the heat transfer coefficient up to 310%. In their research, R134 operating fluid was used to evaluate the thermal performance of the exchanger. Overall, the authors' studies express that the use of heating pipes, in various sectors of industry and also in building works, significantly contributes to improving efficiency, heat transfer, and other relevant indicators(Mosleh et al. 2019).

Delpech et al. demonstrated the need for energy optimization and its importance in the ceramic industry furnace sector, which was the main part of consumption (more than 50% of the total) (Delpech, Axcell, & Jouhara, 2019). Their experimental results showed that the heat pipe was able to recover the heat radiation and natural convection about 4 kW. (Delpech, Axcell, & Jouhara, 2019).

Other studies on pressurized air receivers that are used in solar power systems have been done. In this case, Chu et al. could surprisingly reach a minimum of 85% efficiency based on thermal test results through using pressurized air receivers coupled with sodium-potassium heat pipes (Chu, Bai, Cui, Nie, & Diao, 2020).

To the best knowledge of the authors, there has never been such a survey or researches due to applying heat pipes as heat pipe heat exchangers (HPHE) in natural gas compressor stations for gas cooling instead of air coolers. The advantage of this method is the removal of the air coolers from a natural gas compressor station and reducing the initial cost, energy consumption, and most importantly preventing the pressure drop in air-cooled heat exchangers and ultimately improving the energy performance in natural gas compressor stations. As mentioned before, the pressure drop is an important variable to determine energy performance in the natural gas compressor station, so using a heat pipe could improve pressure drop in compressor station and reduce electrical consumption in air coolers.

First of all, different possible scenarios investigated and designed in previous researches raised, and after on, real compressor station data was determined as boundary conditions during the survey. Then, a heat pipe heat exchanger was designed according to designing principles and using boundary conditions. Eventually, operation conditions in the considered station and energy performance in various conditions were all well evaluated and analyzed. Finally, energy performance improvement analyzed with the simulating process in HYSYS and energy-saving estimated.

2. Material and Methods

Three different scenarios are proposed to evaluate applying the use of heat pipes to reduce the gas temperature of outlet compressor in natural gas compressor stations.

The first scenario is the use of heat pipes in the current design of air coolers. In this design, the heat pipes are deployed into the tube instead of fins and are exposed to blown-in air. This method has some major disadvantages. The highest efficiency in the heat pipe is achieved when the condenser is positioned above the evaporator at 90 degrees. However, in the proposed plan, the heat pipes must be positioned at an angle of 45 to 75 degrees towards the tube to expose the air fans. Thus, only the upper tube can be used to make a heat pipe.

The second scenario is installing the heat pipes on the gas pipelines in the discharge gas compressor line. In other words, in this scenario, it is assumed that the heat pipes are connected vertically to the section of the gas pipeline carrying the gas stream, and natural gas is cooled by heat transfer through the air. This scenario presented has disadvantages as follows:

1- In this design, the thermal resistance is increased due to the connection of two pipes and the heat transfer conductivity between the pipe and the gas.

2- Heat pipes should be positioned vertically because they will have the best efficiency, which will significantly increase the number of heat pipes.

Third method: at the discharge gas compressor, a rectangular chamber is designed for the direct contact of the gas and air so that the heat is transferred to the heat pipe through natural convention and moves the condenser through heat pipe evaporator and then transfers its heat to the blown air by natural or forced convection. For this purpose, two chambers are assumed for transmission of the hot and cold fluid. The upper chamber is a fan-driven air intake chamber that includes the condenser section of the heat pipes and the lower part, is the gas transmission pipe (compressor outlet path) which includes the evaporator section. The proposed system illustrated in fig. 1.

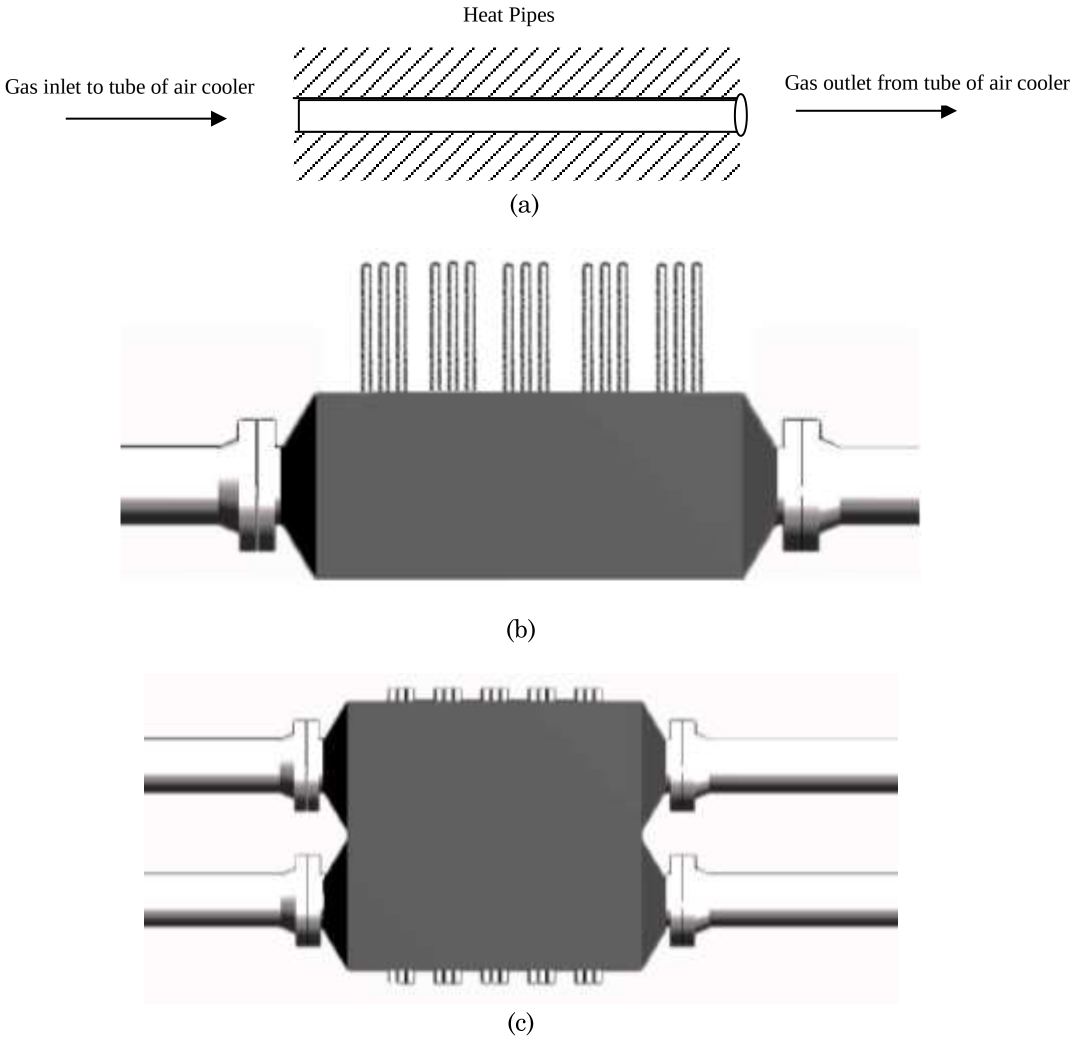

Figure 1. Schematic of the system proposed (a) The first scenario (b) second scenario(c) Third method

In this investigation, according to the previous studies and the use of researchers, the third method is based on the design of heat pipes, and the following steps are planned and calculated.

1- Using the heat exchange capacity of the converter and the energy balance, calculates the output temperatures, determines the appropriate average temperatures and calculates physical properties, such as density, viscosity, conductive heat transfer coefficient, Prandtl number, and so on.

2- The UA calculation is based on the ε-NTU method.

3- For determining the value of f and j must first assume a value for this ratio. One of the common design conjectures is to select the value of 0.28, which can be further corrected.

$$f = (0.25 + \frac{0.118}{(\frac{ST - d}{d})^{1.08}})\,\mathrm{Re}^{-0.16} \tag{1}$$

$$j = 0.195\,\mathrm{Re}^{-0.35} \tag{2}$$

4- Calculating the mass flow rate (G): First, using the j to f ratio, we obtain the mass discharge intensity, then, the Reynolds number is calculated.

$$G_c = \left[\left(\frac{\frac{2P\eta\rho}{2}}{pr^{\frac{2}{3}}}\right)\left(\frac{\frac{\Delta p}{pi}}{NTU}\right)\left(\frac{j}{f}\right)\right]^{\frac{1}{2}} \tag{3}$$

$$\mathrm{Re}_c = (\frac{G * D}{\mu}) \tag{4}$$

5- To calculate the natural convection coefficient, the Reynolds-Colburn equation is commonly used:

$$j = St\,Pr^{\frac{2}{3}} \quad (5)$$

$$h_c = \frac{j * C * G_m}{P_r^{\frac{2}{3}}} \quad (6)$$

To obtain the overall heat transfer, it is obtained based on the surface area of the cold and hot parts:

$$\frac{1}{UA} = \frac{1}{(\eta_c hA)_c} + R_{f,c} + R_{hp} + R_{f,h} + \frac{1}{(\eta_0 hA)_h} \quad (7)$$

6- The number of pipes and pressure drop are calculated based on the following equations:

$$a_c = \frac{\dot{m}}{G} \quad (8)$$

$$n = \frac{a_c}{\pi dl} \quad (9)$$

$$\Delta p_c = 2f\,\frac{G^2 * N_l}{p_m} * \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad (10)$$

In this investigation, the design of heat pipes is based on the actual data of an air-cooled heat exchanger in a real natural gas compressor station as a case study. So the boundary conditions are based on the air-cooled heat exchanger data sheet shown in Table 1:

Table 1: Thermodynamic conditions of an air-cooled heat exchanger

	Parameters	Inlet	Outlet
1	Natural Gas Temperature (°C)	86.2	55
2	Natural Gas Mass Flow Rate (kg/hr)	631336	631336
3	Air Mass Flow Rate (kg/hr)	4574556	4574556
4	Natural Gas Pressure (kPa)	6823	6623
*	Natural gas Density @ inlet tube: 53.23 kg/m³		

Table 2: the summery of air-cooled heat exchanger datasheet

	Parameters	
1	Heat Exchanged (kW)	14300
2	Surface/Unit finned (m2)	52011
3	Number of Electrical Motor Fans	24
4	Electrical Capacity/FAN (kW)	37

To calculate the geometrical size of the heat pipes, several parameters have a great impact on the heat transfer performance of the heat pipes, for instance, the inner diameter, the length of the evaporator, and the condenser section, etc. need to determine carefully. The length of the evaporator, condenser, and adiabatic section, which should be controlled within a range, contributes to the better thermal performance of the heat pipes. These values are dependent on such parameters as the working fluid, the inner diameter, filling ratio, thermal methods as heating or cooling, operating orientations and inclination angle, etc. (Rittidech, Terdtoon, Murakami, Kamonpet, & Jompakdee, 2003). Presently, previous studies on similar cases and existing procedures including definitions and equations in the handbook abled us to determine their size (Jafari Mosleh, Bijarchi, & Shafii, 2019) (Reay & Kew, 2006).

According to obtained calculation results through 1 to 10 equations, required heat pipes system calculation and physical characteristic, represented as Table 3 below:

Table 3: The geometrical specification of heat pipes

Parameters	Value
Heat Pipe Diameter (mm)	5
Heat Pipe Length (mm)	1500
Length of evaporator section (mm)	750
Length of condenser section (mm)	750
Thickness (mm)	3
Number of heat pipe	620
Material	copper
Working Fluid	R 134
Filling ratio (%)	50
Arranged	Triangularly

3. Results and discussion

As mentioned in the design section, for the heat transfer of 14300 kW in the air-cooled heat exchanger, the j to f ratio is initially 0.28 based on conjecture, and after repeated calculations with a perfectly reasonable margin of confidence, the j to f ratio of 0.0866 was achieved. According to the calculation process presented in the previous section, for the air coolers, 620 simple heat pipes are needed to replace with air coolers. A case study on a natural gas compressor station shows that in design conditions, the natural gas must have a pressure increase of about 1.72 MPa throughout the station. On the other hand, the pressure drop in the air coolers in a case study is 0.2 MPa. Actually, about 11% of the total pressure increased by the gas compressor is lost in the cooling section, which affects in next natural gas compressor stations and leads to an increase in fuel gas. In addition, at the station under study, more than 75% of electrical energy consumption is due to the use of air coolers motor drives.

The main target of this study is to investigate the energy performance and analysis the rate of pressure drop reduction in the cooling section and its effect on the energy performance of the natural gas compressor stations. The energy performance indicators at the natural gas compressor stations are defined as the ratio of total energy consumed to the total pressure increase (kJ/ΔP). Energy performance or specific energy consumption (SEC) in natural gas compressor station calculated as equation 1 to 3:

$$SEC\ Thermal = \frac{fuel\ gas\ consumption}{\Delta p\ (increased\ pressure\ in\ gas\ compressor\ station)} \quad (11)$$

$$SEC\ Electrical = \frac{Electrical\ energy\ consumption}{\Delta p\ (increased\ pressure\ in\ gas\ compressor\ station)} \quad (12)$$

$$SEC\ Total = \frac{Total\ energy\ consumption}{\Delta p\ (increased\ pressure\ in\ gas\ compressor\ station)} \quad (13)$$

Therefore, reducing the energy performance indicator for a constant increase in natural gas compressor stations requires a reduction in electricity consumption or fuel consumption in turbines. Reducing the pressure drop in the case study makes compressor station suction gas with higher pressure, which will reduce fuel consumption in the downstream natural gas compressor stations. To evaluate the energy-saving potential, the natural gas compressor studied at the next station was simulated in Aspen HYSYS software and then, the inlet pressure to the station was calculated under two different conditions (cooling by heat pipes & cooling by air coolers).

Some parameters such as natural gas suction pressure and temperature selected to validate the simulation process. So, average daily operation data and simulation results in 30 days compared and uncertainty calculation in Figures 3 and 4 show 0.02 % and 0.09% error in pressure and temperature suction respectively. Deviation means that simulation results are acceptable. Also According to the late surveys, two major equations used in recent simulations were Peng-Robinson and SRK equations (Zabihi & Taghizadeh, 2015)

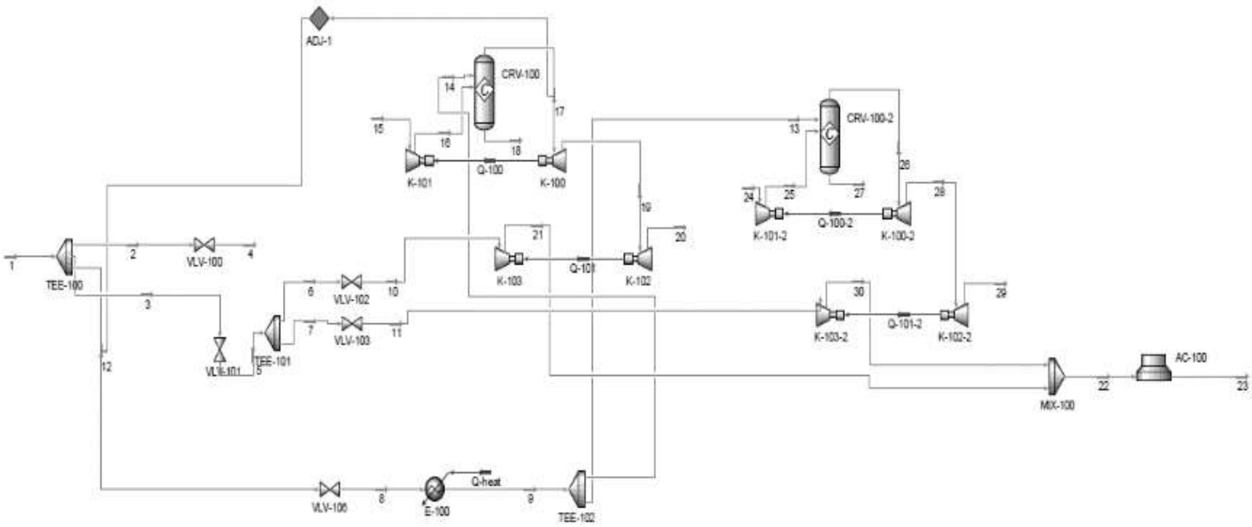

Figure 2. Simulation of natural gas compressor station (case study)

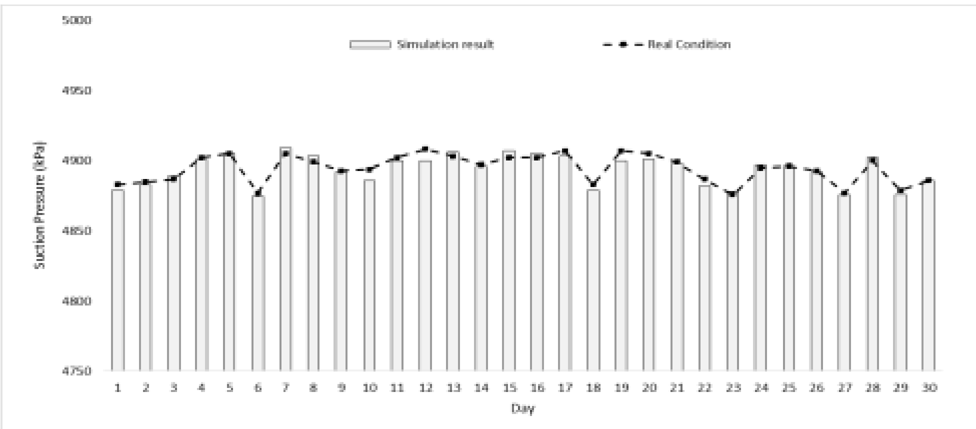

Figure 3. Comparison of real suction natural gas pressure and simulation result

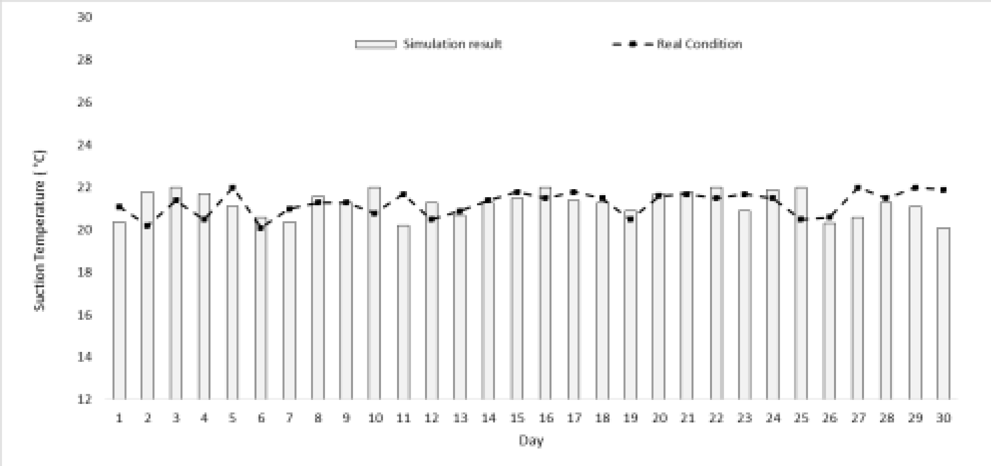

Figure 4. Comparison of real suction natural gas temperature and simulation result

In the simulation results illustrated in figure 2, the inlet gas flow (stream No. 1) at 4903 kPa and temperature 22 °C is initially divided into three parts. The main section (stream No. 3) after compressed by turbo-compressors flows, discharged to the air cooler for cooling. Discharged gas insert to pipeline and will suction in the next compressor station as the same station. So, fuel consumption in gas turbines in 2 conditions in the downstream station, gas cooling by air cooler, and applying heat pipes for cooling, compared. The simulation results show a reduction of the air cooler pressure drop at the previous station will reduce fuel gas turbine consumption assuming the pressure at the gas compressor outlet is constant. Figure 5 shows the effect of increasing the inlet pressure on the natural gas compressor station at different intervals on the fuel consumption of a gas turbine.

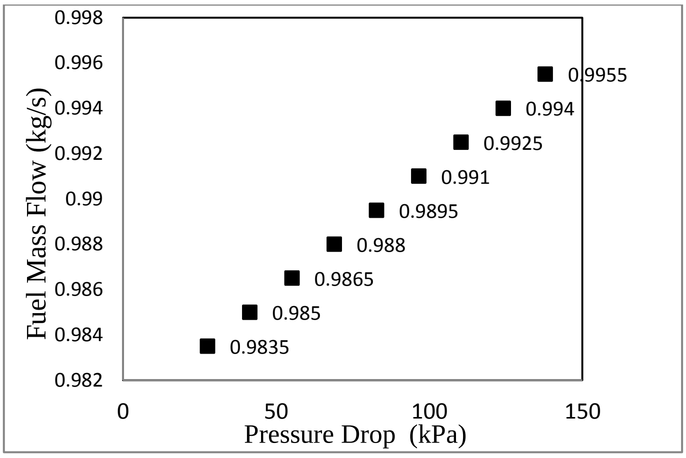

Figure 5: Analysis of pressure drop parameter and its effects on turbine fuel consumption at a natural gas compressor station

It should be noted that the results in figure 5 are calculated for one gas turbine unit. So to estimate the total reduction of turbine fuel consumption, according to the arrangement of the station in the case study, and the use of two turbo-compressors, calculations for two turbine units, and by taking into account continuous operating conditions throughout the year, 1,115,000 SCM fuel-saving is annually estimated.

The results of this study show that the gas pressure drop at the output of the compressor cooled by the heat pipes is a maximum of 1.5 kPa. However, the pressure drop in the air coolers under the operating condition is 200 kPa reported by the air coolers manufacturer in the technical sheet. In other words, the pressure drop in the heat pipes method for cooling natural gas will be approximately 133 times less than the current conditions, which will improve the energy performance of the natural gas pressure station. In addition, using heat pipes for cooling will improve the energy performance indicators. The results are presented in Figures 6 through 8

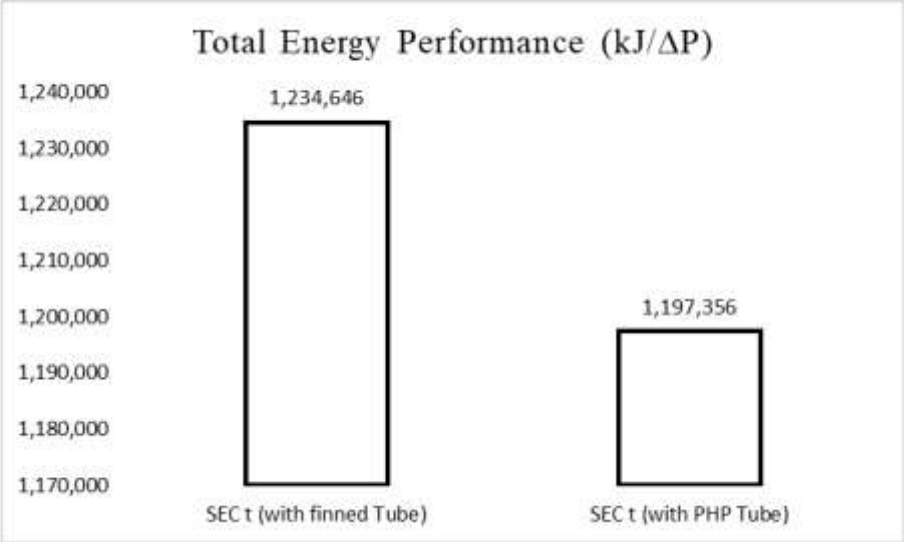

Figure 6: Results of Energy Performance indicator improvement (total SEC)

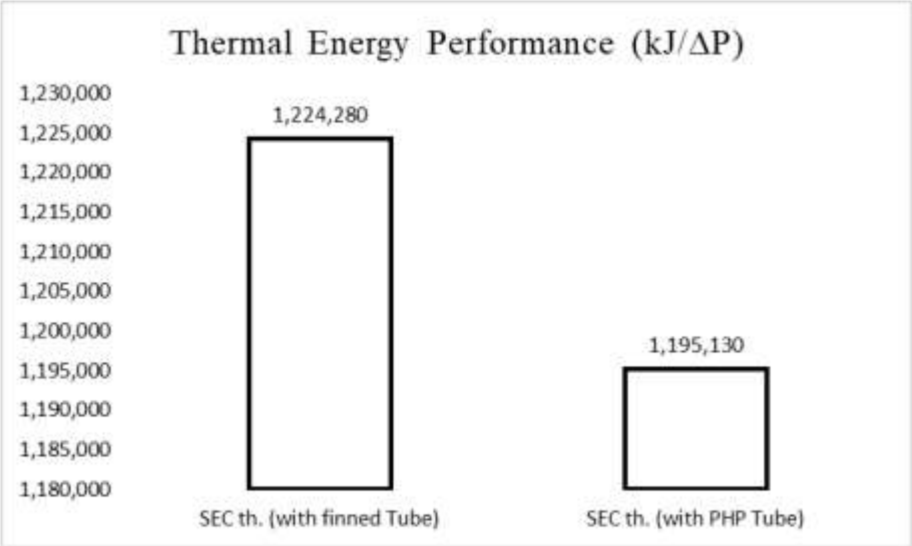

Figure 7: Results of Energy Performance indicator improvement (thermal SEC)

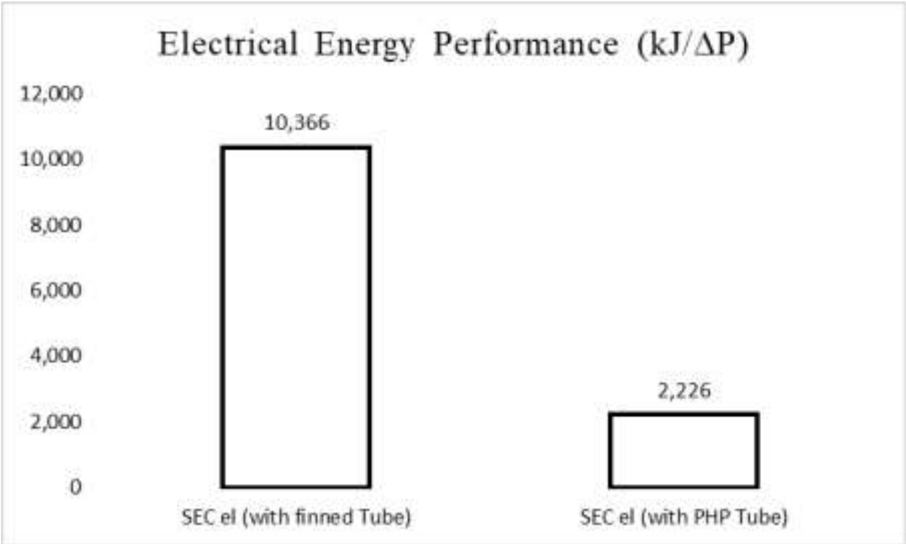

Figure 8: Results of Energy Performance indicator improvement (electrical SEC)

Results in Figures 6 to 8, demonstrate important consequence, electrical and thermal performance improvement accompany. In the calculations, natural gas heat value is 45000 kJ / m³ and the results of operating conditions at the station understudy show that, on average, half of 24 fans in the cooling section are operated throughout the year. In addition, a significant share of the power consumption at each station is dependent on the pressure of the air coolers, thus, having a significant impact on the electrical energy performance illustrated in figure 8, of the station under study. Also, figure 7, shows fuel gas consumption can be improved and saved with applying heat pipes instead of gas coolers. The results of the energy performance calculations show a 3% improvement in the total energy performance indicator, 2.3% improvement in the thermal performance indicator and a 79% improvement in electrical energy performance indicator will be achieved. Energy-saving results illustrated in table 4.

Table 4: Energy-saving results in applying heat pipe heat exchanger in the case study

	Parameters	
	Fuel gas saving per year (*SCM)	1,115,000
	Electrical energy saving per year (MWh)	3,800
*Standard Cubic Meter		

The results of the evaluation in the cooling section of the natural gas compressor station in our study, show that this station can improve the energy performance of the station and reduce energy consumption and improve its performance in operation and a high potential for energy savings is available. In addition, the development of this plan in all compressor stations in the gas pipeline will also hold a very high potential for energy savings. As mentioned before, this plan cause to reduce initial cost and energy cost, together. According to the review on project costs, manufacturing companies and heat exchanger designer inquiry represent that considered station design and instruction cost about 200,000 $. The simple economic calculation showed in table 5.

Table 5: economic calculation in applying heat pipe heat exchanger in the case study

	Parameters	Value
1	*Thermal Energy Saving ($/Year)	2,007,000
2	** Electrical Energy Saving ($/Year)	608,000
3	Total Energy Saving Cost ($/ year)	2,615,000
3	Project Cost ($)	200,000
4	Payback value (year)	less than 1 year
Natural gas international price: 1.8 $/m3 average international electrical price: 0.16 $/kWh		

Also due to fuel gas price in Iran, which calculated as 0.12 $ /m³, applying the HPHE exchanger causes 133,800 $ saving per year. Accordingly, this project payback period value less than 3 years evaluated. Also, applying the HPHE exchanger in a surveyed station causes reducing annual 1652 ton CO^2 emission.

In a similar study, Burlaco et al. analyzed the CFD of a well-designed heat pipe exchanger used in a building (Burlaco, Sosoi, Stefan, Barbuta, & Dora, 2018). This research focused on the development of the heat pipes to be used in the preheating section in the air outlet of an air conditioner. The results of this study were low construction and repair costs, higher thermal efficiency, easy installation of these pipes, and a 30% improvement in thermal energy performance. Based on the literature, the use of heat pipes in various parts of the industry, ventilation systems in buildings, and the electronics industry improve efficiency and heat transfer significantly. In addition, results show energy performance indicator improved by 30% (Hagens, Ganzevles, Vandergeld, & Grooten, 2007).

In addition, a comparison between results obtained from simulation and Chu et al. (Chu, Bai, Cui, Nie, & Diao, 2020) for improving energy performance in a similar study shows that a minimum 85% improvement in efficiency is possible. Also, Mosleh et al. results show that utilizing pulse heating pipes can improve the heat transfer coefficient up to 310% (Mosleh et al. 2019).

4. Conclusion

A heat pipe heat exchanger has been designed for cooling natural gas discharge in the compressor station. Initially, a real compressor station has been determined as a case study. HPHE exchanger was designed thought of the ε-NTU method. Foresaid designed HPHE exchanger consisted of 620 number of heat pipes made of Copper, and working fluid R134a with 50% filing ratio charged; it was designed and instructed in a box with a length of 1500. In order to determine the energy-saving ratio, the natural gas compression station process was simulated in HYSYS software; results were compared to real conditions and results show that simulation error was acceptable. After validation of simulating results, Energy saving and energy performance indicators analyzed. Energy performance calculations for the case study station have revealed the improvement in overall energy performance, thermal performance, and electrical energy performance indices up to 3, 2.3, and 79%, respectively. Besides, the development of this design at all pressure boosting stations will also create a very high potential for energy savings. Simulation results represented that heat pipes able to reduce the natural gas temperature the same air coolers. In addition to energy saving, a reduction in greenhouse gasses emission can be mentioned as one of the most important advantages of heat pipes in natural gas compressor stations. Assuming that gas turbine in compression station was continuously operating based on registered data during 12 months, thermal energy saving would equal 1,115,000 SCM and 3,800 MWh electrical energy saving; and results show 2,615,000 cost saving is possible. Also, this project payback period value less than 1 year evaluated and estimated to avoiding 1652 ton CO^2 emission per year.

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