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Exergetic Optimization of a Turboexpander Ethane Recovery Process Operable Under Different Feed Composition Conditions

Akkaya V.R. and Konukman A.E.S.*
*Author for correspondence
Department of Mechanical Engineering,
Gebze Institute of Technology,
Kocaeli, 41400,
Turkey,
E-mail: konukman@gyte.edu.tr

ABSTRACT

This study presents a method that produces optimal design of a turboexpander ethane recovery process operable with given utilization weight of multiple feeds at minimum exergy destruction. Although exergy destruction is lesser when using individual processes designed for each different feed, using a process operable with multiple feeds is advantageous because of higher capacity utilization rate and lower capital costs.

INTRODUCTION

Natural gas delivered from the well is a complex mixture of various hydrocarbons and inorganic compounds. The compounds such as natural gas liquids (NGL) have their own economical values. Consequently, several recovery methods have been developed. The most common ones are external refrigeration, refrigerated lean oil absorption, Joule-Thompson expansion and turboexpansion [1].

NOMENCLATURE

b	[kJ/kg]	specific exergy
\dot{B}	[kW]	exergy rate
\bar{c}_p	[kJ/kgK]	average specific heat capacity
h	[kJ/kg]	specific enthalpy
\dot{m}	[kg/s]	molar flow rate
\dot{Q}	[kW]	heat rate
T	[K]	temperature
\dot{W}	[kW]	work rate

Subscripts

0	dead state
cold-sep	cold separator
comp	compressor
cu	cold utility
d	destroyed
hot-sep	hot separator
in	inlet
q	heat related
reb	reboiler
ref	refrigeration
turbo	turboexpander
out	outlet
w	work related

External refrigeration processes are simple and suitable for various levels of recovery. Amount of energy used determines recovery ratio, therefore despite its simplicity it is energetically inefficient. The aim of the refrigeration is lowering the temperature of feed gas to dew point. In a refrigerated lean oil process, a refrigerated heavy hydrocarbon liquid stream is used as lean oil. After precooling of feed stream, lean oil absorbs C₂₊ components of the feed in an absorber. This method is more effective when working rich feed gas at relatively lower pressures. An expansion valve is used in a Joule-Thompson process to reach dew point temperature while depressurizing the feed stream. This method is suitable for moderate recovery ratios of small feed flow rates. Turboexpansion method is based on isentropic expansion of the feed gas. Pressure drop due to expansion provides cold temperature [2]. Turboexpander process differs from any other recovery methods because power recovery is also possible together with NGL recovery. Generally, such a process is combined with external refrigeration and Joule-Thompson expansion to increase recovery levels.

Studies over turboexpander ethane recovery processes in literature are limited on economical analyses. Chebbi et. al. [3] compared five turboexpander ethane recovery processes and showed that additional complexity in the process design may cause decrease in ethane recovery. Mehrpooya et. al. [4] simulated an existing NGL recovery plant using HYSYS process simulator. They found heat integrated turboexpander configuration as the best revamping alternative. Genetic algorithm was used to produce design parameters ensuring maximum profit. Different turboexpander configuration operating under a wide selection of natural gas feeds were examined by Jibril et. al. [5]. The study showed that feed composition highly affects the process energy consumption. Jang et. al. [6] optimized economics of an ethane recovery turboexpander process. Stochastic optimization techniques such as Genetic Algorithm and Quadratic Search were used to overcome convergence problems caused by gradient based optimization.

Turboexpander processes are extremely energy intensive because of refrigeration and compression duties. Even small improvements in energy consumption result great savings for such processes. Therefore, efficient use of energy becomes primary objective in design of the process and its performance measurements. The exergy analysis involving both the first and second law of thermodynamics provides the measure of energy performance quantitatively [7].

Graveland and Gisolf [8] integrated a commercial exergy subroutine to Aspen Plus process simulator for the exergy analysis of a vinyl chloride plant. The subroutine calculated the physical and chemical exergies of the process stream and embedded the results into the simulator stream report. An exergy analysis tool for Aspen Plus process simulator were developed and used for an evaporative cycle design by Bram and De Ruyck [9]. Their approach enabled to get exergy information of a selected stream at any phase of the simulation. Akkaya analyzed an ethane recovery turboexpander process in both qualitative and quantitative points of its energy performance [10]. In his study, an exergy calculator tool were developed and integrated to the Aspen Plus process simulator. Study also includes exergetic optimization of the process performed by simultaneous cooperation of the process simulator and Genetic Algorithm tool of MATLAB software.

EXERGY ANALYSIS

Analysis of energy efficiency thermodynamics is the most common analysis for a process. However the analysis based on the first law of thermodynamics lacks the information about the potential work lost in the process.

The second law of thermodynamics should be considered to measure the irreversibility of the process. Therefore, the exergy analysis provides more detailed information about the energy utilization of the process. The exergy analysis in this study was made in the light of the following assumptions.

- Peng-Robinson equation of state is valid
- Minimum approach temperature is 10 K
- Compressors, turboexpanders and pumps have isentropic efficiencies of 0.9
- Isenthalpic expansion occurs in the valves.

Mass and energy is conserved for a closed system. For a control volume, these balances are expressed in terms of mass flow rate (\dot{m}) [kg/s] and enthalpy (h) [kJ/kg]:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (1)$$

$$\sum_{in} \dot{m}h = \sum_{out} \dot{m}h + \dot{Q}_{net} + \dot{W}_{net} \quad (2)$$

where \dot{Q}_{net} and \dot{W}_{net} are net heat and work transferred. Process simulator uses Eqs(1-2) to satisfy its convergence criteria.

The following equation represents the third balance for a control volume, the exergy balance. Due to irreversibilities, exergy is not conserved in a process and some of the input exergy is destructed (\dot{B}_d).

$$\sum_{in} \dot{B} = \sum_{out} \dot{B} + \dot{B}_{q,net} + \dot{B}_{w,net} + \dot{B}_d \quad (3)$$

Exergy is transferred into or out to the system by heat, work or flow stream. At a temperature T, the net exergy transfer by heat stream is expressed as:

$$\dot{B}_q = \dot{Q} \left(1 - \frac{T_0}{T} \right) \quad (4)$$

where stands T_0 for the temperature of the dead state (298.15 K, 1 atm). For a work stream, associated exergy is equal to itself:

$$\dot{B}_w = \dot{W} \quad (5)$$

Exergy of a flow stream consists of physical and chemical parts. However, since the turboexpander process does not undergo chemical reactions, the chemical part of flow exergy is conserved. The physical exergy of a flow stream is:

$$\dot{B} = \dot{m}(h - h_0) - T(s - s_0) \quad (6)$$

EXERGY AND OPTIMIZATION TOOLS

The exergy analysis and stochastic optimization of the process is beyond the capabilities of the process simulator. Therefore, two user tools were developed and introduced to the simulator to accomplish such tasks.

Exergy Calculator Tool

Aspen Plus v7 process simulator provides all the required thermodynamic information for process development [11]. However, what the simulator is missing is the exergy information of the streams. In this study, a method that implements exergy as a stream property into the simulator was proposed. The method calculates exergy carried by the each stream and enables to calculate process overall exergetic performance simultaneously together with the process simulation.

Aspen Plus allows users to extend its capabilities via user models created with FORTRAN. Hence, a model that calculates physical exergy of the stream was introduced to the simulator. The inputs of the model are the thermodynamic properties of the stream at its actual and dead state. Using these data, model calculates and returns value of physical exergy.

Process Simulator – Optimization Tool Interconnection

Aspen Plus process simulator has built-in sequential quadratic programming (SQP) capability. The purpose of SQP method is solving series of quadratic programming sub problems. However, an ethane recovery turboexpander process consists of intricately-connected multiple independent unit of highly nonlinear nature. In a process simulator, convergence of the entire process is achieved by converging each of these units individually. Due to this characteristic of process simulators, derivative based optimization techniques can cause difficulties [6].

This paper proposes to use a derivative-free stochastic optimization method to minimize exergy destruction of the ethane recovery turboexpander process.

Genetic Algorithm (GA) is inspired by “survival of the fittest” principle of Darwin. It imitates natural selection and

natural genetics mechanisms to obtain the optimal solution. The method is population based, thus there are many starting point. An initial population is generated and siblings are derived continuously from it until the optimal solution emerges. New siblings are generated by three primary genetic operators which are selection, crossover and mutation. GA does not require gradient of the objective function and can operate with any kind of function. Therefore, GA is a suitable method for an optimization problem in which the process simulator serves as a function evaluator.

Aspen Plus process simulator does not provide GA based optimization methods. However, the simulator operates as an ActiveX Automation Server [11]. Therefore, COM aware MS Windows™ software programs can access simulation variables and use the simulator as a function evaluator. A tool that connects Aspen Plus process simulator and Genetic Algorithm Toolbox of MATLAB was prepared in this study. In each generation, the tool accesses the population and delivers to the simulator in a proper format. Subsequently, simulator evaluates and returns the value of objective function to generate the next population. The information transfer between the Genetic Algorithm toolbox and the simulator is depicted in **Figure 1**.

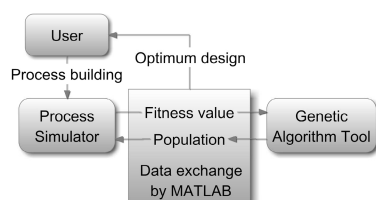


Figure 1 Information transfer between the optimization toolbox and the simulator

PROCESS DESCRIPTION

Typically, an ethane recovery turboexpander process embodies two parts; Chilling and condensation of the feed gas take place in the first part. Next, hydrocarbons are recovered via distillation in the second part. **Figure 2** [10] shows the process analyzed in this study. Initially, feed gas is compressed then split into two substreams. Substream S1 is matched with top product (TOPP) of demethanizer column (DEMETHAN). Bottom product (BOTTEMP) is matched with second substream (S2). S2 cools further while providing reboiler duty (QREB). External refrigeration is also used to achieve desired temperature. S1 and S2 are mixed together before entering the hot flash separator (HOTSEP). Condensed part is depressurized by a valve (V1) then fed to the column. Before entering cold separator (COLDSEP), vapour part is chilled by top product of the column and external refrigeration. Condensate leaving separator is depressurized in a valve (V2) and directed to the column. A turboexpander is used to reduce pressure of the vapour. Hence, beside a decrease in temperature, power recovery is also achieved due to pressure reduction. Stream exiting the turboexpander feeds the column. External refrigeration of the process is accomplished (QCU1 and QCU2) via a simple propane cycle (**Figure 3**).

Three alternative natural gas feeds with different compositions considered in this study [12]. **Table 1** lists

compositions of feed gases. Inlet temperature and pressure of the feeds are 373 K and 1700 kPa.

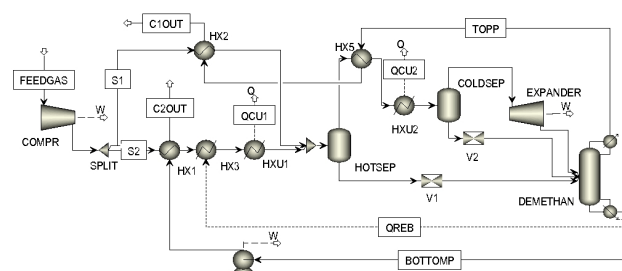


Figure 2 Process flowsheet

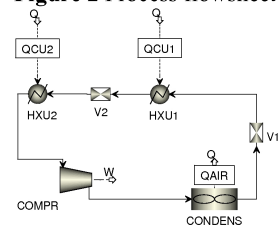


Figure 3 Propane cycle

Table 1 Composition of feed gases in mole fraction

Component	A	B	C
Methane	0.8865	0.7587	0.6797
Ethane	0.0622	0.0836	0.1056
Propane	0.0287	0.0535	0.0905
<i>i</i> -Butane	0.0102	0.0097	0.0302
<i>n</i> -Butane	0.0059	0.0194	0.0402
<i>i</i> -Pentane	0.0003	0.0058	0.0121
<i>n</i> -Butane	0.0002	0.0068	0.0101
<i>n</i> -Hexane	0.0001	0.0002	0.0028
Nitrogen	0.0039	0.0043	0.0012
Carbon dioxide	0.0020	0.0580	0.0276

MINIMIZATION OF EXERGY DESTRUCTION IN ETHANE RECOVERY TURBOEXPANDER PROCESS

This study aims to produce optimum design properties of a turboexpander process operable under multiple natural gas feeds and granting desired level of ethane recovery at minimum exergy destruction. Hence in Case 1, the process was primarily optimized according to single feed scenarios in order to introduce a comparison basis. Considering the results of the first case, the process and the optimization problem were revised then optimum design properties were produced for a common design in which multiple feeds can be processed collectively.

Case 1 – Exergetic optimization of the process operable under a specific feed composition

Previous studies on ethane recovery turboexpander process point out that the parameters influencing ethane recovery level are inlet pressure and temperature of the distillation column [3–6]. As the column inlet temperature decreases, level of ethane recovery improves. This temperature decreases primarily by the cold energy provided by the propane refrigeration cycle and

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product streams of the column. Additional cooling is done by creating pressure drop between compressor and turboexpander. The parameters influencing the recovery level are also related with net work and heat input of the process. Thus, same parameters can be used as decision variables for the exergy minimization problem (Eqn. 7).

$$\min_{\mathbf{x}} \quad \dot{B}_d(\mathbf{x}) \quad (7)$$

subject to :

$$10 \leq x_{1-5} \leq 40$$

$$3000 \leq x_6 \leq 3400$$

$$1000 \leq x_7 \leq 1300$$

$$0.500 \leq x_8 \leq 0.999$$

$$h(\mathbf{x}) - 0.800 = 0$$

where;

x_1, x_2, x_3, x_4, x_5 Minimum approach temperature in heat exchangers HX1, HX2, HX5, HXU1, HXU2 [K]

x_6 Compressor outlet pressure [kPa]

x_7 Turboexpander outlet pressure [kPa]

x_8 Split ratio

$h(\mathbf{x})$ Ethane recovery ratio equality constraint

Stream splitting ratio of SPLIT equipment distributes the heat load between heat exchanger HX1 and HX2. Thus, it was selected as an additional decision variable (x_8).

In preference to controlling outlet temperatures of heat exchangers, minimum approach temperatures were selected as decision variables. This approach helps to avoid use of extra inequality constraints to prevent temperature cross violation. The only constraint of the problem is the level of ethane recovery which is 80%.

Genetic Algorithm Toolbox of MATLAB is used to produce optimum design. Population size for the problem is 20. Selection method is tournament. **Table 2** shows optimum design parameters of the process operating at minimum exergy destruction for given feed composition. Composition of the feed gas determines the thermodynamic properties of streams and outcomes different optimum process design. Feeds A and B operates at same pressure levels. However, feed C requires greater pressure drop to achieve desired ethane recovery. Additionally, heat exchanger HXU1 is bypassed for feeds A and B and external refrigeration is accomplished via second utility exchanger (HXU2) only. Therefore, size of that exchanger is reasonably greater for the feeds A and B. However, cumulative size of utility exchangers is proximate for both feeds.

The exergetic performance of an ethane recovery turboexpander process is primarily determined by its power and heat requirements. Therefore, the first law analysis of the process is accomplished at first. Power duties of the optimum process design for each feed are listed in **Table 3**. Compressor power consumption is relatively high for the Feed C because inlet gas is compressed to higher pressure. Moreover, power recovery via turboexpander is lowest for that feed. Consequently, when the process operates for the Feed C, power requirement is the highest. Optimum compressor and turboexpander outlet pressures are same for the feeds A and B. However, compressor duties are different due to diverse

thermodynamic properties of the feeds. Condensation due to cooling thus amount of passing through the turboexpander differs from feed to feed. Therefore, power recovery via turboexpander is different even for the same exit pressure. Compensation of the compressor duty by turboexpander is highest for the Feed A (61.4%) followed by Feed B (55.9%) and Feed C (47.9%).

Table 2 Feed specific optimum design parameters

	Feed A	Feed B	Feed C
P_{compr} [kPa]	3085	3085	3290
P_{turbo} [kPa]	1092	1092	1050
A_{HX1} [m ²]	773	931	1954
A_{HX2} [m ²]	557	1676	3106
A_{HX5} [m ²]	885	476	365
A_{HXU1} [m ²]	1	1	440
A_{HXU2} [m ²]	564	462	134
Split	0.558	0.556	0.693

Table 3 Power duties of the process

	\dot{W}_{compr}	\dot{W}_{turbo}	\dot{W}_{net}
Feed A	6.466	3.973	2.493
Feed B	6.345	3.548	2.797
Feed C	6.847	3.278	3.569

* All units are in [MW]

Figure 4 shows process cooling duties according to feed. Due to thermodynamic properties, different amount of heat is removed from the feed to acquire desired level of ethane recovery. Feed C requires highest cooling duty and followed by Feed B and A respectively. On the other hand, ratio of heat integration to the total cooling duty is similar for both feeds. Heat integration reduces the external utilization over 88%.

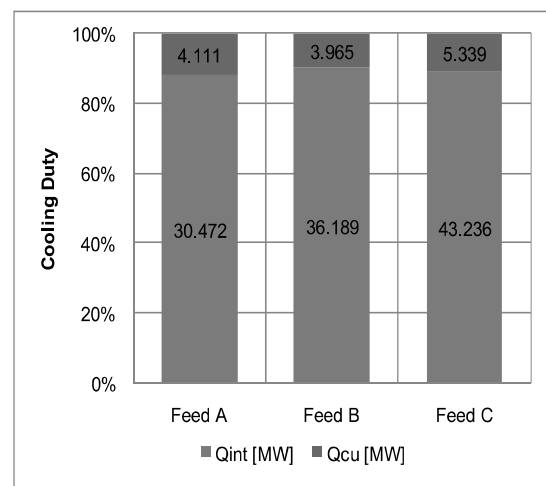


Figure 4 Cooling duties of the process

Exergetic performance of the process is represented in **Figure 5**. Exergy destruction is minimum when operating the process with Feed B. Only 16.6% of inlet exergy is destroyed

throughout the process. For feeds A and C, exergy destruction ratio is %17.8 and 18.7% respectively. Exergy leaves the process via material (C1OUT and C2OUT) and heat streams (condenser of propane refrigeration cycle). Thus, exergy leaving the process through heat stream is wasted. For feeds A and B, around 40% of inlet exergy is wasted which is lower comparing to feed C. Therefore, process operates more efficiently with those feeds.

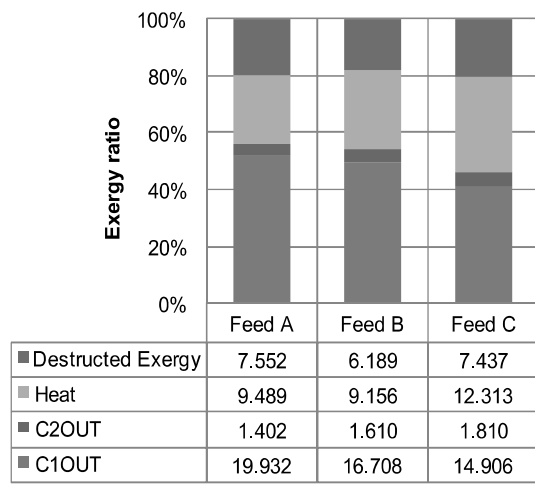


Figure 5 Exergetic performance of the process

Case 2 – Exergetic optimization of the process operable under multiple feed compositions

Composition of natural gas feed is the primary factor that determines the design of turboexpander ethane recovery plant. As emphasized in the first case, operating conditions and size of equipments varies significantly according the selected feed. In case of change in feed composition, ethane recovery target may not be accomplished even the process may not operable as well. Thus, it is essential to redefine minimization of exergy destruction problem and to reproduce the process optimum design for the multiple feed scenarios.

Equipment properties of certain equipment, such as heat exchangers, are determined and set once and for all in the design phase of the process. Optimum design produced in Case 1 shows that size of heat exchangers varies significantly with respect to feed. However, a single size is to be selected for a heat exchanger in the process operable with different feed compositions. If the size is selected greater than the feed specific optimum, violation of minimum approach temperature constraint occurs. Conversely; if a smaller size is selected, lesser amount of heat is recovered and level of ethane recovery reduces. Hence, bypass valves are introduced to the heat exchangers to make the process flexible against varying feed compositions (Figure 6). Design-specs created with process simulator determine the values of bypass openings. In case of violation of constraints, bypassed amount of inlet stream varies and minimum approach temperature is conserved.

Unlike the heat exchangers, specifications of compressor, turboexpander and splitter can be set while process operates. For each feed, these specifications take different values. Hence,

for such process, minimization of exergy destruction is described in Eq. 8.

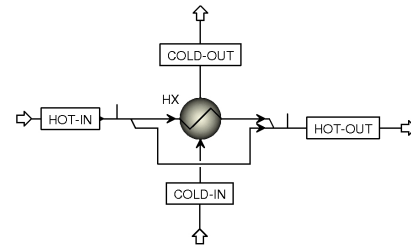


Figure 6 Bypass configuration for heat exchangers

$$\min_{\mathbf{x}} \frac{1}{3} (\dot{B}_{d,A}(\mathbf{x}) + \dot{B}_{d,B}(\mathbf{x}) + \dot{B}_{d,C}(\mathbf{x})) \quad (8)$$

$$\text{subject to :} \quad \begin{aligned} 3000 &\leq x_{1-3} \leq 3400 \\ 1000 &\leq x_{4-6} \leq 1300 \\ 0.500 &\leq x_{7-9} \leq 700 \\ 775 &\leq x_{10} \leq 1950 \\ 560 &\leq x_{11} \leq 3100 \\ 480 &\leq x_{12} \leq 880 \\ 1 &\leq x_{13} \leq 700 \\ 135 &\leq x_{14} \leq 700 \\ h_A(\mathbf{x}) - 0.800 &= 0 \\ h_B(\mathbf{x}) - 0.800 &= 0 \\ h_C(\mathbf{x}) - 0.800 &= 0 \end{aligned}$$

where;

x_1, x_2, x_3	Compressor outlet pressures for feeds A, B and C [kPa]
x_4, x_5, x_6	Turboexpander outlet pressures for feeds A, B and C [kPa]
x_7, x_8, x_9	Split ratios for feeds A, B and C
$x_{10}, x_{11}, x_{12},$ x_{13}, x_{14}	HX1, HX2, HX5, HXU1 and HXU2 heat exchanger areas [m^2]
$h_A(\mathbf{x}), h_B(\mathbf{x}),$ $h_C(\mathbf{x})$	Ethane recovery ratio equality constraint for feeds A, B and C

The upper and lower limits of decision variables are determined considering the first case. Maximum and minimum value according to feed bounds the variable. However, upper limit of the utility exchangers (HXU1 and HXU2) are selected beyond their maximum value calculated at the first case. Otherwise, feed stream would not be cooled adequately and ethane recovery target would be missed.

This optimization problem is also solved using Genetic Algorithm. Method options are selected same as in Case 1. Produced optimum design parameters of the process are given in Table 4. The optimum size of HX1 and HX5 is produced near their upper limits. On the contrary, size of HX2 is produced near its lower limit. According to Case 1, possible

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minimum and maximum size of in-process heat exchangers (HX1, HX2 and HX5) are 1695 m² and 5945 m² respectively. However, optimization results 3612 m² which points out that use of bypass streams is beneficial. Optimum compressor outlet pressures for feeds B and C are higher because worsened heat integration is compensated by pressure drop. Optimum turboexpander outlet pressure is at lower limit for both feeds. Lower pressure would produce higher ethane recovery. On the other hand, as the pressure drops more liquid is forming. This is an undesired result in that kind of equipment and must be limited.

Table 4 Optimum design properties of process in multifeed scenarios

	Feed A	Feed B	Feed C
P_{compr} [kPa]	3085	3160	3365
P_{turbo} [kPa]	1000	1000	1000
Split	0.625	0.610	0.735
A_{HX1} [m ²]		1400	
A_{HX2} [m ²]		759	
A_{HX5} [m ²]		860	
A_{HXU1} [m ²]		33	
A_{HXU2} [m ²]		560	

The energetic and exergetic performance of the process operable for three different feed compositions is given in **Table 5**. Since the operating pressure of the process does not vary significantly with respect to feed, net power requirement of the process is nearly average of the process operating each feed individually. Heat integration compensates 85% of total cooling duty. However, design of the process operable with both feeds is diverged from each individual optimum design. As a consequence, exergy destruction of the process is higher than individual ones.

Table 5 Energetic and exergetic performance of the process in multifeed scenarios

\dot{W}_{compr}	6.724	\dot{Q}_{tot}	40.251
\dot{W}_{turbo}	3.989	\dot{Q}_{int}	33.892
\dot{W}_{net}	2.736	\dot{Q}_{cu}	6.359
\dot{B}_d	9.148		

* All units are in [MW]

Despite its poorer exergetic performance, processing each feed in a common plant has advantages over capital costs and capacity of utilization. If an individual plant operates for each feed, three times more equipments are required. Additionally, when a feed is absent, the plant that designed upon that feed is not operable. Conversely, presence of one feed is adequate to operation of the plant.

CONCLUSION

This study suggests a methodology for exergetic optimization of an ethane recovery turboexpander process and presents required tools for such task: First, an exergy calculator

tool is introduced to Aspen Plus process simulator. Second, process simulator is linked with Genetic Algorithm toolbox of MATLAB software. Exergetic optimization of the process is accomplished in two cases. In the first case, optimum design of the process is produced for three different feed compositions individually. These optimum designs formed a basis of comparison. In the second case, optimal design of the process operable with given utilization weight of three feed composition at minimum exergy destruction is produced. Although, such process results more exergy destruction comparing the individual ones, lower capital costs and higher capacity utilization rate make the process advantageous.

REFERENCES

- [1] Boyun, G., and Ghalambor A., *Natural Gas Engineering Handbook*, Gulf Publishing Company, Houston, Texas, 2005.
- [2] Heinz, P.B., and Soares, C., *Turboexpanders and Process Applications*, Gulf Professional Printing, Dallas, Texas, 2001.
- [3] Chebbi, R., Al-Qaydi, A. S., Al-Amery, A. O., Al-Zaabi, N. S. and Al-Mansouri, H. A., Simulation study compares ethane recovery in turboexpander processes, *Oil & Gas Journal*, Vol. 102, No. 4, January 2004, pp. 64-67.
- [4] Mehrpooya, M., Gharagheizi, F. and Vatani, A., An optimization of capital and operating alternatives in a NGL recovery unit, *Chemical Engineering & Technology*, Vol. 29, No. 12, December 2006, pp. 1469-1480.
- [5] Jibril, K. L., Al-Humaiza, A. I., Idriss, A. A. and Ibrahim, A. A. Simulation study determines optimum turboexpander process for NGL recovery, *Oil & Gas Journal*, Vol. 104, No. 9, March 2006, pp. 58-62.
- [6] Jang, W. H., Hahn, J. and Hall, K. R. Genetic/quadratic search algorithm for plant economic optimizations using a process simulator, *Computers & Chemical Engineering*, Vol. 30, No. 2, December 2005, pp. 285-294.
- [7] Dincer, I. and Rosen, M. *Exergy Energy, Environment and Sustainable Development*, Elsevier, Amsterdam, Netherlands, 2007.
- [8] Graveland, A. J. G. G. and Gisolf, E. Exergy analysis: An efficient tool for process optimization and understanding. Demonstrated on the vinyl-chloride plant of Akzo Nobel, *Computers & Chemical Engineering*, Vol. 22, 1998, pp. 545-552.
- [9] Bram, S. and DeRuyck, J. Exergy analysis tools for ASPEN applied to evaporative cycle design, *Energy Conversion and Management*, Vol. 38, No. 15-17, October/November 1997, pp. 1613-1624.
- [10] Akkaya, V. R. *Exergy Analysis and Optimization of Simultaneous Energy And Ethane Recovery Processes from Natural Gas Streams via Turboexpansion*, Gebze Institute of Technology, Kocaeli, Turkey, 2009.
- [11] *Aspen Plus v7 User Manuals*, Aspen Technology, Inc., Burlington, Massachusetts, 2008.
- [12] Yusoff N., Ramasamy, M., Yusup, S., Profit Optimisation of a Refrigerated Gas Plant, *Platform*, Vol. 6, No. 1, June 2008, pp. 30-38.