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TECHNO-ECONOMICAL STUDY ON THE BACK PRESSURE TURBINE INSTALLATION IN THE WATER, ELECTRICITY AND STEAM UNITS OF THE TEHRAN OIL REFINERY

Amir Ashoori Barmchi[1], *Ahmad Tavasoli*[1, 2], *Babak Behnejad* [1]

[1] *Department of Energy Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran*
[2] *School of Chemistry, College of Science, University of Tehran, Tehran, Iran*

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Abstract

The importance of energy crisis forced all industries to minimize energy consumption of the plants. The waste of energy in PRV (Pressure Reduction Valve) on the line of working fluid with high pressure and temperature in Tehran oil refinery is significant. This refinery uses PRV for reducing pressure of steam flow with 600 $\mathbf{psi_g}$ and 300 $\mathbf{psi_g}$ for some of their drivers such as medium and low pressure pumps and turbo compressors. Because of high amount of energy waste of high pressure working fluid on PRV, this study aimed to use this energy for turning a turbine to make work and making needed low pressure stream for drivers. After simulating the lines with turbines, some lines have output stream with lower temperature of targeted output stream temperature. To solve these problems, two extra simulations were performed: One with placing preheater on input steam stream to turbine and other with reducing input stream to turbine and mixing it with high pressure and temperature on outlet stream to increasing the temperature and pressure of stream to the targeted output conditions. Also, Economic calculations were done to choose optimal alternatives. The results of simulation and economical calculations showed that, the values of SPP for all simulated lines were less than one year and the IRR for all of them are significant. So investment on all lines for turbo expander installation is recommended. For second line of North Water, Electricity and Steam unit, investment on addition of turbo expander and preheater and for second line of Isomerization unit, investment on addition of turbo expander and mixer splitter are the optimal alternatives.

Keywords: Back Pressure Turbine; Pressure Reduction Valve; Thermoflex, Steam.

1. Introduction

Recent energy crisis and high costs of energy products encourage every plants and refineries to optimize and reduce energy consumptions of their products and utility lines.

Tehran oil refinery was established in 1974 by an American company (FLUOR) that involves two similar plants, Northern and Southern refineries. The steam networks in the two oil refineries are similar. A 16 inch 650 psig steam line and a 8 inch 60 Psig steam line interconnects the north and south refinery steam systems to provide operational flexibility and assist in the startup of refineries [1]. Figure 1 shows the complex steam network system [1].

Three units (North Water, Electricity and Steam unit, South Water, Electricity and Steam unit and Isomerization unit [2] use PRVs for converting High Pressure (HP) stream to Medium pressure (MP) or Low Pressure (LP) stream to utilize them for their drivers in utility units such as Heating Systems, Steam Strippers, Reboilers, Heating Coil Tanks, Utility stations, Distillation Ejectors and Mechanical Turbo Pumps. By Replacing Turbines with these PRVs, we can reduce the line steam stream pressure while produce work with the turbine.

1.1. Current schematic of the lines

The current schematic for every line is shown in Figure 2.

The purpose of the steam source in figure 2 is HP, MP and LP lines mentioned in figure 1 and the purpose of the steam sink is Drivers in utility units of the mentioned earlier lines such as Heating Systems, Steam Strippers, Reboilers, Heating Coil Tanks, Utility stations, Distillation Ejectors and Mechanical Turbo Pumps.

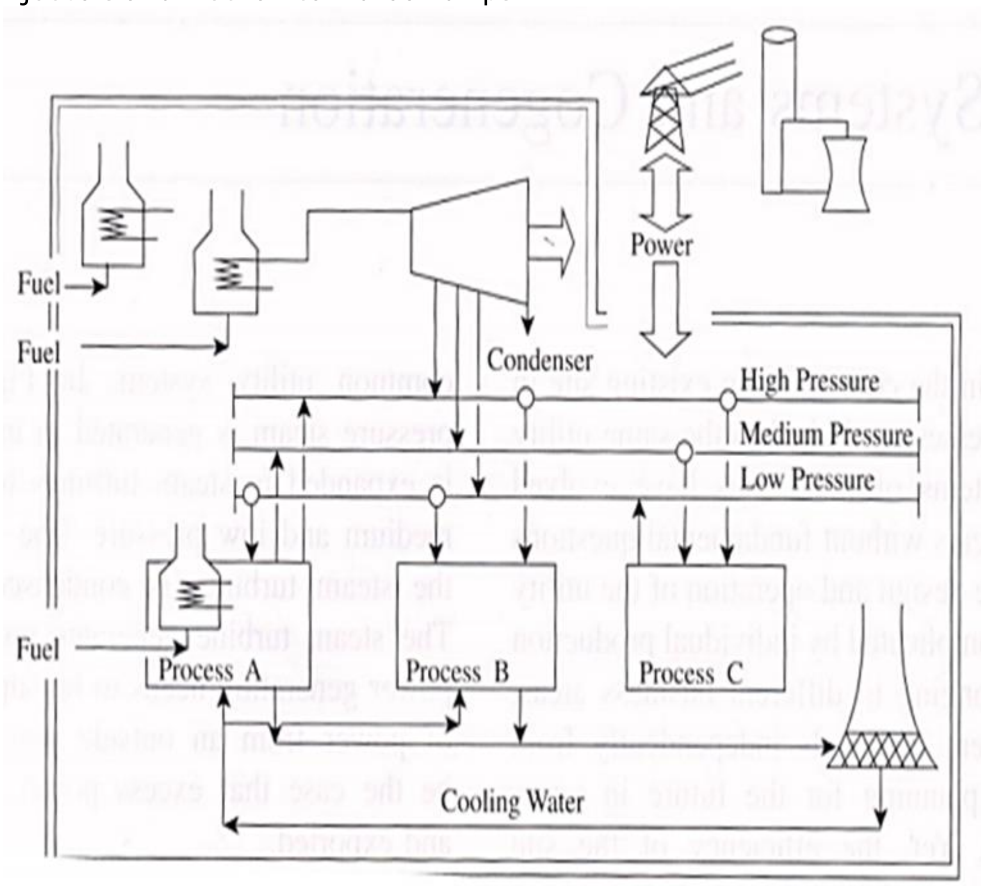

Figure1. Schematic of steam network

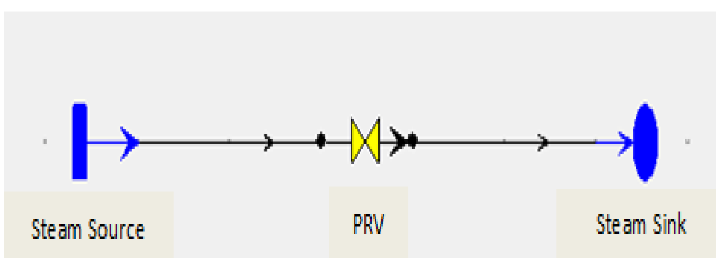

Figure2. Current schematic for reducing pressure of steam stream for every line

1.2. Thermodynamic properties and Irreversibility Intensity of Current Conditions

The thermodynamic properties of inlet and outlet stream of PRV of every line are presented in table 1. Using Equation 1 [3] and assuming (T_0 =298.15K) the irreversibility intensity were calculated for the current operating condition of PRVs for every line and were presented in Table 1.

$$\dot{I} = \dot{m}T_0\dot{s}_{gen} = \dot{m}(\psi_i - \psi_e) = W_{rev} - W = \dot{m}[(h_i - h_e) - T_0(s_i - s_e)] \qquad (1)$$

Table 1. The thermodynamic properties of inlet and outlet stream of PRV for every line at current operational conditions

Unit	Stream	T[℃]	P_{abs}[MPa]	h[KJ/Kg]	s[KJ/Kg.K]	İ (KW)
1st line of north unit	PRV Inlet	371.111	4.238	3139	6.631	745.684
	PRV Outlet	272.5	2.170	2952	6.604	
2nd line of north unit	PRV Inlet	279.44	2.170	2969	6.635	1129.6895
	PRV Outlet	212.778	0.515	2882	7.101	
Line of south unit	PRV Inlet	371.111	4.238	3139	6.631	497.123
	PRV Outlet	272.5	2.170	2952	6.604	
1st line of Isomerization unit	PRV Inlet	371.111	4.238	3139	6.631	1491.190
	PRV Outlet	272.5	2.170	2952	6.604	
2nd line of Isomerization unit	PRV Inlet	371.111	4.238	3139	6.631	4964.131
	PRV Outlet	212.778	0.515	2882	7.101	

2. Review of previous studies

For many years, Turbo expanders have been used in cryogenic processing plants to provide low-temperature refrigeration. Current commercial models of Turbo expanders exist in the power range of 75 KW to +25 MW, so many applications are possible. Many Turbo expanders are designed to operate in the pressure within 130-200 bars. According to some publications [4] and the marketing web sites [5], the Turbo expanders are now available from 75 KW up to 130 MW. Natural gas expansion through Turbo expanders generates electric power with far greater efficiency than the conventional thermal power utilities burning gas as fuel. In addition, the Turbo expanders do not create greenhouse gases or significant environmental pollutions [6]. For more reliability and safety of operation, the existing conventional pressure reduction valves are held, and the expansion turbines are installed in parallel with them. In this condition, the redundant standby regulator valve ensures continued safe operation in the event of Turbo expander failure [7]. Most gases cool during the expansion (Joule-Thompson effect) [8]. Nevertheless, a temperature drop of the gas is high in the case of employing the Turbo expanders so; preheating of the gas is required to avoid gas freezing at the outlet [9]. In some gas compositions, water or liquid hydrocarbons are produced at low temperatures which yield to hydrates, blockage of the pipeline, corrosion of the blades of the turbine and failure of the equipment. Therefore, it is essential to keep the outlet temperature above the hydrate formation range [10].

Khodaei *et al.* [1] simulated Steam Network with STAR used for determining optimized conditions and with this method energy saving potential and total operational cost in two states (fixed fuel proportion and variable fuel proportion) were calculated. Khodaei *et al.* selected the Tehran refinery steam network as a case study and after steam network simulation and optimization, best scenario with lowest total cost and minimum reduction of CO_2 gas were determined. Neelis *et al.* [11] used backpressure turbines for reducing produced steam pressure in process that extra produced energy recovery in this turbines is possible and this turbines are the best alternative stead of PRVs (that waste working fluid energy). US Department of energy [12] emphasized on using ultra-high-pressure boilers and mentioned to increase operational power of steam boilers because of reduction outlet steam temperature when substituting PRVs with Backpressure turbines that it's like as preheating inlet stream of backpressure turbines. They also reminded modern steam boilers have efficiency about 80%. Another study [6] used backpressure turbines for energy recovery of gas pressure reduction stations stead of PRVs. They used Dresser Flo System reference to show the amount of power generation. Howard [7] studied the performance of a hybrid Turbo expander and fuel cell (HTEFC) system for power recovery at natural gas pressure reduction stations. He preheated inlet stream to Turbo expander in order to compensate temperature reduction of outlet stream of Turbo expander. Andrei *et al.* [13] investigated the recovery of wasted mechanical energy from the reduction of natural gas pressure.

3. Energy recovery, power production, validation and economic evaluation method

3.1. Using Turbo expander for reducing pressure of steam stream for all lines in order to energy recovery during pressure reduction

In order to recover the lost energy during steam stream pressure reduction in three mentioned earlier units, the schematic shown in Figure 3 is used.

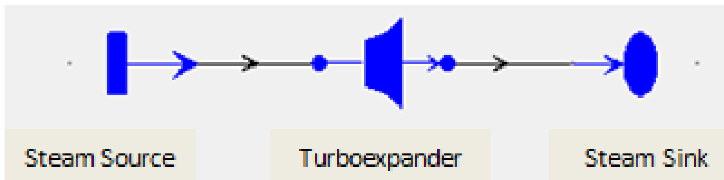

Figure3. Alternative schematic for reducing pressure of steam stream for every line

For this schematic, the amount of produced work with Turbo expander is calculated using Equation 2, and the amount of irreversibility intensity is calculated by Equation 1.

$$\dot{m}h_i = \dot{m}h_e + \dot{w} \quad (2)$$

The efficiency of Turbo expander is calculated by:

$$\eta = \dot{w}_a / \dot{w}_s = \frac{h_{iTu} - h_{eTu}}{h_{iTu} - h_{esTu}} \quad (3)$$

The simulated Turbo expander with Thermoflex Lite Version 13.0 (Thermoflow Inc, USA;) has throttle inlet pressure control, and it is a single shaft with 3600 rpm shaft speed. After simulation with thermoflex, we realized that by Turbo expander with outlet pressure of 74.69 psi_a, the outlet stream temperature will be lower than the desired temperature, and therefore we need to preheat inlet stream in order to achieve desired outlet stream temperature. Two scenarios are offered: First, by preheating inlet stream with gas fired pre-heater that is illustrated in Figure 4 and second with reducing inlet stream to Turbo expander and mixing its outlet stream with inlet remain stream didn't pass of Turbo expander in order to achieve desired outlet condition as illustrated in Figure 5.

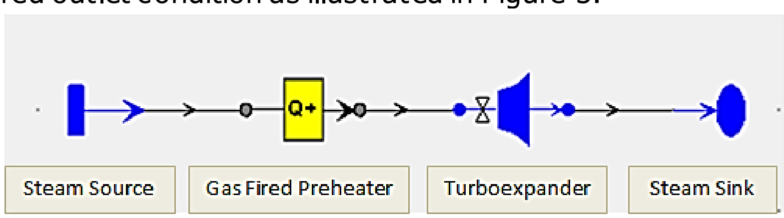

Figure 4. First Alternative schematic for lines with outlet pressure 74.69 psi_{abs}

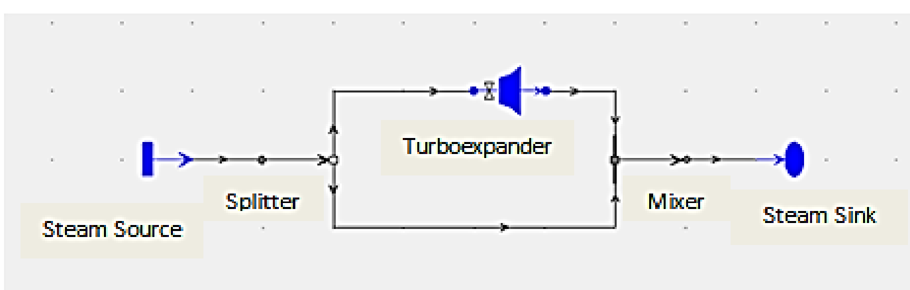

Figure 5. Second Alternative schematic for lines with outlet pressure 74.69 psi_{abs}

The amount of produced work for a unit with Turbo expander and preheater is calculated using Equation 4 and the amount of irreversibility intensity is calculated with Equation 5. The calculations were done with first low efficiency equal to 80% for gas fired preheater [3].

$$\dot{m}h_i + \dot{Q} = \dot{m}h_e + \dot{w} \quad (4)$$

$$\dot{I} = T_0\dot{S}_{gen} = \Sigma(1-\frac{T_0}{T})\,\dot{Q}_{c.v} + \dot{m}[(h_i - h_e) - T_0(s_i - s_e)] - \dot{W} \quad (5)$$

The value of irreversibility is depended to the hot reservoir temperature [14]. So for making results of produce work for a unit with Turbo expander and preheater more comparable with the results of the unit with Turbo expander and splitter-mixer, we did all calculations at the same temperature for inlet stream and temperature of gas fired preheater.

Thus for working based on desired inlet and outlet thermodynamic properties, the stream splitting coefficient (x) in splitter is calculated by equations 3, 6 and 7 and real produced work of Turbo expander is calculated by equation 8 [3].

$$x\dot{m}h_i = x\dot{m}h_{es_{Tu}} + \dot{w}_{s_{Tu}} \quad (6)$$

$$x\dot{m}h_{e_{Tu}} + (1-x)\,\dot{m}h_i = \dot{m}h_e \quad (7)$$

$$\dot{w}_{ac_{Tu}} = x\dot{m}(h_{i_{Tu}} - h_{e_{Tu}}) \quad (8)$$

Also for all units, we assume the first low efficiency of the generator is equal to 75%.

3.2. Economic evaluation method

In order to economic evaluation, we used the initial cost data from Tehran oil refinery and HHV of methane gas [15] as presented in Table 2 and for the prices of turbo expander & preheater, we used equations 9 and 10 [16]. The coefficients to calculate the cost of preheater is shown on Table 3.

$$\mathbf{C_{Tur}} = 0.378(\mathbf{HP})^{\mathbf{0.81}}\ \text{K\$},\ 20 < HP < 5000\ \ (1HP = 0.7457KW) \quad (9)$$

$$\mathbf{C_{PreH}} = 1.218\ k\ (1+\boldsymbol{f_d}+\boldsymbol{f_p})\boldsymbol{Q}^{\mathbf{0.82}}\ \text{K\$},\ 2 < Q < 30\ M\ Btu/hr(1Btu = 1055.06J) \quad (10)$$

Table 2. Provided cost data from Tehran oil refinery

Variable	Total cost (IRR)	Total cost (USD)
1 ton of HP Steam production	580 000	17.576
Cost of production 1KWh electricity	4 800	0.145
Cost of annual maintenance	16 500 000	500
Price per cubic meter of methane gas with ρ=0.8 kg/m^3	3 000	0.091
HHV per cubic meter of methane gas with ρ=0.8 kg/m^3 ≈ 39 MJ ≈ 10.833 KWh [15]		
Inflation Rate = 20%	Discount Rate = 22%	

1USD ≈ 33000 IRR

Table 3. Coefficients of preheater capital cost equation

Tube Material	k	Design Type	f_d	Design Pressure (psi)	f_p
Carbon steel	27.3	Cylindrical	0	Up to 500	0
Cr Mo steel	40.2	Dowtherm	0.33	1,000	0.15
Stainless	42.0			1,500	0.20

We selected stainless tube material and cylindrical type of preheater for our calculations, and so in equation 10 we will have k=42 and f_d= 0.

To estimate the cost of generator we used figure 6 [17], where in A is synchronous power generator in terms of KW and n is allowed generator speed and we assume it is 3600 rpm. In addition, we assume 1Euro ≈ 1.12946$.

We used equations 11-14 [18] to plot cash flow diagram and for calculating Simple Payback Period (SPP), Net Present Value (NPV) and Internal Rate of Return (IRR) for every line in a period of 15 years that is almost equal to the useful life of the equipment.

$$DF = (1+\frac{DR}{100})^{-n} \quad (11)$$

$$\text{IF} = \left(1 + \frac{IR}{100}\right)^{-n} \quad (12)$$

$$\text{Real Interest Rate} = \text{Discount Rate - Inflation Rate} \quad (13)$$

$$\text{Simple Payback Period} = \frac{\text{Capital Cost}}{\text{Annul Net Cost Saving}} \quad (14)$$

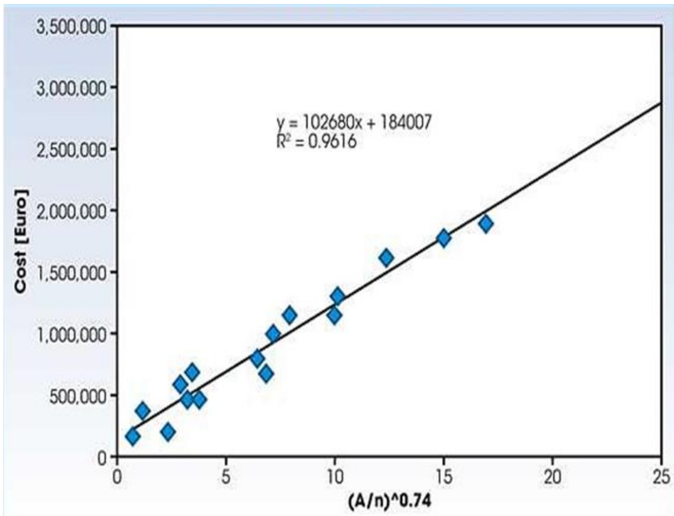

Figure 6. Synchronous generator capital cost in terms of its power and speed.

4. Results of technical simulation and economic evaluation

4.1. Results of Thermoflex software simulation

4.1.1. Results of the first line of North Water, Electricity and Steam unit with Turbo expander simulation

Having thermodynamic properties of inlet and outlet Stream of PRV of the first line of the north unit, simulation of the system was performed. The results are shown on Table 4 and Figure 7.

Table 4. Results of first North Water, Electricity and Steam unit simulation with Turbo expander

Component	Sat. T [℃]	P [bar]	T [℃]	M $[ton/h]$	h[KJ/Kg]	s[KJ/Kg. K]
H_2O in	253.9	42.38	371.10	15	3141.82	6.631
H_2O out	216.6	21.70	296.64	15	3011.50	6.708
Shaft Power = 434.4 KW_e				Total Generator = 324.7 KW		
Overall apparent isentropic efficiency = 76.07%				Steam Superheat = 80.10 ℃		

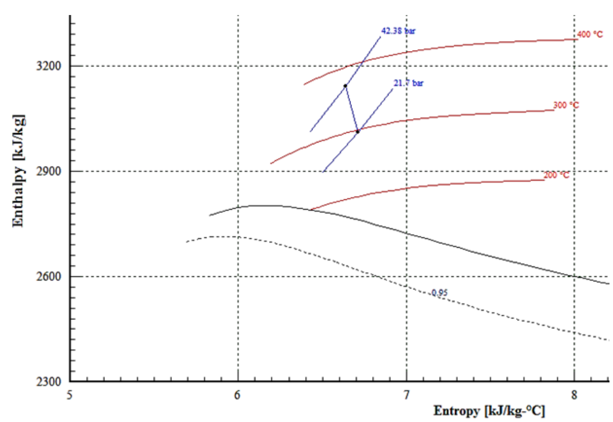

Figure 7. Process plot of enthalpy in terms of entropy of first line of north unit with Turbo expander

4.1.2. Results of second North Water, Electricity, and Steam unit simulation

4.1.2.1. Results of the second line of North Water, Electricity and Steam unit with Turbo expander and gas fired preheater simulation

By simulation line in accordance with Figure 4 and based on Considering the thermodynamic properties of inlet and outlet stream of PRV of the second line of the north unit (Table 1) and the data on Figure 4, the line is simulated, and the results are shown in Table 5 and Figure 8.

Table 5.Output results of second North Water, Electricity and Steam unit with Turbo expander and gas fired preheater simulation

Component	T [℃] Sat	P [bar]	T [℃]	M $[ton/h]$	h[KJ/Kg]	s[KJ/Kg. K]
1.Input to Heat Adder	216.51	21.688	279.4	18	2969.67	6.635
2.Output of Heat Adder	215.5	21.263	341.77	18	3118.01	6.895
3.Output of Steam Turbine	152.96	5.150	225.64	18	2909.23	7.157
Heat input to Heat Adder = 741.7 kW			Heat transferred from external source			
Shaft Power = 835.2 KW_e			Total Generator = 624.2 KW			
Overall apparent isentropic efficiency = 63.39%			Steam Superheat = 72.68 ℃			

4.1.2.2. Results of second North Water, Electricity, and Steam unit with Turbo expander and mixer-splitter simulation

Having thermodynamic properties of inlet and outlet Stream of PRV of the second line of the north unit, simulation of the system was performed. The results are shown on table 6 and figure 9.

Table 6.Output results of second North Water, Electricity and Steam unit with turboexpander and mixer-splitter simulation

Component	T [℃] Sat	P [bar]	T [℃]	M $[ton/h]$	h[KJ/Kg]	s[KJ/Kg. K]
1.Input of Source	216.6	21.698	279.40	18	2969.67	6.635
2. Input to Turbine	216.6	21.698	279.40	12.5856	2969.67	6.635
3.Output of Turbine to Mixer	173.845	8.68	204	12.5856	2844.5748	6.791
4.Output of Splitter to Mixer	216.6	21.698	279.40	5.4144	2969.67	6.635
5.Output to Sink	152.96	5.150	212.8	18	2882	7.101
Shaft Power = 434.9905 KW_e			Total Generator = 326.2 KW			
Overall apparent isentropic efficiency = 63.16%			Steam Superheat = 59.22℃			

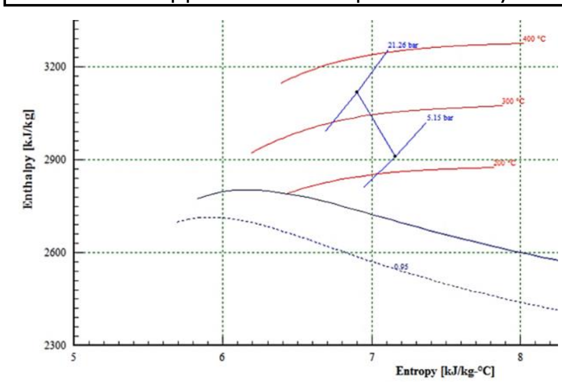

Figure 8. Process plot of enthalpy in terms of entropy of second line of north unit with turboexpander and gas fired preheater

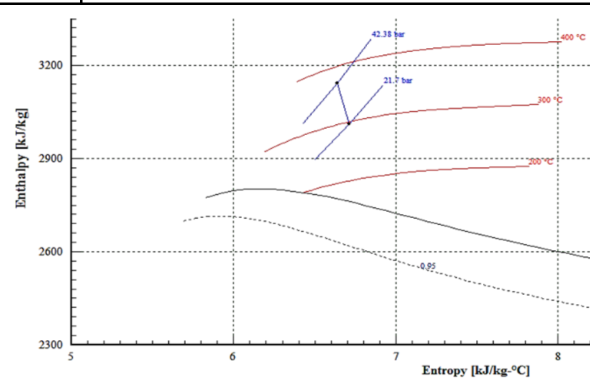

Figure 9. Process plot of enthalpy in terms of entropy of second line of north unit with turbo-expander and mixer-splitter

4.1.3. Results of South Water, Electricity and Steam unit with turboexpander simulation

Having thermodynamic properties of inlet and outlet Stream of PRV of the first line of the north unit on table 1, simulation of the system was performed. The results are shown on table 7 and figure 10.

Table 7. Output results of South Water, Electricity and Steam unit simulation with Turbo expander

Component	Sat. T [℃]	P [bar]	T [℃]	M $[ton/h]$	h[KJ/Kg]	s[KJ/Kg. K]
H_2O in	253.9	42.38	371.10	10	3141.82	6.631
H_2O out	216.6	21.70	296.63	10	3011.50	6.708
Shaft Power = 289.6 KW_e				Total Generator = 216.5 KW		
Overall apparent isentropic efficiency =76.06%				Steam Superheat = 80.9℃		

4.1.4. Results of Isomerization unit simulation

4.1.4.1. Results of the first line of Isomerization unit simulation with Turbo expander

Having thermodynamic data, simulation of first line of isomerization unit was performed. The results are shown on table 8 and figure 11.

Table 8. Output results of first line of Isomerization unit simulation with turboexpander

Component	Sat. T [℃]	P [bar]	T [℃]	M $[ton/h]$	h[KJ/Kg]	s[KJ/Kg. K]
H_2O in	253.9	42.38	371.10	30	3141.82	6.631
H_2O out	216.6	21.70	296.64	30	3011.50	6.708
Shaft Power = 868.8 KW_e				Total Generator = 649.3 KW		
Overall apparent isentropic efficiency =76.07%				Steam Superheat = 80.10℃		

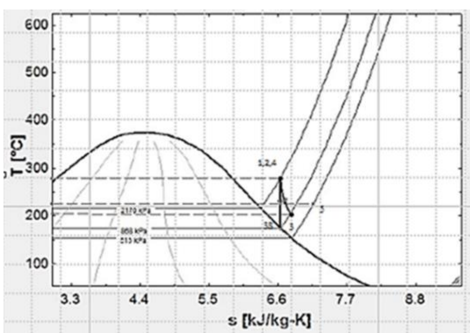

Figure 10. Process plot of enthalpy in terms of entropy of South Water, Electricity and Steam unit simulation with turboexpander

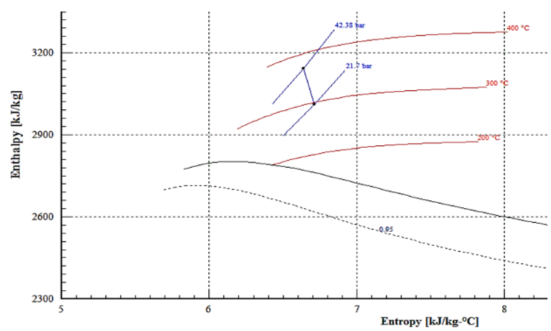

Figure 11. Process plot of enthalpy in terms of entropy of first line of Isomerization unit simulation with turboexpander

4.1.4.2. Results of the second line of isomerization unit simulation with Turbo expander and gas fired preheater

Having thermodynamic data, simulation of the second line of isomerization unit with Turbo expander and gas fired preheater was performed. The results are shown in table 9 and figure 12.

Table 9. Output results of second line of Isomerization unit simulation with turboexpander and gas fired preheater

Component	Sat. T [℃]	P [bar]	T [℃]	M [t/h]	h[KJ/Kg]	s[KJ/Kg. K]
1. Input to Heat Adder	253.76	42.38	371.11	45	3141.82	6.631
2. Output of Heat Adder	252.57	41.532	458.94	45	3349.39	6.945
3. Output of Steam Turbine	152.96	5.150	232.07	45	2922.89	7.183
Heat input to Heat Adder = 2594.5648 kW		Heat transferred from external source				
Shaft Power = 4265 KW_e				Total Generator = 3187.6 KW		
Overall apparent isentropic efficiency = 79.2%				Steam Superheat = 79.11℃		

4.1.4.3. Results of the second line of Isomerization unit simulation with turboexpander and mixer-splitter

Having thermodynamic data, simulation second line of isomerization unit with Turbo expander and mixer-splitter was performed. The results are shown on table 10 and figure 13 (x= 0.8948).

Table 10. Output results of second line of Isomerization unit simulation with turboexpander and mixer-splitter

Component	T [℃] Sat	P [bar]	T [℃]	M, [ton/h]	h[KJ/Kg]	s[KJ/Kg. K]
1.Input of Source	253.9	42.38	371.11	45	3141.82	6.631
2. Input to Turbine	253.9	42.38	371.11	40.266	3141.82	6.631
3.Output of Turbine to Mixer	174.4	8.786	207.2	40.266	2844.574	6.8
4.Output of Splitter to Mixer	253.9	42.38	371.11	4.734	3141.82	6.631
5.Output to Sink	152.96	5.150	212.778	45	2882	7.101
Shaft Power = 3247.75KW_e			Total Generator = 2435.8125 KW			
Overall apparent isentropic efficiency = 78.73%			Steam Superheat = 59.818 ℃			

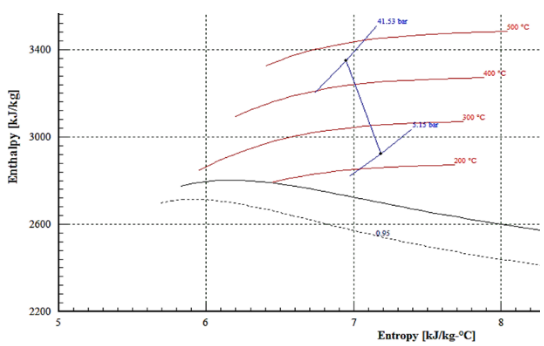

Figure 12. Process plot of enthalpy in terms of entropy of second line of Isomerization unit simulation with Turbo expander and gas fired preheater

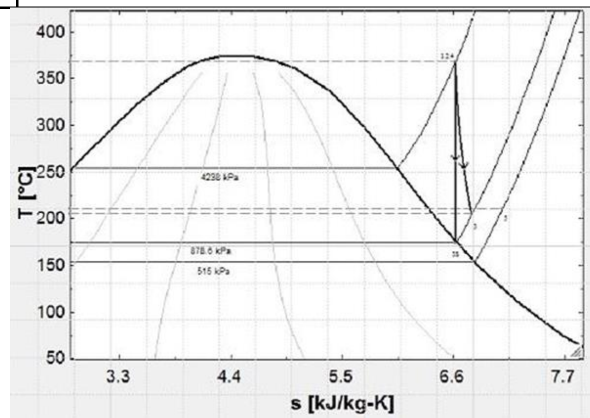

Figure 13. Process plot of enthalpy in terms of entropy of second line of Isomerization unit simulation with Turbo expander and mixer-splitter

4.2. Final results of Thermoflex software simulation

Considering the thermodynamic data in table 1 and figure 3, 4 and 5, the system was simulated with Thermoflex. The results are presented on table 11.

Table11. Results of turboexpander power generation and manual irreversibility intensity calculations

Num	Unit	P_i (psi_g)	P_o (psi_g)	$\dot{m}$ (ton/hr)	$\eta_{1lawTur}$ (%)	P_{Tur} (KW)	$\dot{I}_{PRV\ Line}$ (KW)	$\dot{I}$ (KW)	$P_{Gen\ with\ \eta=75\%}$ (KW)
1	1N	614.69	314.69	15	76.07	434.4	745.68	204.31	324.7
2	2N with Preheater	314.69	74.69	18	63.39	835.2	1129.69	678.65	624.2
3	2N with Mixer Splitter	314.69	125.89	12.58	63.16	434.99	1129.69	694.69	326.2
4	South	614.69	314.69	10	76.06	289.6	497.12	136.17	216.5
5	1ISO	614.69	314.69	30	76.07	868.8	1491.19	408.51	649.3
6	2ISO with Preheater	614.69	74.69	45	79.2	4265	4964.13	2521.71	3187.6
7	2ISO with Mixer Splitter	614.69	127.43	40.27	78.73	3247.75	4964.13	1751.63	2435.81

4.3. Results of economic evaluation

We calculated equipment capital cost with equations 9 and 10 and figure 6 and an annual investment of working fluid, annual net real energy product and annual net real saving of energy product. The results are presented in table 12. Cash flow diagrams are presented in figures 14 to 20 for lines and SPP, NPV and IRR presented in table 13.

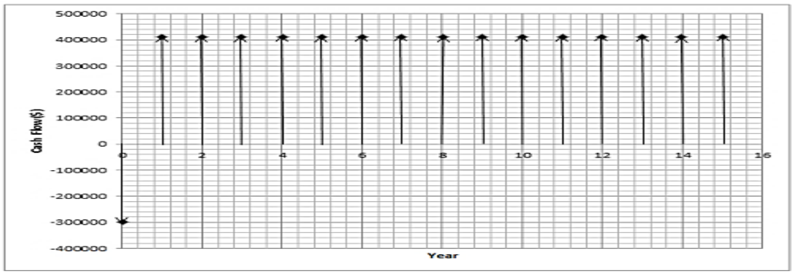

Figure 14. Cash flow diagram of first line of north unit

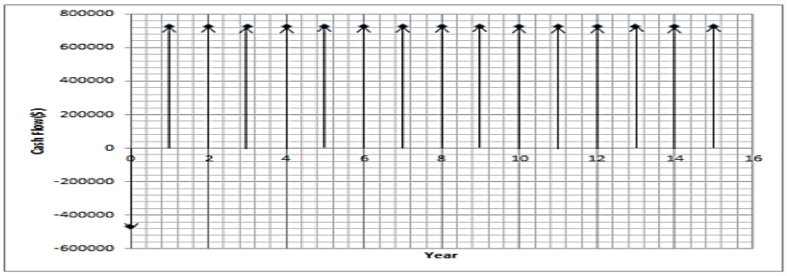

Figure 15. Cash flow diagram of second line of north unit with preheater

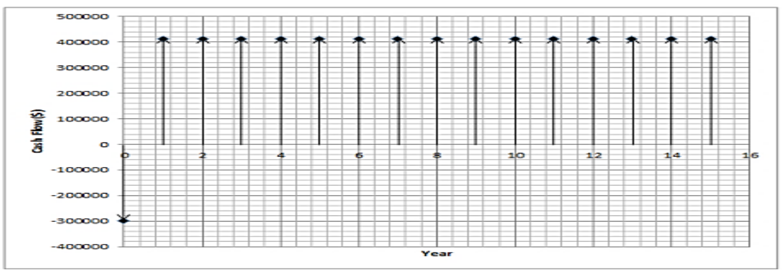

Figure 16. Cash flow diagram of second line of north unit with mixer and splitter

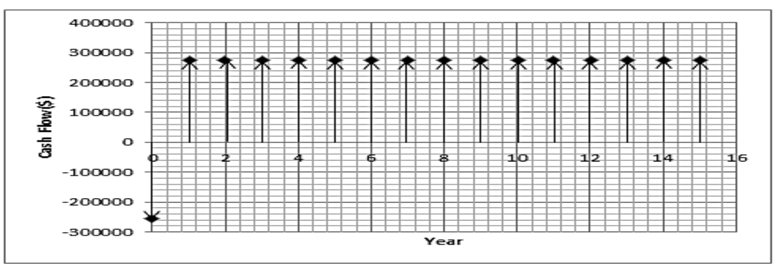

Figure 17. Cash flow diagram of south unit line

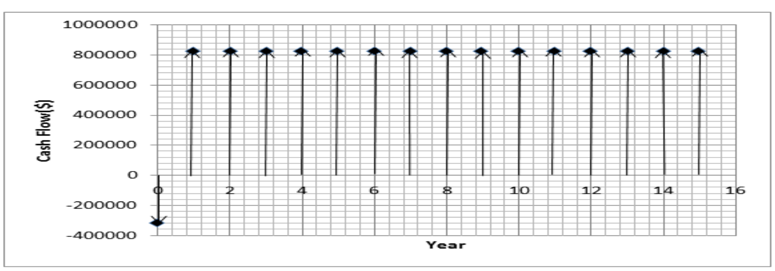

Figure 18. Cash flow diagram of first line of Isomerization unit

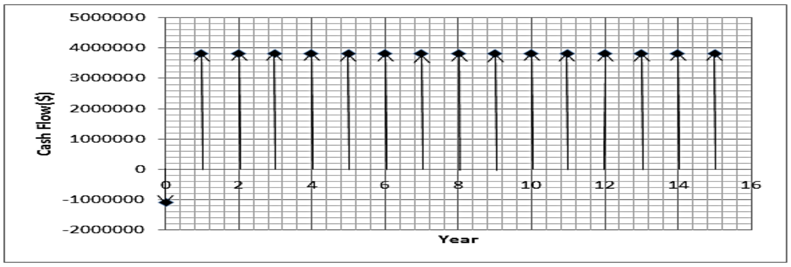

Figure 19. Cash flow diagram of second line of Isomerization unit with preheater

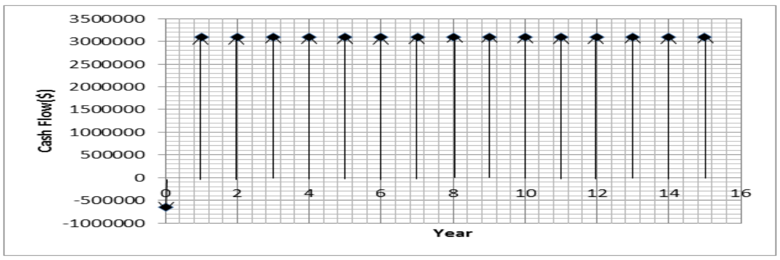

Figure 20. Cash flow diagram of second line of Isomerization unit with mixer and splitter

Table 12. Annual investment of working fluid, annual net real saving of energy product and equipment capital cost of simulated lines

Num	Unit	Annual maintenance capital cost ($)	Annual investment of working fluid ($)	Annual fuel cost of preheater ($)	Annual net real energy product (kWh)	Annual net real saving of energy product ($)
1	1N	500	2309486.4	-	2844372	412433.94
2	2N with Preheater	500	2771383.68	68223.66	5467992	792858.84
3	2N with Mixer Splitter	500	2771383.68	-	2857512	414339.24
4	South	500	1539657.6	-	1896540	274998.3
5	1ISO	500	4618972.8	-	5687868	824740.86
6	2ISO with Preheater	500	692845.92	238655.4135	27923376	4048889.52
7	2ISO with Mixer Splitter	500	692845.92	-	213377.5	3093969.038

Num	Unit	Annul net real saving ($)	Turboexpander capital cost ($)	Gas fired preheater capital cost ($)	Generator capital cost ($)	Capital cost of project ($)
1	1N	411933.94	65675	-	232080	297755
2	2N with Preheater	724135.17	111523	109538	247167	468228
3	2N with Mixer Splitter	413839.24	65748	-	232104	297852
4	South	274498.3	29399	-	225794	255193
5	1ISO	824240.86	71580	-	248332	319912
6	2ISO with Preheater	3809734.107	417781.6	351729	339300.5	1108811.1
7	2ISO with Mixer Splitter	3093469.038	335040.1	21337717.5	315292.8	650333

Table 13. SPP, NPV and IRR of simulated lines

Num	Line	Capital cost of project ($)	SPP (year)	NPV ($)	IRR (%)
1	1N	297755	0.7228	1452549.145	98.62
2	2N with Preheater	468228	0.6466	2608616.793	112.211
3	2N with Mixer Splitter	297852	0.7197	1460547.75	99.1176
4	South	255193	0.9297	911148.1672	72.969
5	1ISO	319912	0.388	3182281.08	198.038
6	2ISO with Preheater	1108811.1	0.291	15078719.8	269.656
7	2ISO with Mixer Splitter	650333	0.21023	12493793.2	379.729

5. Discussion

5.1. Turbo expanders power production validation

We compared our results of turbo expander power production with Figure 21 that shows power production potential at various levels of steam pressure reduction [12]. Figure 21 shows lines of constant power output (expressed in kW of electrical output per 1,000 pounds per hour of steam throughput) as a function of turbine inlet and exhaust pressures. We specified results pressure reduction points of 5 units of Tehran refinery that are simulated in this project on Figure 21 for comparison of our simulation results. The results are shown on tables 14 and 15.

Table 14. Approximate turbo expander power production potential prediction of US Dept. of Energy

Num	Unit	$\eta_{1law_{Tur}}$ (%)	$\eta_{1law_{Gen}}$ (%)	P_{Tur} (KW)	$\eta_{1law_{Line}}$ (%)	$\eta_{1law_{Energy\ tip}}$ %	$P_{Gen\ with\ \eta=75\%}$ (KW)	$P_{Tu_{Es}}$ (KW)
1	1N	76.07	75	434.4	57.05	48	324.7	231.483
2	2N with Preheater	63.39	75	835.2	47.54	48	624.2	595.242
3	2N with Mixer Splitter	63.16	75	434.99	47.37	48	326.2	277.339
4	South	76.06	75	289.6	57.045	48	216.5	154.322
5	1ISO	76.07	75	868.8	57.05	48	649.3	462.966
6	2ISO with Preheater	79.2	75	4265	59.4	48	3187.6	2083.347
7	2ISO with Mixer Splitter	78.73	75	3247.75	59.047	48	2435.81	1509.247

Table 15. Comparison results of Thermoflex turbo expander power production simulation with turbo expander power production prediction of US Dept. of Energy.

P_i/P_o	Electrical Power Generation $(KW/Mlb-hr)$	Electrical Power Generation $(KW/1\ {}^{ton}/_{hr})$
614.69/314.69	7	15.4322
614.69/127.43	17	37.4782
214.69/74.69	21	46.2966
314.69/125.89	10	22.046
314.69/74.69	15	33.069

In order to better compare, we plotted our results of turbo expander power production of Thermoflex simulation and turbo expander power production prediction of US Dept. of Energy on Figure 22.

As Figure 22 shows, the results are almost the same between points 1 to 5. For points 6 and 7 the results are rather different which is due to different turbo expander and generator first law efficiency and the mass flow rate of these two points.

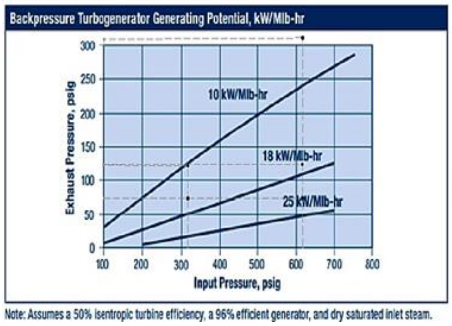

Figure 21. Backpressure Turbo generator Gene-rating potential (kW/Mlb-hour)

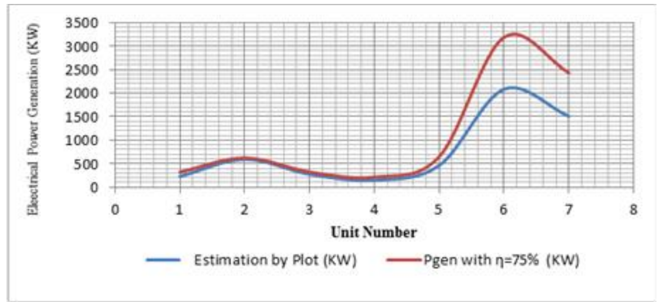

Figure 22. Results of turbo expander power production of Thermoflex simulation and turbo expander power production prediction of US Dept. of Energy

6. Conclusion

The values of SPP for all simulated lines are less than one year, and the IRR for all of them are significant. So, investment on all lines for turbo expander installation is recommended. Also for lines with two options (second line of North Water, Electricity and Steam unit and second line of Isomerization unit), higher IRR has a more significant role on investment. For the second line of North Water, Electricity, and Steam unit, investment on the addition of turbo expander and preheater and for the second line of Isomerization unit, investment on the addition of turbo expander and mixer splitter is the optimal alternatives.

Nomenclature

PRV	Pressure Reduction Valve	$\dot{w}_s$	Rate of Isentropic Work
HP	High Pressure	$h_{i_{Tu}}$	Inlet Stream Enthalpy to Turboexpander
MP	Medium Pressure	$h_{e_{Tu}}$	Outlet Stream Enthalpy of Turboexpander
LP	Low Pressure	$h_{es_{Tu}}$	Outlet Stream Isentropic Enthalpy of Turboexpander
$\dot{I}$	Rate of Irreversibility	$\dot{Q}$	Rate of Heating of Gas Fired Preheater
$\dot{m}$	Mass Flow Rate	$\dot{Q}_{c.v}$	Rate of Heating of Hot Reservoir
M	Mass Flow Rate	X	stream splitting coefficient
T	Temperature	HHV	High Heat Value
T_0	Environment Temperature	ρ	Density
T_i	Inlet Stream Temperature	C_{Tur}	Turboexpander Capital Cost
T_o	Outlet Stream Temperature	HP	Horse Power
P_i	Inlet Stream Pressure	C_{PreH}	Capital Cost of Gas Fired Preheater
P_o	Outlet Stream Pressure	SPP	Simple Payback Period
$\dot{s}_{gen}$	Rate of Entropy Generation	NPV	Net Present Value
ψ_i	Inlet Stream Availability	IRR	Internal Rate of Return
ψ_e	Outlet Stream Availability	DF	Discount Factor
W_{rev}	Reversible Work	DR	Discount Rate
W	Real Work	IF	Inflation Factor
h_i	Inlet Stream Enthalpy	IR	Inflation Rate
h_e	Outlet Stream Enthalpy	1N	First Line of North Water, Electricity and Steam Unit
s_i	Inlet Stream Entropy	South	South Water, Electricity and Steam Unit
s_e	Outlet Stream Entropy	1ISO	First Line of Isomerization unit
P_{abs}	Absolute Pressure	2ISO	Second Line of Isomerization unit
MCFC	Molten Carbonate Fuel Cell	P_{Tur}	Real Power Production of Turboexpander
η	Efficiency	P_{Gen}	Real Power Production of Generator
$\dot{w}$	Rate of Work	$P_{Tu_{Es}}$	Turboexpander Power Production Estimation by US Dept. of Energy Plot
$\dot{w}_a$	Rate of Real Work	$\dot{w}_{ac_{Tu}}$	Rate of Real Work of Turboexpander
$\eta_{1law_{Tur}}$	First Law Efficiency of Turboexpander	$\eta_{1law_{Line}}$	Multiplication $\eta_{1law_{Tur}}$ and $\eta_{1law_{Gen}}$
$\eta_{1law_{Gen}}$	First Law Efficiency of Generator	$\eta_{1law_{Energy\,tip}}$	Multiplication $\eta_{1law_{Tur}}$ and $\eta_{1law_{Gen}}$ of US Dept. of Energy Power Prediction Plot

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To whom correspondence should be addressed: MSC Amir Ashoori Barmchi, Department of Energy Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran, a.ashoori@srbiau.ac.ir