

Investigation of energy consumption reduction in multistage compression process and its solutions

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ABSTRACT

During hot seasons the inlet temperature of Nitrogen increases, as a result compressor consumes more power for compressing a specific mass ratio of fluid and consequently total energy consumption of the compressor increases as well. In this research, a three stage centrifugal compressor with intercooler was modeled thermodynamically to decrease the energy consumption of the compressor. In each compressor, isentropic efficiency, outlet temperature of the Nitrogen gas and power compression was studied. The effect of inlet Nitrogen temperature and cooling water temperature on intercoolers' efficiency were investigated. In this study, Nitrogen gas is considered as an ideal gas. It is found that, in each compressor any growth in inlet temperature of the Nitrogen gas will result in linear increase in the outlet temperature of the Nitrogen gas and power compression furthermore, observed that increasing the temperature of Nitrogen gas has the most negative effect on efficiency and power compression of the first compressor in comparison to the second and the third compressor, it will result in a 10% decrease in special power compression specially during summer time. According to these results, it is figured out that any growth in inlet Nitrogen temperature causes a smooth decline in isentropic and Power Compression of the first, second and third compressors besides increasing the temperature of the Nitrogen gas increases the isentropic efficiency up to 3% and increasing the cooling water temperature decreases the intercooler efficiency up to 7%.

1. Introduction

Today, as awareness of the constraints on energy sources as well as the increased demand for energy on one side, and the considerable energy losses in thermal systems, on the other hand, has led the scientific community to study the energy systems, following a solution to reduce the energy losses of these systems. Research has shown that roughly 10 percent of the total electric energy consumption in the industry is allocated to the production of compressed air. Of the total cost of producing compressed air, 75% is spent on energy, 15% is spent on initial investment, and 10% of the rest is spent on maintenance [1, 2]. Hamilton and et.al [3] presented an optimum design procedure for the intercooler where the objective function includes not only the reduction of compressor power but the reduction of pumping power for the intercooler water and the initial cost of the intercooler. The procedure permits relative weighting of the importance of the

combined power reduction compared to the intercooler cost. The multi-stage compressor system is optimized by optimizing each stage independently assuming no coupling effect due to temperature. In this research the pumping cost of cooling water and the cost of intercooler has been presented. Sathyaraj [4] compared CFD analysis and experimental data of intercooler. the circular cross section pins are inserted normal to the flow direction of air in existing finned tube heat exchanger (intercooler) of two stage reciprocating air compressors to increase the convective surface contact area and create the turbulence resulting in an increase the rate of heat transfer. The rate of heat transfer has been increased in modified intercooler to 10-22% of the existing intercooler. The outlet temperature of the intercooler has been reduced to 1.5%-2.5% of the inlet temperature in the modified intercooler. Modified intercooler has 1% - 1.5% efficient than existing. Royyta and et.al [5] wrote an interesting article concerning the optimization of a refrigeration

process with a two-stage centrifugal compressor and flash intercooler. The two-stage centrifugal compressor stages are on the same shaft and the electric motor is cooled with the refrigerant. The performance of the centrifugal compressor is evaluated based on semi-empirical specific-speed curves and the effect of the Reynolds Number, surface roughness and tip clearance have also been taken into account. Song and et.al [6] presented hybrid modeling technique of ideal thermodynamic models and empirical modeling method to predict the efficiency and actual power consumption of multistage centrifugal compressors. The optimization technique was applied to CDA compressor network in LCD industry and about 5 % of power consumption was saved. Hansen and et.al [7] worked on design and modeling of centrifugal compressor by Hysys software. The model has been used to investigate the performance of the gas compression system at off-design conditions. Through the simulations it has been shown that the system can handle sluggish flow at amplitudes of 30 % of normal flow at a period length of 8 minutes. Wang and et.al [8] improved the performance of the transcritical CO₂ compression cycle. The theoretical analysis and experimental research on transcritical CO₂ two stage compression cycle with two gas coolers (TSCC + TG) and the two stage compression cycle with intercooler (TSCC + IC) were employed, respectively. They found that theoretical calculation coefficient of performance is better than the experimental testing value. Sadeghzadeh and et.al [9] optimized a finned shell and tube heat exchanger using a multi-objective genetic algorithm with the objective functions of maximizing heat transfer rate and minimizing total cost. Nine decision variables are considered, including tube arrangement, tube pitch ratio, number of tubes, tube length, tube diameter, fin height, fin thickness, number of fins per unit length and baffle spacing ratio. Ghorbanian and et.al [10] investigated on the capability of different types of ANN such as general regression neural network, a modified technique based on GRNN, multilayer perceptron network, and radial basis function network in reconstructing compressor performance map. It has been found that while rotated general regression neural network has the least mean error and closest agreement to the experimental data. Further, the compressor efficiency based on the multilayer perceptron network technique is determined. Wang and et.al [11] worked on a theoretical analysis of benefits from the different options of active compressor cooling for refrigerants R22, R134a, R410A and R744 as working fluids. They found that the potential COP improvement for R134a system is the least among four refrigerants investigated since R134a has a relatively high molecular mass and low discharge temperature. A review of previous studies has shown that the thermodynamic study of a three-stage centrifugal compressor, in which the fluid gas Nitrogen is working fluid, has not been studied. In this research, based on experimental data recorded and monitored from the control room, the effect of inlet Nitrogen gas temperature on the efficiency, outlet Nitrogen temperature, power consumption and compression ratio of the three-stage centrifugal compressor with intercooler are investigated. Finally solutions for controlling the inlet temperature of Nitrogen gas as an idea and research innovation are presented. In this study, the effect of inlet Nitrogen temperature on the efficiency of the first intercooler and also the effect of cooling water temperature on the efficiency of the first intercooler, the second stage compressor efficiency and the compressor power consumption are investigated which in the past researches has not been studied.

2. System description

The main Nitrogen compressor which is studied in this article is located in Fajr Petrochemical Company of Iran .The type of Subjected Compressor is three-stage centrifugal compressor with two Intercoolers that are mounted between the stages and a cooler mounted after stage three. At first, the Nitrogen passes through inlet Nitrogen filter. The inlet Nitrogen filter consists of two high efficiency filters and pre-filter pads. Compressed Nitrogen after leaving each stage, while passing through the intercoolers, is cooled by cooling water and enters the next stage of Compression. Types of intercoolers are shell and tube with floating head. To avoid temperature increases, the Nitrogen is cooled twice while passing compressor, between stage one and stage two and three. The case study compressor is shown in Figures 1 and 2.

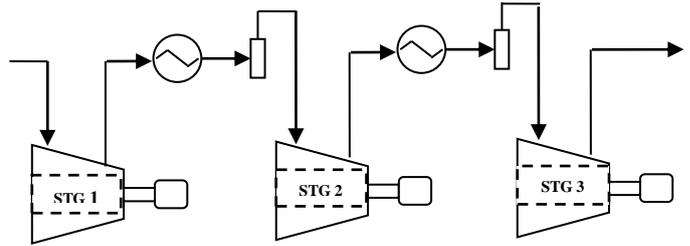


Figure 1. System Description.



Figure 2. Case study compressor and its intercooler.

3. Equation

Thermodynamics rules that used to calculate the power and efficiency of the compressors are independent of compressor performance. The compressor can be considered as one control volume by applying these rules. According to first thermodynamics rule in the compressor, energy equation can be written as follow [12]:

$$\dot{m}_2 \left(h_2 + \frac{v_2^2}{2} + gz_2 \right) - \dot{m}_1 \left(h_1 + \frac{v_1^2}{2} + gz_1 \right) = q_{12} + w_{12} \quad (1)$$

Here In the centrifugal compressors, due to small surface of heat transferring, in comparison with other energy terms, the heat transfer can be neglected in equation (1). Also the terms of the potential difference on both sides of this equation can be neglected. Regarding this assumptions equation 1 rewritten as follows:

$$\dot{m}_2 \left(h_2 + \frac{v_2^2}{2} \right) - \dot{m}_1 \left(h_1 + \frac{v_1^2}{2} \right) = w_{12} \quad (2)$$

According to the principle of mass conservation and also we assume that the $h + \frac{v^2}{2} = h_t$ equals to static enthalpy, Compression power of a compressor equals to gradient in the fluid enthalpy from entering to exiting the compressor:

$$w_{12} = \dot{m}(h_{t2} - h_{t1}) \quad (3)$$

Now, by considering the Nitrogen as an ideal gas, the enthalpy gradient in an ideal gas is only a function of temperature, the compressor compression power can be calculated as follows:

$$w_{12} = \dot{m}c_p(T_2 - T_1) \quad (4)$$

It is assumed that the compressor is a turbo machine, its function can be considered adiabatic. So, the ideal mode of operation is the isentropic state. The isentropic efficiency of compressors can be written as follow:

$$\eta = \frac{W_s}{W_a} \quad (5)$$

Since the heat transfer from the fluid to the environment is negligible compared with the work done on the fluid the isentropic efficiency of compressors can be written as follow:

$$\eta = \frac{\Delta h_s}{\Delta h_a} = \frac{T_{2s} - T_1}{T_{2a} - T_1} \quad (6)$$

outlet Nitrogen compressor temperatures are the same. On the other hand, outlet Nitrogen temperature is calculated from:

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{R_i}{C_p}} \quad (7)$$

P_1 is the inlet Nitrogen compressor pressure and P_2 is the outlet Nitrogen compressor pressure. The remarkable thing about the 12 is that $\overline{C_p}$ in the average temperature of inlet and outlet Nitrogen compressor is calculated.

Entropy change over the compressor is determined by:

$$S_2 - S_1 = S_2^0 - S_1^0 - R \ln \frac{P_2}{P_1} \quad (8)$$

Where R is the gas constant of Nitrogen and s_1^0 and s_2^0 are the entropy of Nitrogen at inlet and outlet temperature, respectively.

For an adiabatic compressor with negligible kinetic and potential energies, the second-law efficiency becomes:

$$\eta_{second'low} = 1 - \frac{T_0(S_2 - S_1)}{h_2 - h_1} \quad (9)$$

Hypotheses done in modeling the shell and tube intercooler are as follow [13]:

- heat conductivity during heat exchanger is negligible.
- Kinetic and potential energy changes is negligible.
- Fullig Resistance changes with temperature changes is disregarded.
- The heat transfer between the heat exchanger and its surrounding is disregarded.

Efficiency factor of heat exchanger based on heat transfer concepts is defined based on the inlet and outlet temperature of working fluid and cooler, but in this research due to the aim followed, efficiency factor for intercooler is defined by inlet temperature of Nitrogen to first compressor, the outlet temperature of first compressor (inlet temperature to intercooler) and the outlet temperature of intercooler (inlet temperature of second compressor) [14].

$$\varepsilon_1 = \frac{T_2 - T_3}{T_2 - T_1} \quad (10)$$

4. Results and discussion for modeling first stage of compressor

As the behavior of compressors in three stage of compression process is the same, the behavior of compressor at first stage is studied. The inlet Nitrogen temperature range is 13.5 to 37.10. The range of pressure in inlet Nitrogen is also 1.41 to 1.5 bar. Based on empirical data and inlet Nitrogen temperature to compressor at first stage the results and diagrams are as follow:

4.1. The effect of inlet Nitrogen temperature on first stage compressor

The inlet Nitrogen temperature to compressor has a direct effect on its isentropic efficiency. Pressure ratio of compression and shaft speed are constant. As shown in figure 3, by increasing the inlet Nitrogen temperature to compressor at first stage, the isentropic efficiency and second low efficiency decreases. Polytropic efficiency changes of first stage compressor based on inlet Nitrogen temperature is also shown in figure 3. When the inlet Nitrogen temperature increases, compressor gets out of its designed condition and it seems predictable that its efficiency decreases. One can figures out that if the inlet Nitrogen temperature increases 1°C, the isentropic efficiency reduces about 1%. The results shown that using air instead of nitrogen, isentropic efficiency decreases about 7%. This results have a good agreement with the reference [15].

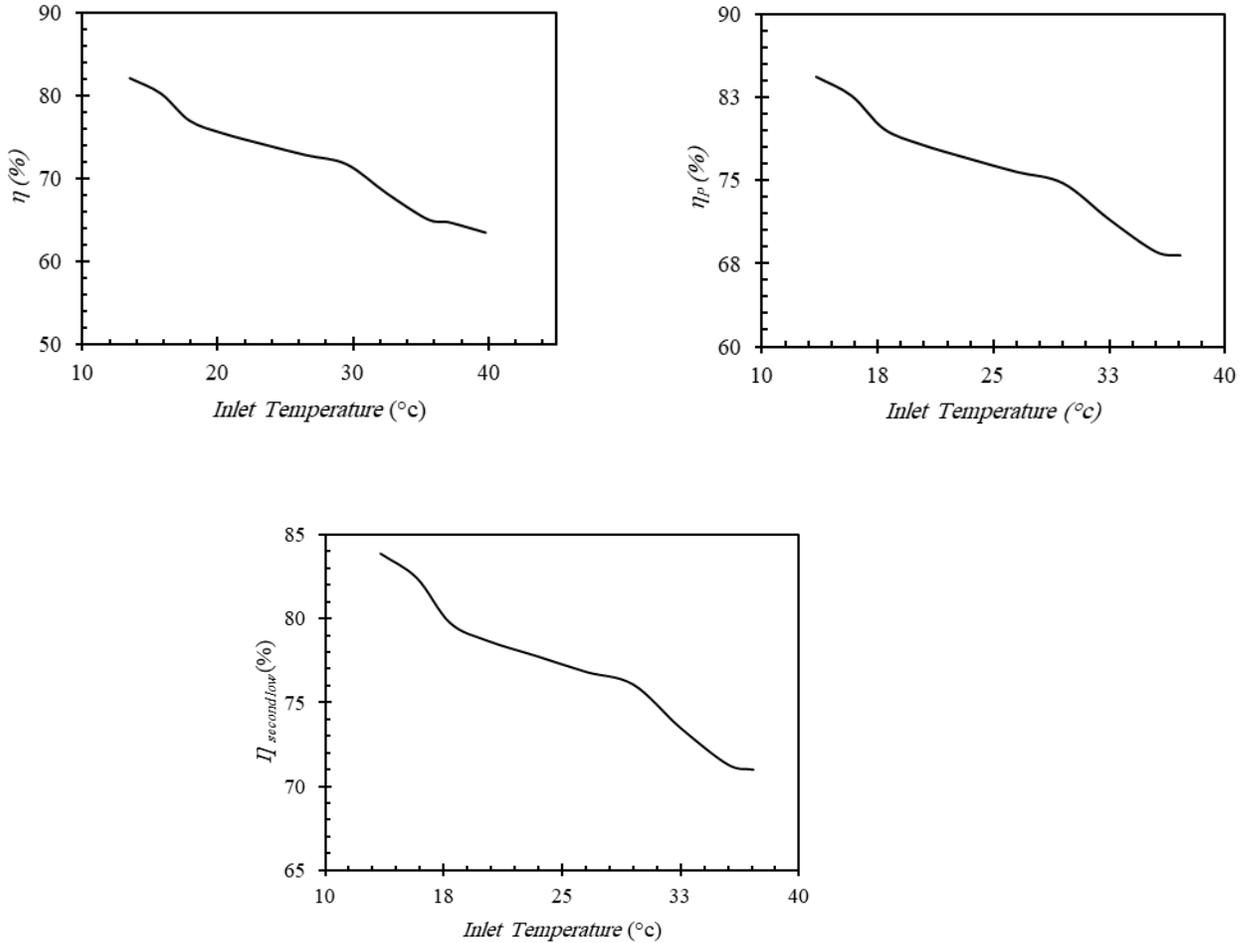


Figure 3. Efficiency changes in terms of inlet temperature.

One can extract the diagram for outlet Nitrogen temperature changes from first compressor based on its inlet temperature. As shown in figure 4, by increasing inlet Nitrogen temperature to first compressor, its outlet Nitrogen temperature is always increasing by a fairly constant slope.

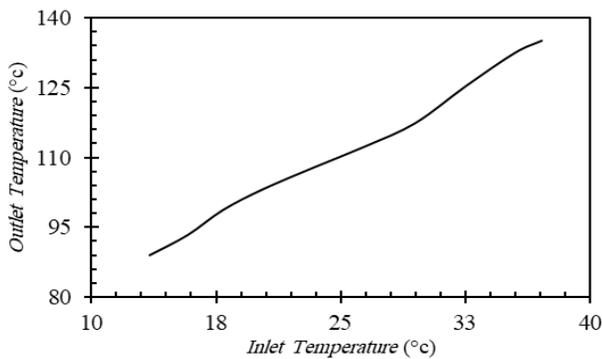


Figure 4. Outlet temperature changes in terms of inlet temperature.

Specific compression power (power on mass flow rate unit) of compressor doesn't change by increasing temperature but the compressor compresses less Nitrogen because it compresses a specific volume of Nitrogen in fixed rotating shaft. Nitrogen density decreases when temperature increases and mass flow rate of compressed Nitrogen also decreases. So, for studying the effect of inlet Nitrogen temperature, one can do thermodynamic modeling of first stage compressor by defining Specific compression power (power on mass flow rate unit) and thermodynamic equations. Effect of inlet Nitrogen temperature on the compression power was also modeled. As shown in Figure 5, the pressure ratio of compression decreases when the inlet Nitrogen temperature increases with increasing inlet Nitrogen temperature and Specific compression power increases linearly. When the inlet Nitrogen temperature is increased the amount of electromotor ampere increases and compressor endures more energy to provide necessary pressure. So the results were expected physically.

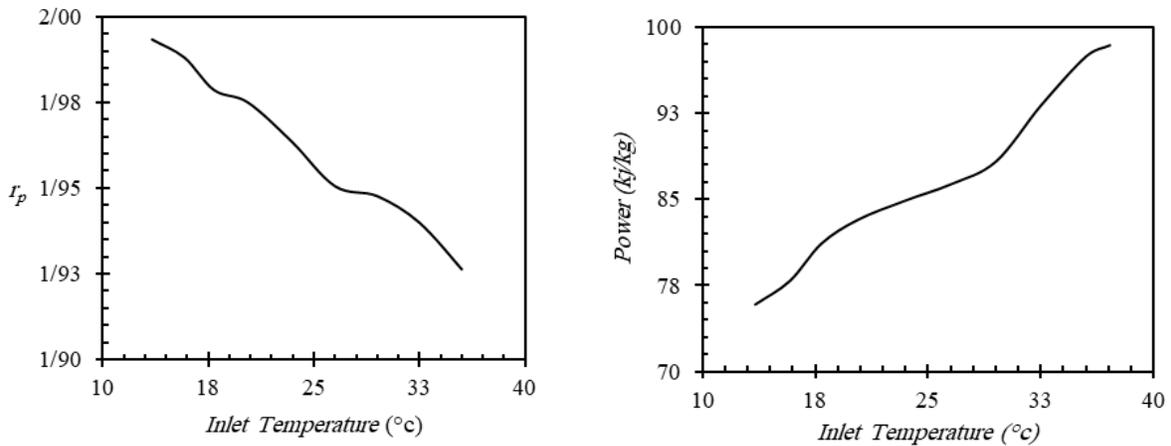


Figure 5. The effect of inlet Nitrogen temperature on Specific compression power.

It can be seen from figure 6 that there is an increase in enthalpy changes and entropy changes when inlet Nitrogen temperature increases. One can figures out that

if the inlet Nitrogen temperature increases 1°C , the enthalpy changes and entropy changes increase about 1kj/kg and 0.2 kj/kg respectively.

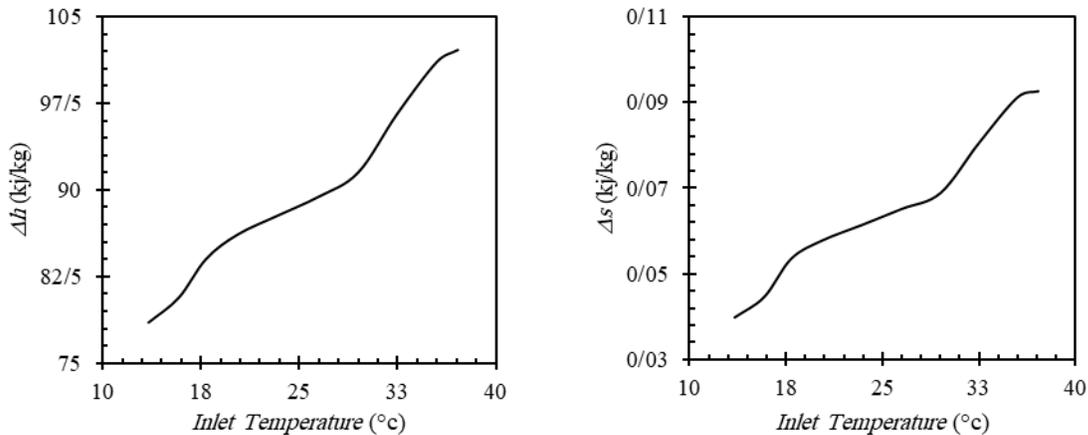


Figure 6. Enthalpy and entropy changes in terms of inlet temperature.

4.2. Suggested solution to control the inlet Nitrogen temperature to first compressor

As increasing the inlet Nitrogen temperature has the highest effect on first compressor so the results are just studied for first compressor.

A: inlet Nitrogen temperature from cold box was fixed in all seasons and about 10°C . Studies done shows that if one can do something to prevent increasing the Nitrogen temperature of output line from cold box to compressor we can see about 3 to 7 percent increase in efficiency at first stage. By using rock wool insulator

one can prohibit heating Nitrogen line especially in hot seasons. So following this suggestion one can prohibit heating increase about 8°C in Nitrogen temperature in its line to compressor. As a result, isentropic efficiency of compressor increases about 3 to 7 percent (figure 7) and specific compression power of compressor decreases about 6 to 10 percent (figure 8). As compression power in summer is about 26 percent more than winter, so this reduction power can be an effective step toward improving the compressor performance.

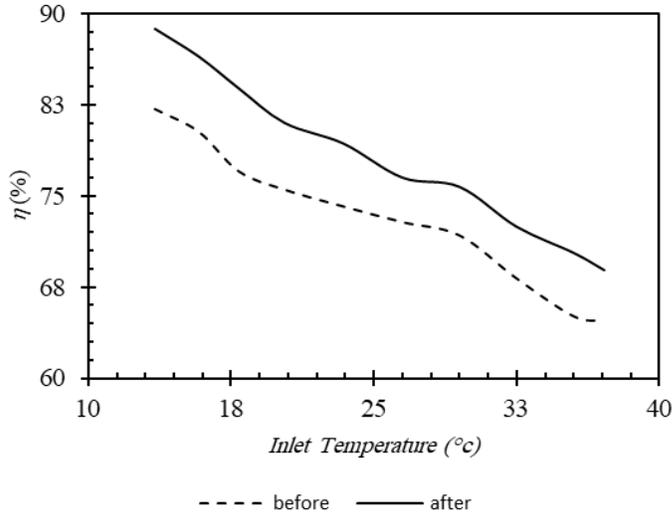


Figure 7. Isentropic efficiency changes in first compressor before and after insulating inlet Nitrogen line.

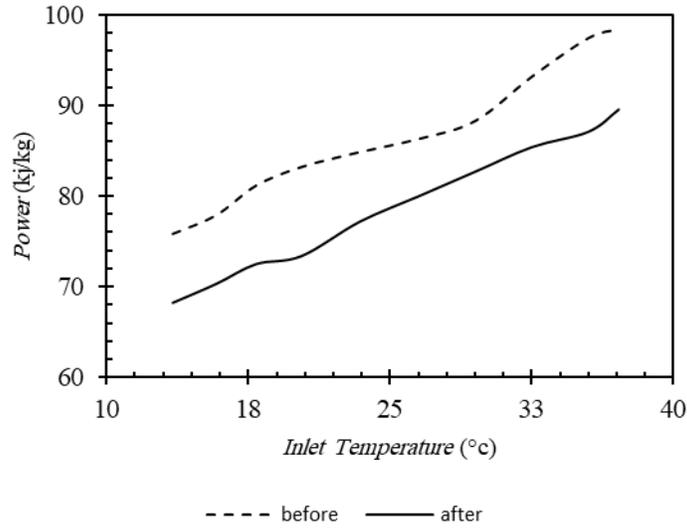


Figure 8. Compression power changes in first compressor before and after insulating inlet Nitrogen line.

B: In process and productions of Nitrogen unit, liquid Nitrogen is produced in 220C°. parts of this Nitrogen heated through water vapor produced in plant and is available to consumer in a gas form. As liquid Nitrogen is produced by spending a lot of money and energy and there is a cost for producing water vapor, a proper strategy to reduce the consumption of produced energies is using inlet Nitrogen to compressor as a mean to heat liquid nitrogen. In this way inlet Nitrogen to compressor

is in thermal exchange with high cold Nitrogen so the inlet Nitrogen will have a noticeable temperature reduction. Reduction in inlet temperature to compressor, efficiency increases and consumed power decreases. As a result, instead of using water vapor which energy is consumed to be produced its better to use inlet Nitrogen to compressor, then this process is an optimal improvement toward reducing energy consumption.

5. Studying the efficiency of first intercooler

Intercooler efficiency is a function of inlet and outlet temperature to cooler inlet and outlet water temperature of cooler, volume flow rate of nitrogen, etc. As its clear in figure 9, increasing the inlet Nitrogen temperature to first intercooler increases the intercooler efficiency clearly. As, the outlet Nitrogen temperature is in a definite range so by increasing inlet Nitrogen temperature the cooling amount done will be more so the intercooler performance and its efficiency will increase. Results showed that if the inlet Nitrogen temperature increases 1°C , the intercooler efficiency increases about 1%.

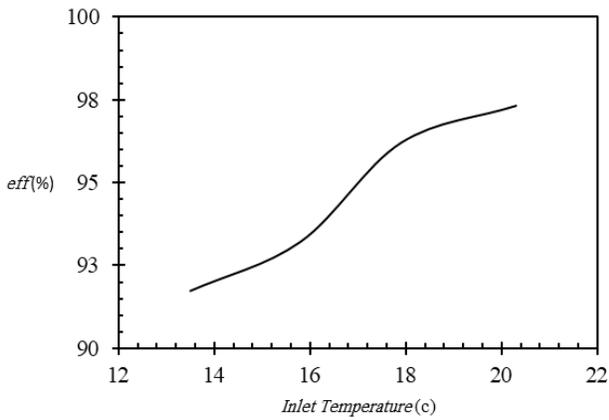


Figure 9. The effect of inlet Nitrogen temperature to first intercooler on its efficiency.

Given the results of the modeling, the cooling water temperature has a negative effect on the efficiency of first intercooler and the efficiency of intercooler decreases when the inlet water temperature to first intercooler increases. As it is shown in figure 10, through increasing water temperature the efficiency of first intercooler will decrease linearly with a slight slope. Results showed that if the cooling water temperature increases 2°C , the intercooler efficiency increases about 1%.

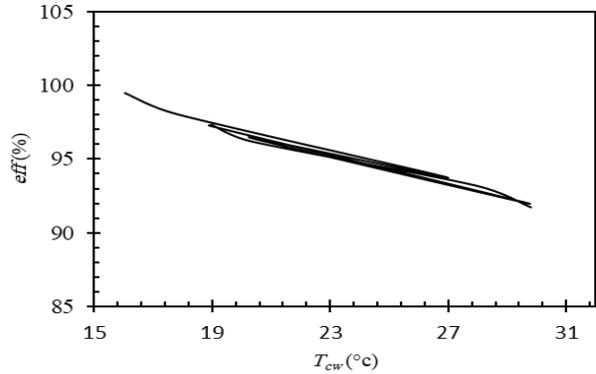


Figure 10. The effect of cooling water temperature on efficiency of first intercooler.

As it is shown in figure 11, by increasing inlet water temperature to second intercooler, the efficiency of intercooler decreases expectedly, so the efficiency of compressor in stage two will decrease, although this reduction has a less slope than first intercooler, its shows that increasing the water temperature has more effect on first intercooler than second one.

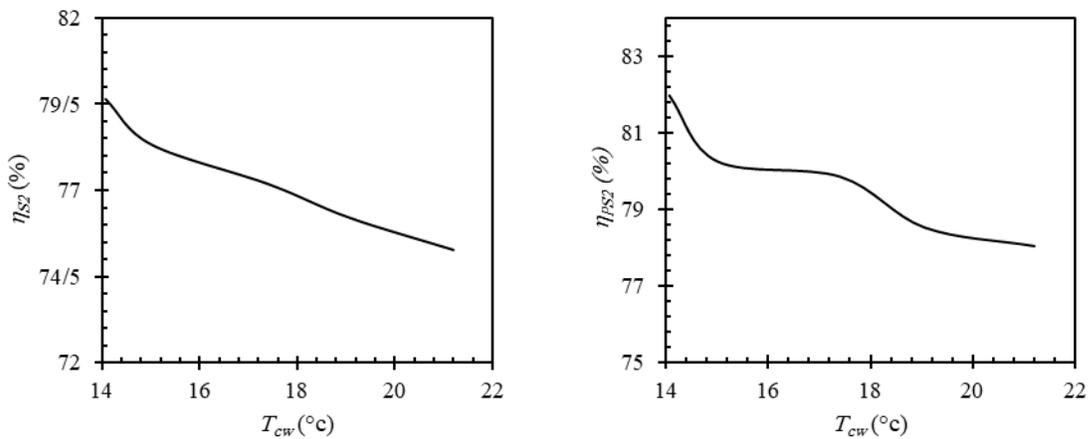


Figure 11. The effect of cooling water temperature on efficiency of second stage compressor.

6. Specific compression power of second compressor based on cooling water temperature

Specific compression power changes can be studied based on inlet water temperature as it is shown in figure 12. By increasing inlet water temperature in first

intercooler the specific compression power of second stage compressor will also increase linearly with a slight slope. Results showed that if the cooling water temperature increases 1°C , the Specific compression power increases about 0.6 kJ/kg .

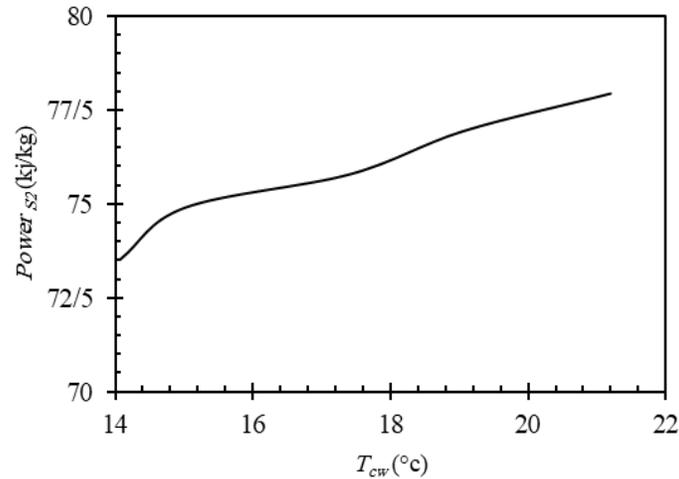


Figure 12. The effect of cooling water temperature on specific compression power of second stage compressor.

7. Conclusion

In country's power network, summer production is less than winter production while the most demands for power consumption happens in summer. The main reason for this difference is the efficiency dependence and specific power of industrial compressors to averments temperature which has an effect on their performance. Three stage centrifugal Compressor with intercooler is studied in this research to control energy consumption in summer comparing to winter. The results are briefly as follow:

1. Isentropic efficiency of compressor for first compression stage during this study was between 64.7 to 82.1 that isentropic efficiency has been decreased when the inlet Nitrogen temperature is increased.
2. Outlet Nitrogen temperature of first compressor increases linearly when the inlet Nitrogen temperature increases so it can be said that for 5°C increase in inlet Nitrogen temperature of first compressor the outlet Nitrogen temperature will increase 8 to 10°C .
3. specific compression power in first compressor will increase linearly under the effect of increasing inlet Nitrogen temperature. Compression power is 15% to 20% more in summer than winter.
4. the outlet Nitrogen temperature of first intercooler is a function of inlet Nitrogen temperature of first intercooler in its highest difference in this study (comparing summer to winter) led to 3% increase in intercooler's efficiency. Increasingly the inlet water temperature to first intercooler has decreased intercooler efficiency 8% in its highest condition.
5. under the effect of inlet Nitrogen temperature specific compression power of second compressor with a slope less than the first compressor will also increase linearly.

8. nomenclature

\dot{m}	Mass flow rate (kg/s)	T_s	Isentropic temperature (K)
Δh	Enthalpy changes (kJ/kg)	T_a	Actual temperature
v	velocity of Nitrogen (m/s)	T	Nitrogen temperature (K)
Q	Heat transfer rate (w)	P	Nitrogen pressure (pa)
W	Work (w)	R	Nitrogen constant (j/Kmol.K)
W_s	Isentropic Work (w)	\bar{c}_p	Specific heat capacity for (j/kg. K)
W_a	Actual Work (w)	S	Entropy (kj/kg)

9. Greek symbols

η	Efficiency of compressor
$\eta_{\text{second law}}$	Second-law efficiency of compressor
E	Thermal effectiveness of the intercooler

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