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ANALYSIS OF ISENTROPIC EFFICIENCY AND PRESSURE RATIO IN A THREE-STAGE CENTRIFUGAL COMPRESSOR BY THERMODYNAMIC MODELING AND NEURAL NETWORK MODELING ALGORITHM

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ABSTRACT

In this research, a three-stage centrifugal compressor with two intercoolers has been studied. According to experimental data which were taken every moment in the control room, the compressor has been modeled by using neural network modeling Algorithm and governing thermodynamic equations. According to governing thermodynamic equations, the effect of inlet air temperature to every Compression stages on isentropic efficiency was studied. During the study,it was found that, in first stage,isentropic efficiencyis between 67.16 – 75.36 and in second stage, isentropic efficiency is between 74 – 79.49 and by increasing inlet air temperature, alwaysisentropic efficiency is reduced, in third stage, isentropic efficiency is between 64.15 –74.64 and against first and second stages, by increasing inlet air temperature, isentropic efficiency is increased. By increasing inlet air temperature, pressure ratio in first and second stages was decreased and in third stage was increased. Finally the use of evaporative cooling system has been proposed in order to increase isentropic efficiencyin summer, by this method the compressor isentropic efficiencycan be increasedup to 4%.

KEYWORDS: Centrifugal compressor, Thermodynamic modeling, Isentropic efficiency , Pressure ratio

The main air 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 air passes through inlet air filter. The inlet air filter consists of two high efficiency filters and pre-filter pads. Referring to the document of the equipment, it can be found that acceptable air pressure loss (pressure drop) is about 100 mm of water (10 milli bar) while air passes the filter. Inlet air filters can be washed by water, if after washing, pressure drop is greater than 5 milli bar, the filter should be replaced. Compressed air 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. Electromotor Consumption is 2850 kW and rotational speed is 2980 rpm. Inlet air volumetric Flow rate the compressor at design conditions is 25,291 normal cubic meters per hour. To avoid temperature increases, the air is cooled twice while passing compressor, between stage one and stage two and three. Finally the air exits the compressor with pressure of 6/6 bar and a temperature of about 126 ° C. Ki Wook Song et.al. In 2010, worked on thermodynamic and experimental modeling of a multi-stage centrifugal compressor in order to increase the efficiency and optimization of its energy consumption and finally they could reduce energy consumption in the mentioned compressor for 5%. Claus Hansen et.al (2008) worked on design and modeling of centrifugal compressor by Haysy software. Tarek Abdel Salem et.al (2007) worked on thermodynamic simulation of a multi-stage centrifugal compressor by experimental data and the equations (efficiency, pressure ratio, etc.) and compared it with computer modeling. Bosel (2009) compared the thermodynamic analysis of single-stage and multi-stage compressors and discussed about theirs efficiency and energy. Seriar et.al (2008) involved in the accurate thermodynamic modeling of a cooling compressor using experimental data and related equations, to develop and improve efficiency of the compressor.

Thermodynamic behavior of the compressor subject of study

In this study, the thermodynamic behavior of equipment, in both summer and winter, including the most thermodynamic ranges, was considered. The minimum and maximum values for each parameter are indicated on the chart. Consumption power, inlet air volumetric Flow rate, relative humidity and inlet air density of the compressor used in this study are shown in Figures 1, 2, 3 and 4.

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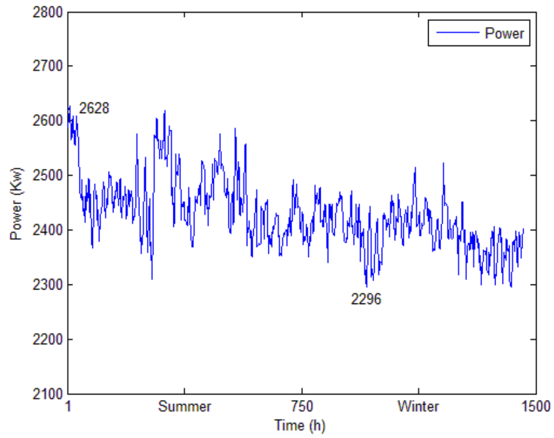

Figure 1. **Power consumption of the compressor subject of study**

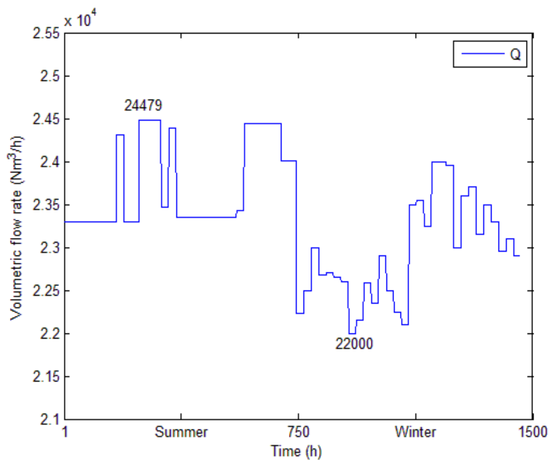

Figure 2. **inlet air volumetric Flow rate of compressor**

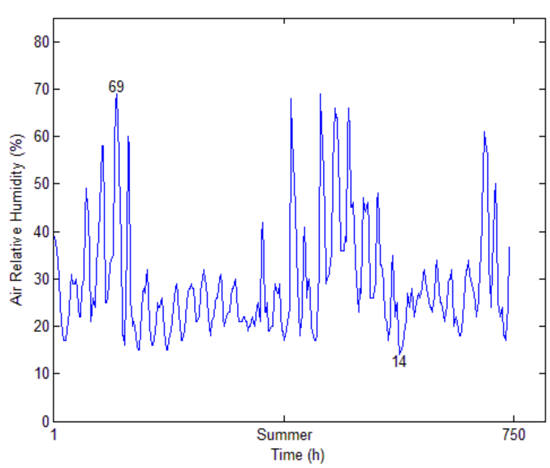

Figure 3. **inletair relative humidity of compressor**

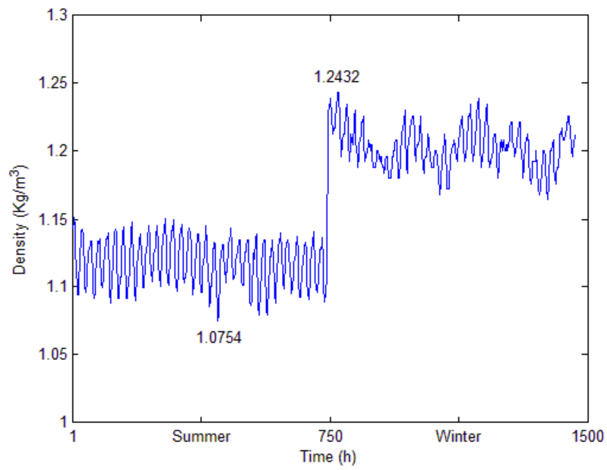

Figure 4. inlet air density of compressor

FIRST STAGE OF COMPRESSOR

For first stage of Compression, ranges of temperature and pressure of the inlet and outlet air the compressor are shown in Figures 5 and 6:

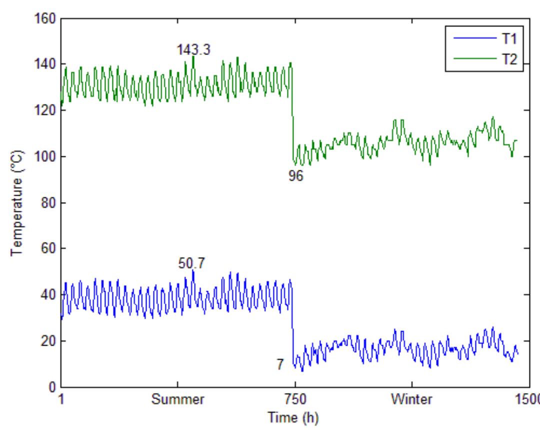

Figure 5. inlet and outlet air temperature of first stage

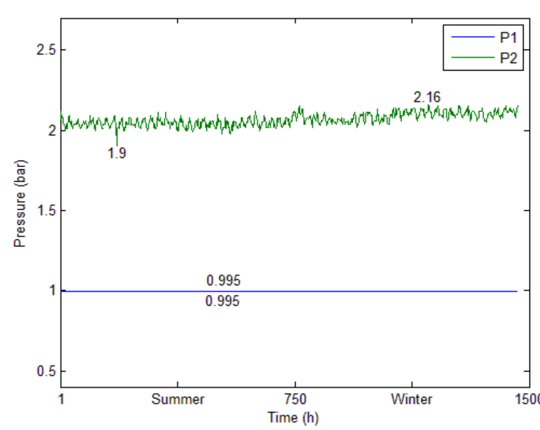

Figure 6. inlet and outlet air pressure of first stage

FIRST INTERCOOLER

As it is shown in Figures 7, 8 and 9, for the first intercooler, the inlet and outlet air temperature and pressure of intercooler and the inlet and outlet water temperature of intercooler were studied.

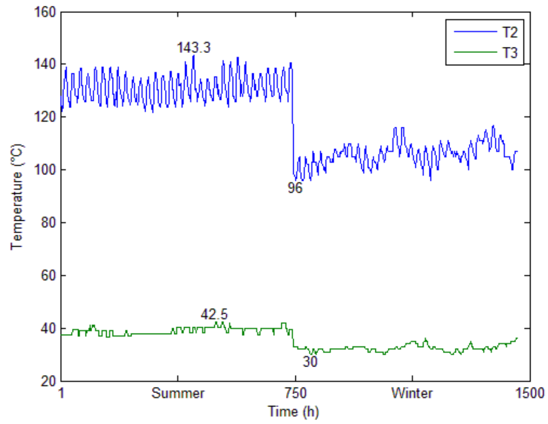

Figure 7. **inletand outletair temperature of first intercooler**

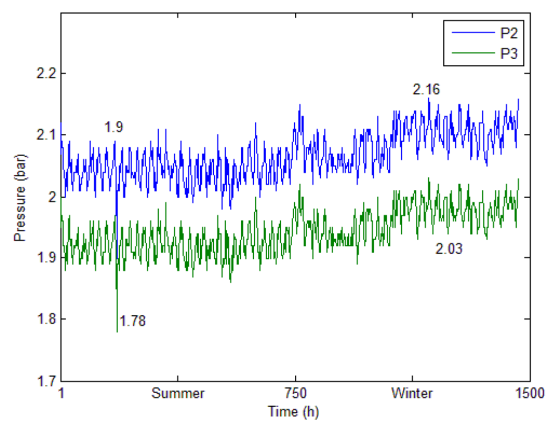

Figure 8. **inlet and outlet air pressure of first intercooler**

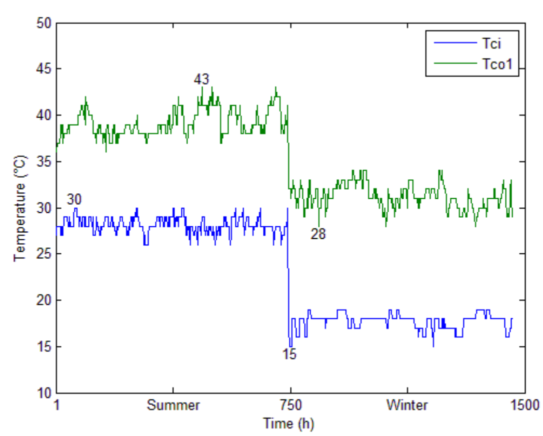

Figure 9. **inlet and outlet water temperature of first intercooler**

SECOND STAGE OF COMPRESSOR

For the second stage of Compression, similar to the first stage, ranges of temperature and pressure of the inlet and outlet air the compressor were reviewed and they are shown in Figures 10 and 11:

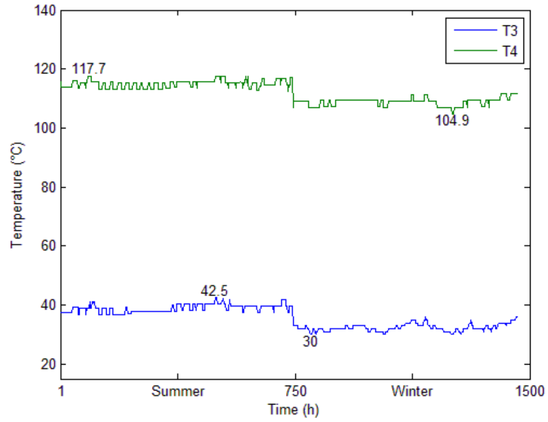

Figure 10. inlet and outlet air temperature of second stage

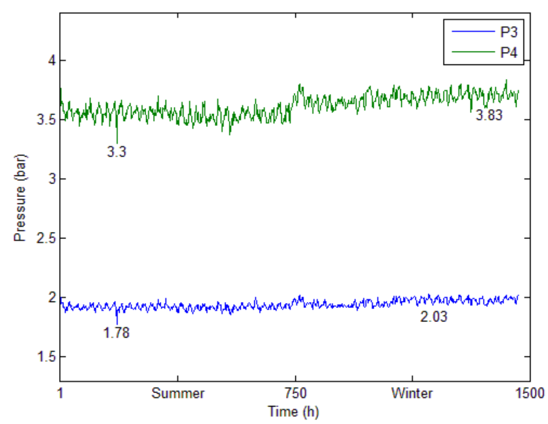

Figure 11. inlet and outlet air pressure of secondstage

SECOND INTERCOOLER

In the second intercooler, similar to first intercooler, the inlet and outlet air temperature and pressure of intercooler and the inlet and outlet water temperature of intercooler were investigated (Figs. 12,13,14).

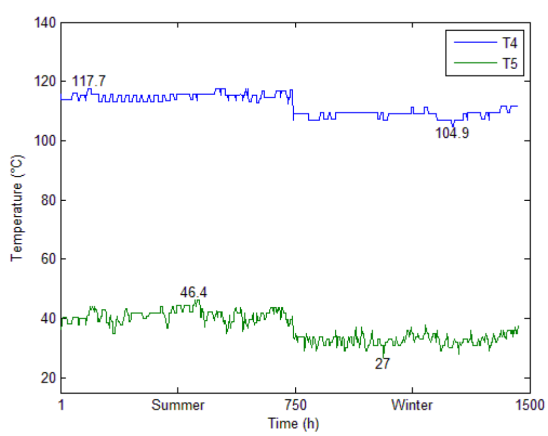

Figure 12. inletand outletair temperature of second intercooler

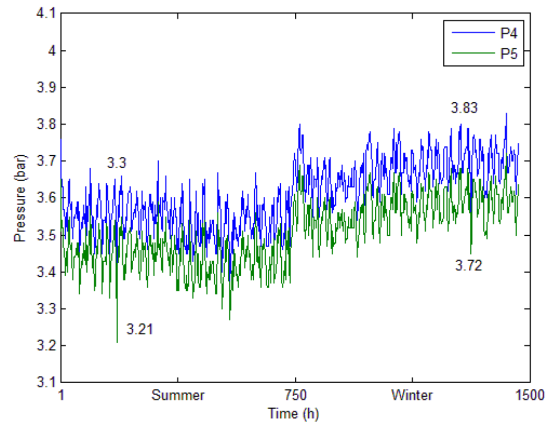

Figure 13. inlet and outlet air pressure of second intercooler

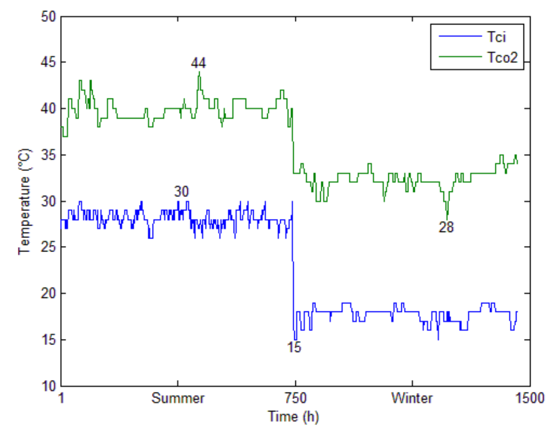

Figure 14. inlet and outlet water temperature of second intercooler

THIRD STAGE OF COMPRESSOR

As shown in Figures 15 and 16, for the third stage of Compression similar to the first stage, ranges of temperature and pressure of the inlet and outlet air the compressor have been investigated:

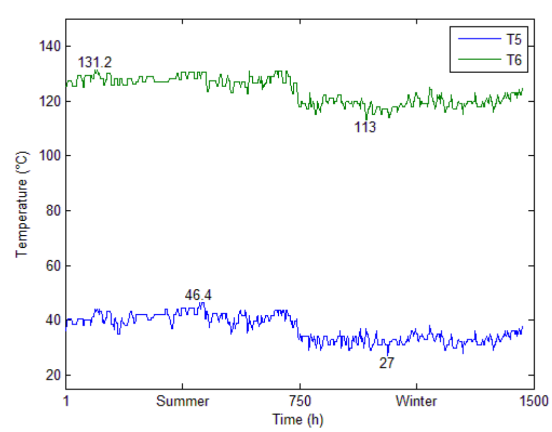

Figure 15. inlet and outlet air temperature of third stage

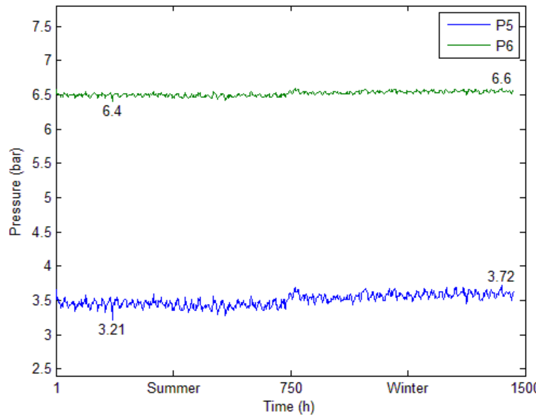

Figure 16. inlet and outlet air pressure of third stage

EQUATION

The governing equations in this study are:

The Governing Equationsof Compression

Thermodynamics rules that used to calculate the power and efficiency of the compressors are independent of the 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 relation 1:

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

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

Now, by considering the air 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:

$$W_{12}=\dot{m}(h_{t2}-h_{t1})=\dot{m}\left(C_{p,ha}(T_2)T_2-C_{p,ha}(T_1)T_1\right) \quad (2)$$

It is assumed that the air humidity is constant during the air compression process due to a dryer system which is mounted between the stages of the compressor. The dryer system can control the air humidity and keep the content of humidity to be within normal range. On the other hand humidity content of the inlet air of the first stage is similar to second and third stages. Compression power of the compressor can be calculated regarding to equations 1 & 2 and inlet air temperature of the second and third stages:

$$W_{34}=\dot{m}(h_{t4}-h_{t3})=\dot{m}\left(C_{p,ha}(T_4)T_4-C_{p,ha}(T_3)T_3\right) \quad (3)$$

$$W_{56}=\dot{m}(h_{t6}-h_{t5})=\dot{m}\left(C_{p,ha}(T_6)T_6-C_{p,ha}(T_5)T_5\right) \quad (4)$$

Enthalpy Governing Equation Considering The Effect Of Humidity

In the air, there is always some water vapor. The amount of water vapor in the air is defined by the vapor pressure of the air.Vapor pressure in the air, cannot be greater than the saturated vapor pressure because in this case, the water must be solid or liquid in air.

Relative humidity expresses the relationship between and the pressure of water vapor in the air and the pressure of saturated water vapor at the same temperature. Relative humidity can be calculated using the following equation 5.

$$\phi = \frac{P_{vap}}{P'_{vap}} \quad (5)$$

In order to assess the influence of relative humidity, saturated water vapor should be calculated. In many references approximate relationship is used to calculate saturated water vapor pressure. To do this, the saturated vapor pressure can be calculated by a regression exponential correlation for temperature range from 273.16 to 647.14 Kelvin,through Equation 6 in which saturated water vapor pressure will be calculated in terms of bar.

$$P'_{vap}(T) = P_{cr} e^{\left[\frac{T}{T_{cr}}(a_1\tau + a_2\tau^{1.5} + a_3\tau^3 + a_4\tau^{3.5} + a_5\tau^4 + a_6\tau^{7.5})\right]}$$

$$P_{cr} = 220\ (bar)$$

$$\tau = 1 - \frac{T_1}{T_{cr}} \qquad T_{cr} = 647/14(k) \quad (6)$$

$$a_1 = -7.85823 \qquad a_2 = 1.83991 \qquad a_3 = -11.7811 \qquad a_4 = 22.6705$$

$$a_5 = -15.9393 \qquad a_6 = 1.77516$$

As the air is considered as an ideal gas, the water vapor in the air can also be considered as an ideal gas. To calculate the constant pressure heat capacity of water vapor, the equation 7 is used to establish the $200\ (k) < T < 1800(k)$ temperature range.

$$C_{pw}(T) = a_w + b_w(T) + c_w(T)^2 + d_w(T)^3$$

$$a_w = 1.80768 \qquad b_w = 17.9273E - 6 \quad (7)$$

$$c_w = 68.0617E - 8 \qquad d_w = -22.443E - 11$$

The air is considered as a combination of dry and water vapor. Therefore, to calculate the constant pressure heat capacity of air, constant pressure heat capacity of dry air should also be considered.

$$C_{pa}(T) = a_a + b_a(T) + c_a(T)^2 + d_a(T)^3$$

$$a_a = 0.982076 \qquad b_a = 16.4395E - 6 \quad (8)$$

$$c_a = 22.868E - 8 \qquad d_a = -88.1495E - 11$$

To calculate the heat capacity of humid air, mole fraction of water vapor should be calculated. Then heat capacity of humid air is achieved:

$$X_{vap} = \frac{P_{vap}}{P_1} = \frac{\phi P'_{vap}}{P_1} \quad (9)$$

$$C_{p,ha} = X_{vap}C_{pw} + (1 - X_{vap})C_{pa} \quad (10)$$

Isentropicgoverning Equation

It is assumed that the compressor is a turbo machine; its function can be considered adiabatic. Based on conventionalgoverning thermodynamic equations the compressor:

(11)

T_1 is the inlet air compressor temperature and T_2 is the outlet air compressor temperatures are the same On the other hand, outlet air temperature is calculated from

(12)

P_1 is the inlet air compressor pressure and P_2 is the outlet air compressor pressure The remarkable thing about the 12 is that in the average temperature of inlet and outlet air compressor is calculated.

MODELING

This modeling is based on by isentropic efficiency Equations and compression power of each stage. Parameters affecting isentropic efficiency in a centrifugal compressor are inlet air temperature, pressure ratio of compression and shaft speed (Ulf Bossel, 2009).shaft speed is constant and air considered as an ideal gas, the pressure ratio is related to inlet air temperature. For thermodynamic modeling of each stage, apart from the effects of humidity due to its negligible impact (Ulf Bossel, 2009), first isentropic efficiency of each compressor is calculated using related equations by taking specific heat coefficient at constant pressure in terms of air temperature and relative humidity of air, and the graph was extracted in terms of the inlet air temperature to each stage of Compression. According to the equations, the outlet air temperature of each stage is modeled in terms of isentropic efficiency of that stage, neural network modeling was performed to study the effect of the inlet air temperature on pressure ratio of each stages.

Accordingly, Data like temperature and pressure of the inlet and outlet air of each stage, temperature of inlet and outlet water of the first and second intercoolers and inlet air volumetric Flow rate were given to the neural network as input data and the desired output were obtained from the most precise neural network. As shown in Figure 17, in this simulation, the neural network composed of four layers, 3 hidden layers (with 50, 100, 11 neurons) and an output layer (10 neurons). The regression of the mentioned neural network is shown in Figure 18 with an accuracy of 0.99

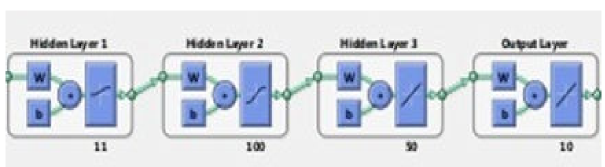

Figure 17. neuralnetwork modeling Algorithm

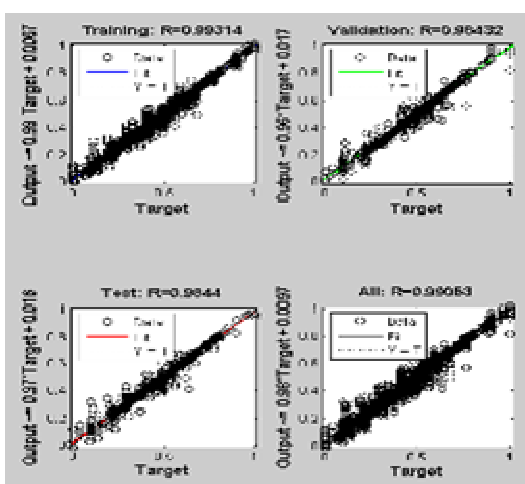

Figure 18. **Regression of neuralnetwork modeling Algorithm**

RESULTS

Based on experimental data, thermodynamic modeling and modeling by neural network algorithm, the following results were obtained and for each stage of compression, effect of inlet air temperature on the isentropic efficiency and pressure ratio is examined:

FIRST STAGE OF COMPRESSION:

as shown in Figure 19 pressure ratio has decreased by increasing the inlet air temperature:

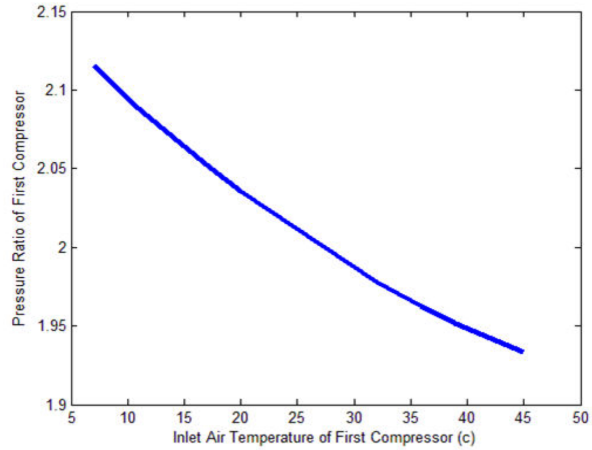

Figure 19. **STAGE1, EFFECT OF INLET AIR TEMPERATURE ON PRESSURE RATIO**

inlet air temperature has a direct effect on theisentropic efficiency, regardless the humidity effects, by considering a constant pressure ratio and shaft speed,As shown in Figure 20,isentropic efficiency has decreased by increasing the inlet air temperature:

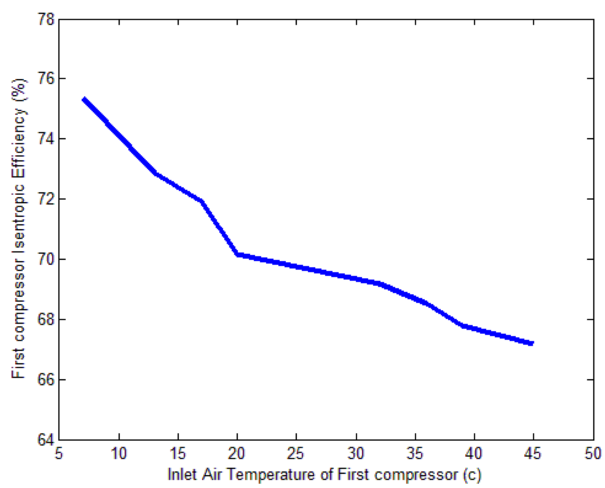

Figure 20. **Stage1, effect of inlet air temperature on isentropic efficiency**

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SECOND STAGE OF COMPRESSION:

as shown in Figure 21,similar to the first stage,pressure ratio has decreased by increasing the inlet air temperature:

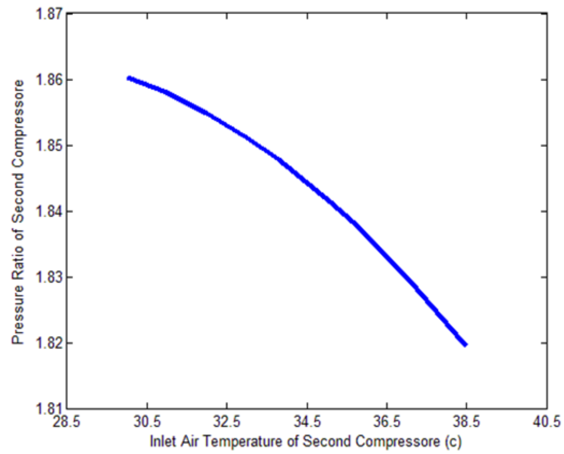

Figure 21. **Stage2, effect of inlet air temperature on pressure ratio**

similar to the first stage,isentropic efficiency has decreased by increasing the inlet air temperature (figure 22):

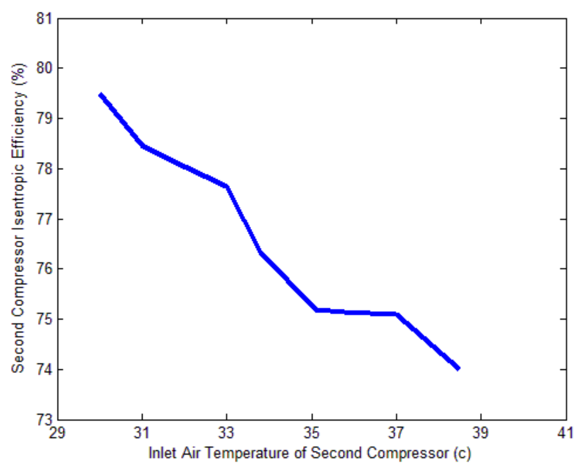

Figure 22. **Stage 2, effect of inlet air temperature on isentropic efficiency**

THIRD STAGE OF COMPRESSION:

According to the line pressure, the outlet pressure of the compressor needs to be constant. As a result the reduction of pressure ratio in previouse stages, should be compensated, there for pressure ratio in third stage, needs to be increased by any increasing in inlet air temperature (figure 23).

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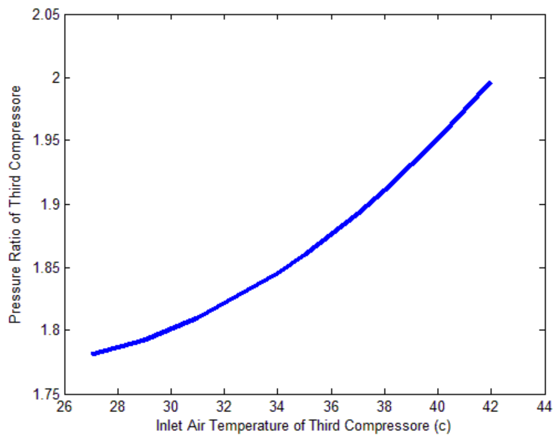

Figure 23. Stage 3, effect of inlet air temperature on pressure ratio

As shown in figure 24, according to the increasing pressure ratio at third stage, isentropic efficiency against first and second stages, increased by any increasing in inlet air temperature .

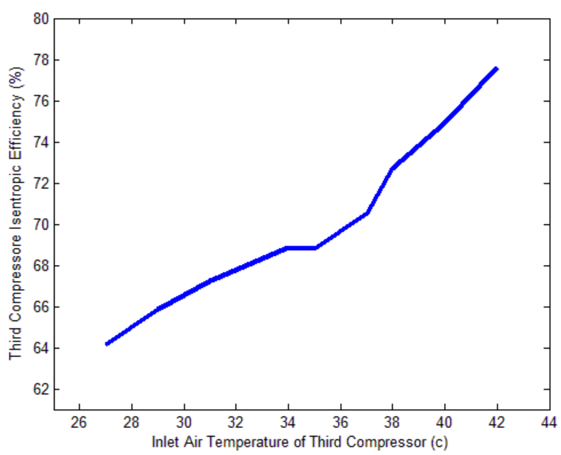

Figure 24. Stage 3, effect of inlet air temperature on isentropic efficiency

SOLUTION TO IMPROVE THE COMPRESSOR PERFORMANCE

Fag evaporative cooling system works by spraying water using sprinklers which are inserted before the filter and cool the air before entering the filter. By this way, decrease in inlet air temperature can cause a significant reduction in compressor's compression power and increase in its efficiency. Based on studies conducted on the method of cooling the inlet air gas turbines of Fajr Petrochemical Company, given the climate and climatic conditions of Mahshahr Special Economic Zone, Fag evaporative cooling system is the most appropriate method and it was observed that by these methods, depending on the relative humidity of the air, the ambient air temperature can be cooled up to 15-10 ° C. According to the study of economic benefits of Fag evaporative cooling method, it seems that, in the studied compressor, this method is the most appropriate strategy for cooling the inlet air the compressor, reducing compression power and increasing its efficiency. Since increase in the inlet air temperature has the greatest effects on the first compressor, therefore only the results of the first compressor are investigated. Based on the studies and modeling of the studied compressor, it was observed that if the ambient temperature can be reduced up to 15-10 ° C, isentropic efficiencyof the first compressor will be increased about 4% (Figure 27).

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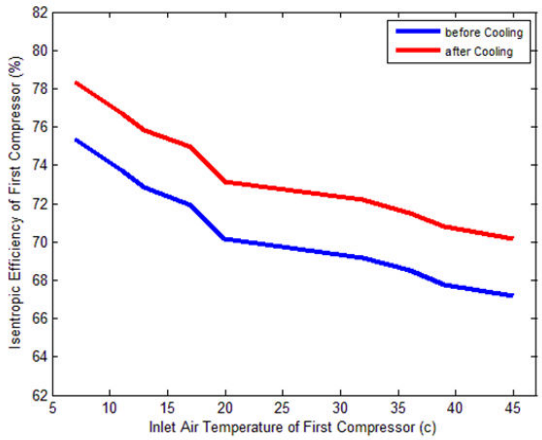

Figure 25. Effect Of Inlet Air Temperature Onisentropic Efficiency Before And After Cooling

CONCLUSION

Based on thermodynamic modeling and modeling by neural network algorithm in this study it was observed that in the first and second stage of compressor,isentropic efficiency and pressure ratio decreased by increasing the inlet air temperature. The negative effect of increasing temperature on the first stage is more than second stage.in third stage,isentropic efficiency and pressure ratio increased by increasing the inlet air temperature,against first and second stages.

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