Flexibility Analysis and Steady-State Optimizing Control of a Turbo–Expander Plant with Flexible Energy Integration

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Abstract – Flexibility and steady-state optimizing control of a typical Turbo-Expander Plant (TEP) are investigated with emphasis on its Heat-Exchanger Network (HEN) that strongly interacts with the TEP. In the analyses, the process flowsheet simulator HYSYS is used with its optimization capability. Bypass streams around heat exchangers are added to increase flexibility and disturbance-rejection ability of the HEN. Together with the bypasses, the split fractions in the HEN are used as the manipulated variables in investigating the steady-state optimizing-control of the TEP. The emphasis is given to the assessment of flexibility of the process in maintaining desired level of cooling in the HEN, and desired levels of ethane recovery and methane rejection under natural-gas feed-stream temperature and pressure disturbances.

Introduction

The increasing demand for the Natural-Gas Liquids (NGLs), especially for ethane as a petrochemical feedstock, resulted in the construction of TEPs that recover ethane from lean (dry) natural-gas streams at cryogenic temperatures as low as –95^{o}C. The TEPs involve gas turbo-expansion cycles to attain, possibly without external refrigeration, the low temperatures desired for enhanced ethane recovery as high as 95%.

Many TEPs built during the last 20 years use a conventional single-stage turbo-expander scheme for moderately high (70-80%) ethane recoveries. There are other alternative TEP designs that can achieve higher ethane or propane recoveries, that can process feed streams with relatively high CO_2 content without formation of solid CO_2 due to freezing, and that can show flexibility to operate either in ethane- or propane-recovery modes with very high methane rejection (Wilkinson and Hudson, 1982; Wilkinson and Hudson, 1992; Wilkinson and Hudson, 1993; Lee at al., 1999). Maintaining a high ethane recovery is crucial for the TEPs, since even a less than 1% increase in recovery may amount to a significant increase in profits due to processing of high volumes of feed.

In this very preliminary work, we adopt the flowsheet of a typical, industry-standard single-stage TEP. We concentrate on the HEN part of the TEP and on its role in maintaining a desired level of cooling to achieve, in turn, a desired level of ethane recovery and methane rejection. For this purpose, bypass streams around the heat exchangers are added to increase the flexibility and disturbance-rejection ability of the HEN. The stream splits in the HEN, together with the bypasses, are used as the manipulated variables in controlling the temperature of the HEN's main target stream, the level of which dictates the ethane-recovery/methane-rejection values.

Description of the TEP

The simplified flowsheet of the TEP used in this work is shown in Fig.1. In a typical TEP, the natural gas is cooled to extremely low temperatures through a HEN after which the cold liquid and vapor are separated in a Low-Temperature Separator (LTS). The liquid stream of the LTS is flashed across a JT valve for pressure reduction and additional cooling. The vapor stream of the LTS is fed to the expander side of the TEP where temperature is further reduced and the work produced is utilized for recompression. The liquid generated by the expander is separated in the Vapor-Liquid separator (VLS). This liquid as well as the JT valve outlet are both fed to the top of the Demethanizer Tower (DT) (a reboiled absorber), the bottom product of which is the ethane-rich stream. The vapors from the DT and VLS are combined and fed back to the HEN to help cooling the incoming natural-gas stream. The residue-gas (sales gas) stream (rich in methane) leaving the HEN is partially compressed using the energy released in the expander.

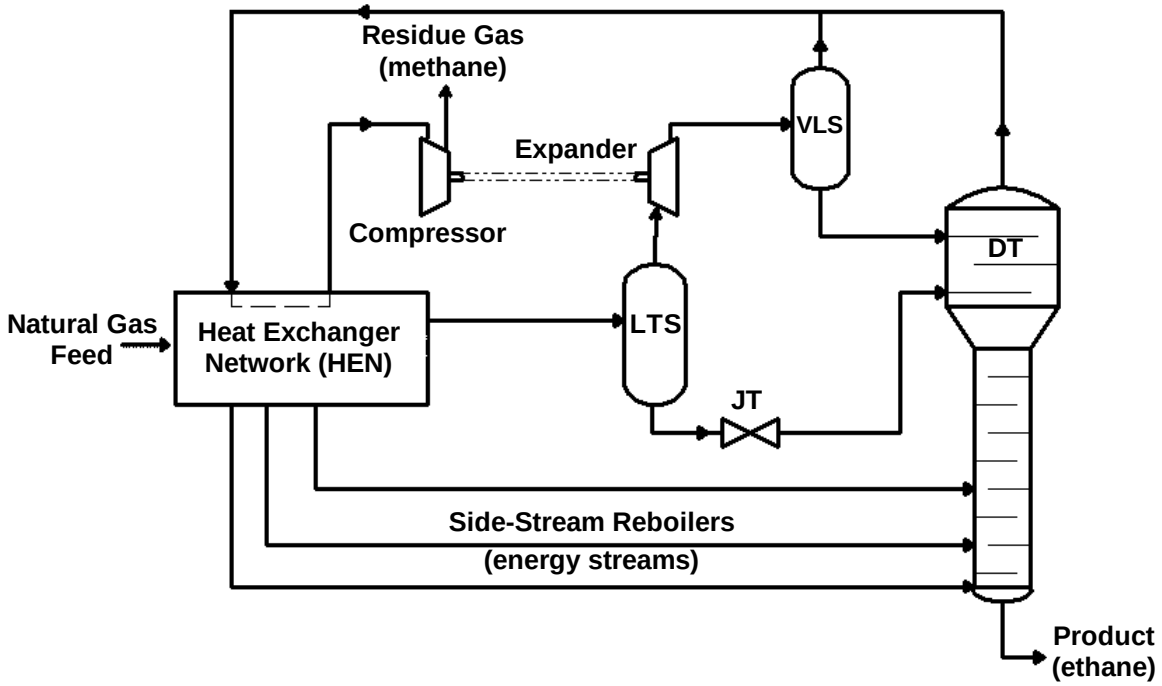


Figure 1. Simplified flowsheet of the turbo-expander plant.

Efficient heat integration in the HEN, which is used to pre-cool the feed to the LTS, is of major importance in the design of TEPs. The HEN should maximize the cooling of the feed by matching it with the overhead (methane-rich) stream and with the side reboilers of the DT. The HEN also helps maintaining high ethane recovery and high methane rejection in the bottoms of the DT.

As can be understood from the above brief description of a typical TEP, the heat-integration efficiency, flexibility, and operability of the HEN are of crucial importance in reducing the cost of the operation as well as in maintaining high ethane recovery and purity (methane rejection).

The HYSYS Model of the TEP

We started with the TEP flowsheet/model which was available the application-case library of HYSYS (G-3: Deep-Cut Turbo-Expander Plant). We did not change the natural-gas feed-stream composition and the options related to thermodynamics (Peng-Robinson equation of state, binary-interaction parameters, enthalpy-calculation options, etc). The available HYSYS model had been developed mainly for design purposes rather than for performance calculations. For example, in the HEN part of the TEP flowsheet, some approach temperatures had been fixed and the UA (the product of the overall heat-transfer coefficient and the overall heat-transfer area) of the heat exchangers were being calculated based on the input/output temperatures. Furthermore, in the HEN, the temperatures of the splits, before mixing of the branches, had been set as equal to each other. Also, the split ratios in the HEN were being calculated from the specified approach temperatures and from the heat duties related to side-stream reboilers and the main reboiler of the DT. On the other hand, in the DT, the boil-up ratio, the component ratio (methane/ethane molar ratio in the bottoms product), and the ratios of the heat flows (duty ratios) of the side-stream reboilers to the heat flow of the reboiler had all been specified. In the expander part of the TEP, the pressures of the streams leaving the JT valve and the expander had been specified as well. Other details can be found in the HYSYS's web site (http:// www.hyprotech.com/ support/ examples/ newdeep/ deepcut.htm). Since these design specifications were not suitable for our performance-calculation purposes, all of the specifications were removed and the new HYSYS model ready for pure simulation was prepared. We did not change the suggested pressure-drop values for various units such as the heat exchangers, DT trays, etc. The major change we did was in the HEN part of the flowsheet; we added bypass streams around the two rigorous heat exchangers which match the combined cold vapors from the DT and VLS with the relatively hot incoming natural-gas feed stream. The HYSYS process flowsheet diagrams of the main TEP, the HEN sub-flowsheet, and the DT sub-flowsheet are shown in Figs. 2, 3, and 4, respectively.

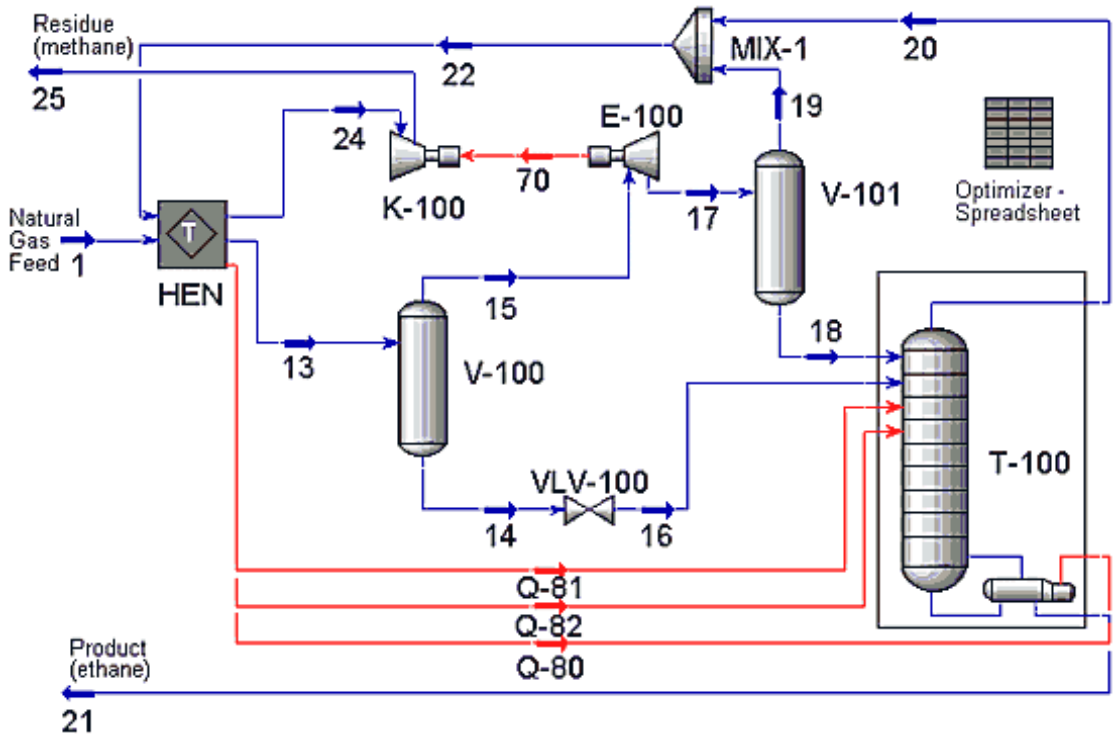


Figure 2. The HYSYS process flowsheet diagram of the main TEP.

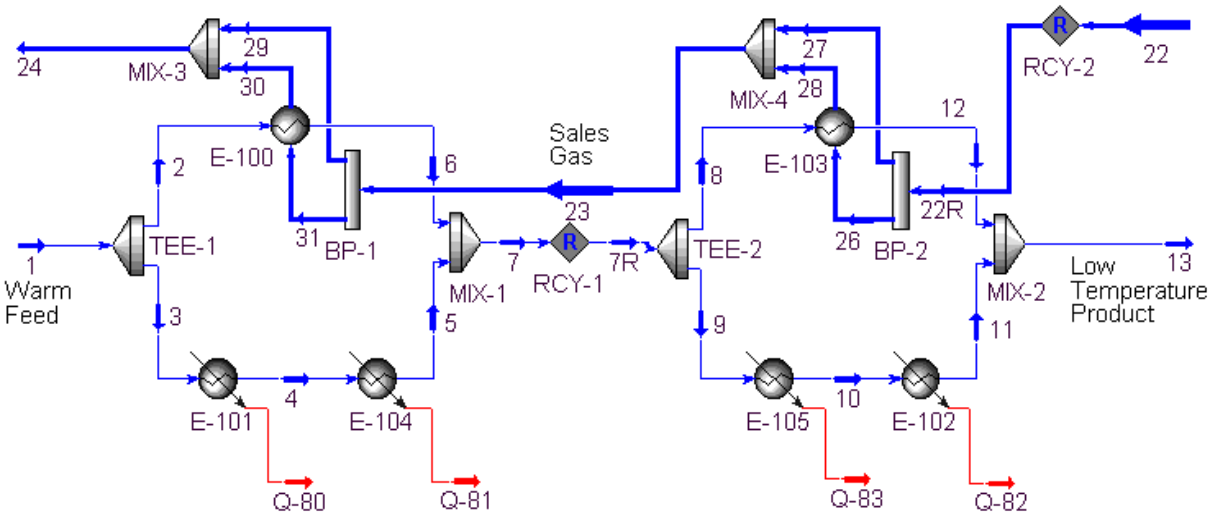


Figure 3. The HYSYS process sub-flowsheet diagram of the HEN.

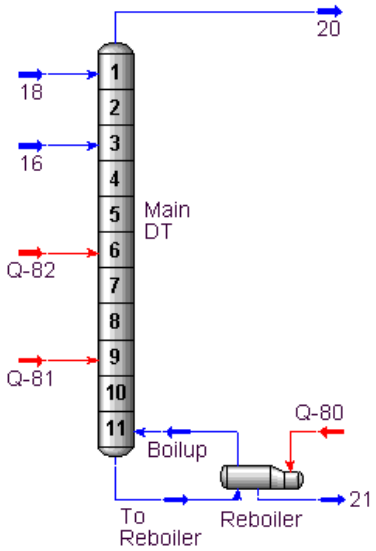


Figure 4. The HYSYS process sub-flowsheet diagram of the DT.

In the HEN sub-flowsheet (Fig.3), the exchangers E-100 and E-103 are rigorous heat exchangers. The methane-rich residue stream (cold fluid) entering/leaving the exchangers (Streams 22, 23, 24) is a gas stream, however, the natural-gas feed stream (hot fluid) entering/leaving the exchangers (Streams 2, 6, 8, 12) is of two phase (mostly vapor). Therefore, there are phase changes in the hot (tube) sides of exchangers E-100 and E-103.

Exchanger E-101 (Fig.3) is not a rigorous heat exchanger. Exchanger E-101 supplies heat to the reboiler of the DT (Fig.4) and provides cooling of the natural-gas stream. We set the duty of this exchanger through the DT specification such that the boil-up ratio in the reboiler was always 0.5. Otherwise (if the duty is set independently as a constant), interestingly, the complete TEP exhibits multiple steady-state solutions; varying with the natural-gas feed-stream temperature. Therefore, the temperature of Stream 4 is calculated through the heat duty of E-101 (Q-80) as dictated by the boil-up ratio in the DT's reboiler.

Exchangers E-102 and E-104 (Fig.3) are not rigorous heat exchangers either. They represent the side-stream reboilers of the DT (Fig.4). We set the heat duties of exchangers E-102 (Q-82) and E-104 (Q-81) as constants (in accordance with the original HYSYS application-case solution). Their fixed duties enter the corresponding trays of the DT as heat inputs (Q-81 to stage 9 and Q-82 to stage 6). Similarly, we set the heat duty of exchanger E-105 (Q-83), which represents the additional cooling by an external cold utility, as constant. Exchanger E-102 and E-105 cannot be lumped into a single exchanger to consider it as a side reboiler of the DT, since this causes either insufficient cooling of the natural gas or excessive vapor formation in the corresponding tray of the DT.

It should be mentioned that we also considered exchangers E-102 and E-104 as rigorous; by drawing out a certain fraction of the liquid leaving Stage 5 and matching it in E-102 with Stream 10 before returning it to Stage 6 and by drawing out a certain fraction of the liquid leaving Stage 8 and matching it in E-104 with Stream 4 before returning it to Stage 9. This more realistic approach worked well, however, it required two additional recycle-convergence blocks which interacted with the other recycle-convergence blocks (Fig.3), and thus increased the solution time significantly. Therefore, for this preliminary work, we decided not to consider the side reboilers as rigorous exchangers and went forward as explained before.

The major modification we did in the HEN part of the flowsheet was the addition of two bypass streams (BP-1 and BP-2) around the two rigorous heat exchangers (E-100 and E-103) which match the very cold combined vapors from the DT and VLS with the relatively hot incoming natural-gas feed stream (Fig. 3). We considered non-zero bypass fractions at the nominal (base-case) operating conditions. This gave the flexibility to manipulate the bypass flows in either the decreasing or increasing directions as dependent on the direction of the disturbance (i.e., decrease or increase in the natural-gas feed temperature). However, the use of non-zero nominal bypass fractions required higher UA values for exchangers E-100 and E-103 to match the nominal values of the target temperatures of these exchangers with those corresponding to the nominal operating conditions.

The Base-Case Solution Summary

Table 1 lists the major parameters used for the base case solution. Others can be found in the HYSYS's web site.

Table 1. Major parameters used for the base-case solution.

TEE-1:	nominal split ratio (Stream 2 to Stream 1)	0.60
TEE-2:	nominal split ratio (Stream 8 to Stream 7)	0.75
BP-1:	nominal bypass fraction (Stream 29 to Stream 6)	0.20
BP-2:	nominal bypass fraction (Stream 27 to Stream 22)	0.20
Q-80:	nominal heat duty	4.1542×10^6 kJ/h
Q-81:	fixed heat duty	2.5500×10^6 kJ/h
Q-82:	fixed heat duty	2.5500×10^6 kJ/h
Q-83:	fixed heat duty	3.2500×10^6 kJ/h
E-100:	UA	1.5×10^6 kJ/^{o}C-h
E-103:	UA	1.0×10^6 kJ/^{o}C-h
DT Reboiler:	boil-up ratio ("Boilup" over Stream 21)	0.5

Table 2 shows the conditions and compositions of the natural-gas-feed, ethane-rich product, and methane-rich residue streams at the base-case solution.

Table 2. The conditions and compositions of the natural-gas-feed, ethane-rich product, and methane-rich residue streams at the base-case solution.

streams & conditions	Natural Gas Feed Stream (Stream 1)	Methane-Rich Residue (Stream 25)	Ethane-Rich Product (Stream 21)
Vapor Fraction	0.9975	1	0
Temperature [^{o}C]	35	41.8	12.5
Pressure [atm]	60	21.9	19.1
Molar Flow [kgmole/h]	5000	4378.1	621.9
components	**mole fractions**		
Nitrogen	0.00550	0.00628	0.00000
CO_2	0.00910	0.00597	0.03113
Methane	**0.84570**	**0.96538**	**0.00311**
Ethane	**0.08200**	**0.02162**	**0.50705**
Propane	0.03400	0.00072	0.26832
i-Butane	0.00580	0.00002	0.04653
n-Butane	0.00860	0.00001	0.06908
i-Pentane	0.00280	0.00000	0.02251
n-Pentane	0.00210	0.00000	0.01688
n-Hexane	0.00180	0.00000	0.01447
n-Heptane	0.00120	0.00000	0.00965
n-Octane	0.00050	0.00000	0.00402
n-Nonane	0.00040	0.00000	0.00322
n-Decane	0.00050	0.00000	0.00402
Ethane recovery = 76.91%		Methane rejection = 99.95%	

As can be seen from Table 2, the natural-gas feed is rich in methane (84.57%) and lean in ethane (8.20%). At the base-case operating conditions, the TEP is capable of concentrating the ethane in its product stream (50.71%) with a small ethane loss in the residue stream (2.16%). The product stream contains very low methane (0.31%); all of the methane is basically concentrated in the residue stream (96.54%). The output streams of the plant are not balanced; the molar flow of the ethane-rich product stream (621.9 kgmole/h) is only 12.44% of the feed, and the molar flow of the methane-rich residue stream (4378.1 kgmole/h) is 87.56% of the feed. In Table 2, the ethane recovery (76.91%) is calculated as the ratio of the molar flow of ethane in Stream 21 (product) to the molar flow of ethane in Stream 1 (natural-gas feed), and the methane rejection (99.95%) is calculated as the ratio of the molar flow of methane in Stream 25 (residue) to the molar flow of methane in Stream 1 (natural-gas feed).

Effect of the Feed-Stream Temperature

The effects of the changing natural-gas-feed (Stream 1) temperature on ethane recovery, methane rejection, and on mole fractions of methane and ethane in the residue (Stream 24) and product (Stream 21) were investigated conveniently by the use of HYSYS's "databook" capability which automates the repetitive solution of the TEP for varying values of the feed-stream temperature.

Fig. 5 shows the ethane recovery and methane rejection as a function of the feed-stream temperature (nominal value was 35°C as given in Table 2). The ethane recovery is inversely related to the feed-stream temperature; recovery increases with decreasing feed-stream temperature. The methane rejection, however is directly related to the feed-stream temperature. The scales of the graph indicate that the methane rejection is not very sensitive to the feed-stream temperature; especially for temperatures greater than 37.5°C (just above the nominal feed temperature).

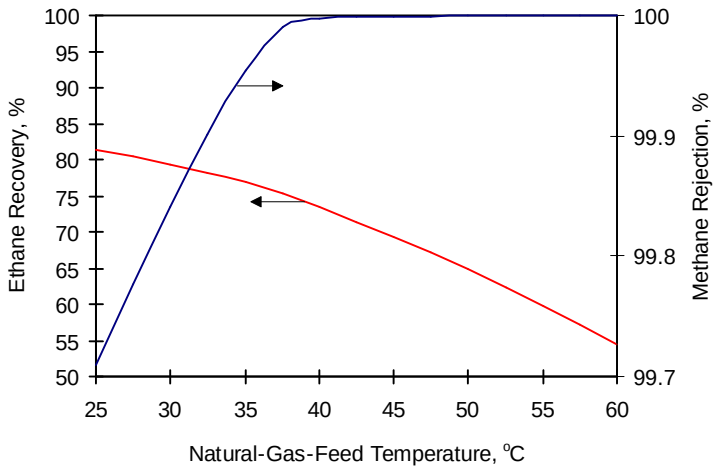


Figure 5. Ethane recovery and methane rejection as a function of the natural-gas feed-stream temperature.

Fig. 6 shows the mole fractions of ethane and methane in the residue and product streams as a function of the natural-gas feed-stream temperature. The mole fraction of methane in the product (Stream 21) becomes negligible for feed temperatures greater than 37.5°C. Furthermore, the mole fraction of ethane in the product is almost constant for feed temperatures up to about 35°C. Therefore, 35°C nominal feed temperature seems to be optimal both considering the ethane-recovery and methane-rejection levels in the product stream. The methane mole fraction in the residue (Stream 24) is not very sensitive to the feed temperature. However, the ethane mole fraction increases appreciably with increasing feed temperature; indicating the increasing loss of ethane in the residue.

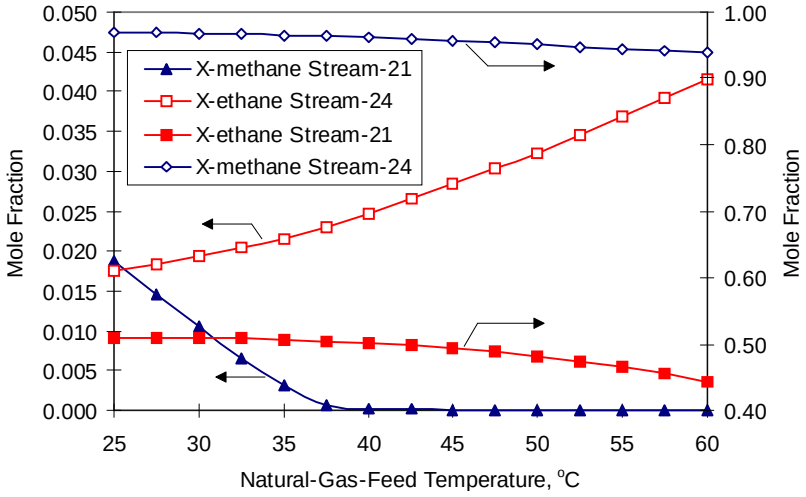


Figure 6. Mole fractions of ethane and methane in the residue and product streams as a function of the natural-gas feed-stream temperature.

Fig. 7 shows the temperature of the HEN outlet (Stream 13), which is the chilled natural-gas stream entering

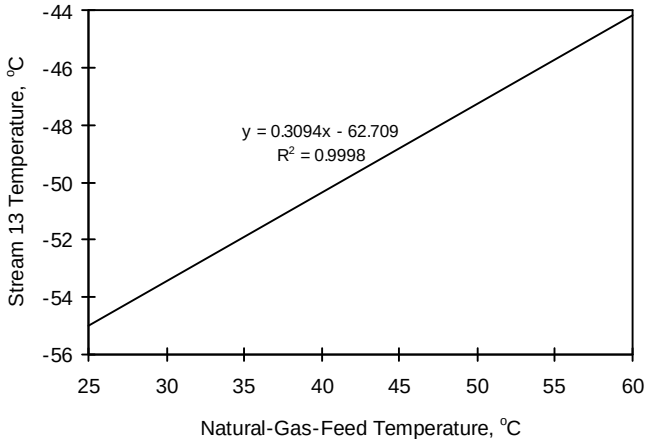


Figure 7. Temperature of the HEN outlet (natural-gas stream entering the main TEP) as a function of the natural-gas feed-stream temperature.

the expander side of the TEP, as a function of the natural-gas feed-stream temperature. It is seen that the temperature of Stream 13 depends on the feed-stream temperature perfectly linearly (the coefficient of correlation is almost unity). This is an important observation since it implies that there is a one-to-one correspondence with the temperature of the outlet stream of the HEN and the ethane-recovery/methane-rejection levels. In other words, if the temperature of the HEN outlet can be controlled at a desired level, then it is possible to control the ethane-recovery by inferring its level from the HEN outlet temperature. The temperature of the HEN outlet stream corresponding to the nominal natural-gas feed-stream temperature (35°C) is –51.9°C.

Effect of the Feed-Stream Pressure

The effect of the changing natural-gas-feed (Stream 1) pressure on the ethane recovery, methane rejection, and on the mole fractions of methane and ethane in the residue (Stream 24) and product (Stream 21) were also investigated conveniently by the use of HYSYS's "databook" capability which automates the repetitive solution of the TEP for varying values of feed-stream pressure.

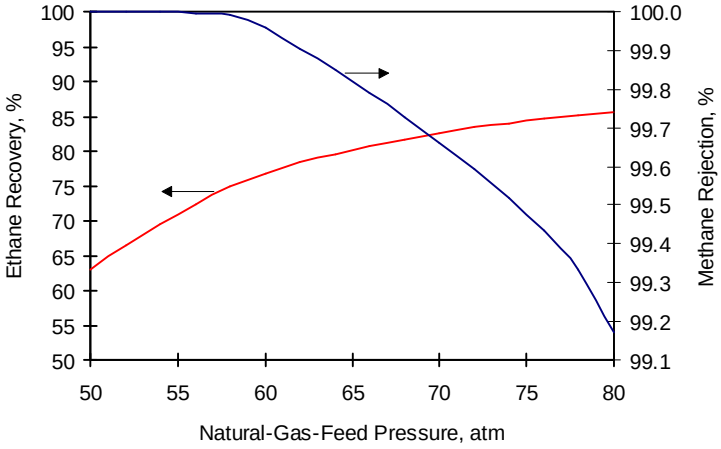


Figure 8. Ethane recovery and methane rejection as a function of the natural-gas feed-stream pressure.

Fig. 8 shows the ethane recovery and methane rejection as a function of the feed-stream pressure (nominal value was 60 atm as given in Table 2). The ethane recovery is directly related to the feed-stream pressure; recovery increases with increasing feed-stream pressure. The methane rejection, however is inversely related to the feed-stream pressure. The scales of the graph indicate that the methane rejection is not as sensitive as the ethane rejection to the feed-stream pressure; especially for feed-stream pressures lower than 58 atm (just below the nominal feed pressure). The effects of the feed temperature and pressure on the ethane recovery are comparable, however, the methane rejection is more sensitive to changes in the feed pressure.

Fig. 9 shows the mole fractions of ethane and methane in the residue and product streams as a function of the natural-gas feed-stream pressure. The mole fraction of methane in the product (Stream 21) is

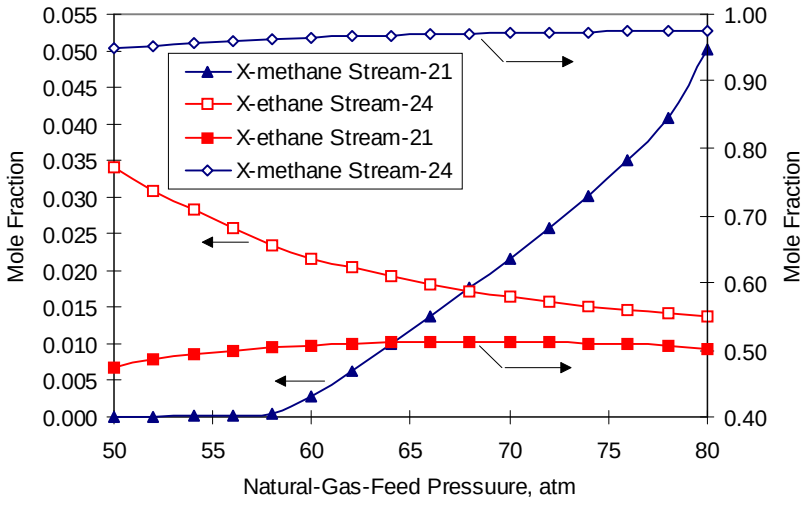


Figure 9. Mole fractions of ethane and methane in the residue and product streams as a function of the natural-gas feed-stream pressure.

negligible for feed pressures lower than about 57.5 atm. Furthermore, the mole fraction of ethane in the product is almost constant for feed pressures above about 60 atm. Therefore, 60 atm nominal feed-stream pressure seems to be optimal both considering the ethane-recovery and methane-rejection levels in the product stream. The methane mole fraction in the residue (Stream 24) is not very sensitive to the feed pressure. However, the ethane mole fraction decreases appreciably with increasing feed pressure; indicating the decreasing loss of ethane in the residue with increasing feed pressure.

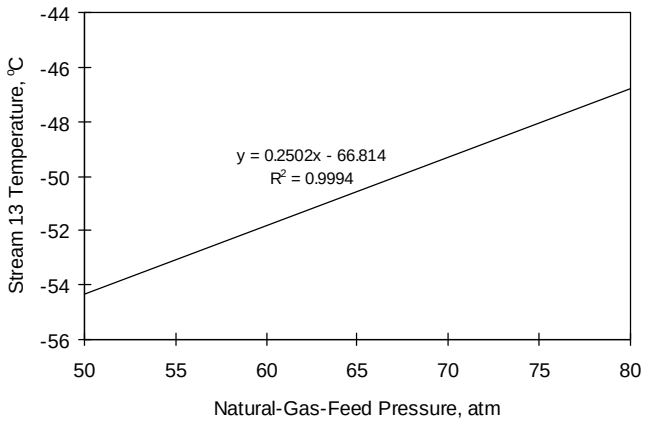


Figure 10. Temperature of the HEN outlet (natural-gas stream entering the main TEP) as a function of the natural-gas feed-stream pressure.

Fig. 10 shows the temperature of the HEN outlet (Stream 13), which is the chilled natural-gas stream entering the expander side of the TEP, as a function of the natural-gas feed-stream pressure. It is seen that the temperature of Stream 13 depends on the feed-stream pressure perfectly linearly (the coefficient of correlation is almost unity).

Effects of the HEN Control Variables

Since we concentrate on the HEN of the TEP in this preliminary work, all control variables (manipulated variables) were selected within the HEN structure. The four manipulated variables (Fig. 3) are TEE-1 split fraction (Stream 2 to Stream 1), TEE-2 split fraction (Stream 8 to Stream 7), BP-1 bypass fraction (Stream 29 to Stream 6), and BP-2 bypass fraction (Stream 27 to Stream 22). The effects of the changes in these manipulated variables on ethane recovery, methane rejection, and on mole fractions of methane and ethane in the residue (Stream 24) and product (Stream 21) were investigated conveniently by the use of HYSYS's "databook" capability which automates the repetitive solution of the TEP for varying values of the manipulated variables.

TEE-1 Split Fraction:

Fig. 11 shows the ethane recovery and methane rejection as a function of TEE-1 split (nominal value was 0.6 as given in Table 1). The ethane recovery can be controlled via TEE-1 split up to a split fraction of about 0.65; beyond which the split manipulation becomes ineffective for the control. In the most effective region of the TEE-1 split (less than 0.5) the methane rejection, contrary to ethane recovery, becomes insensitive to TEE-1 split manipulations.

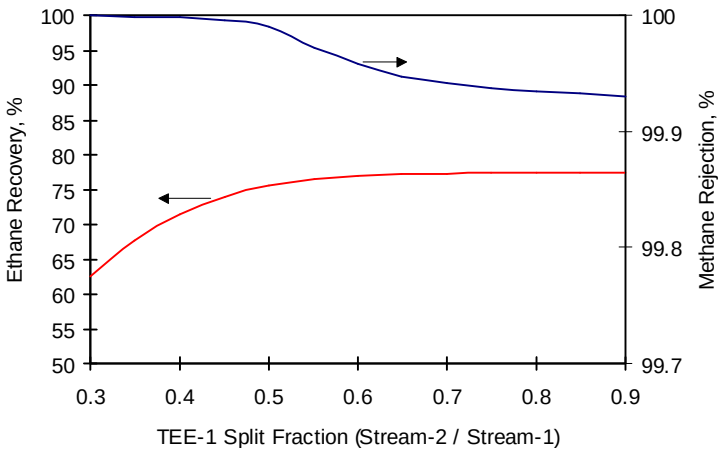


Figure 11. Ethane recovery and methane rejection as a function of TEE-1 split fraction.

Fig. 12 shows the mole fractions of ethane and methane in the residue and product streams as a function of TEE-1 split. The mole fraction of methane in the product (Stream 21) becomes negligible for split fractions less than about 0.5. Furthermore, the mole fraction of ethane in the product is almost constant for split fractions beyond about 0.6. Therefore, the nominal TEE-1 split fraction of 0.6 seems to be optimal both considering the ethane-recovery and methane-rejection levels in the product stream. The methane mole fraction in the residue (Stream 24) is not very sensitive to TEE-1 split. However, the ethane mole fraction decreases appreciably with increasing split up to 0.6; indicating the decreasing loss of ethane in the residue for lower TEE-1 splits.

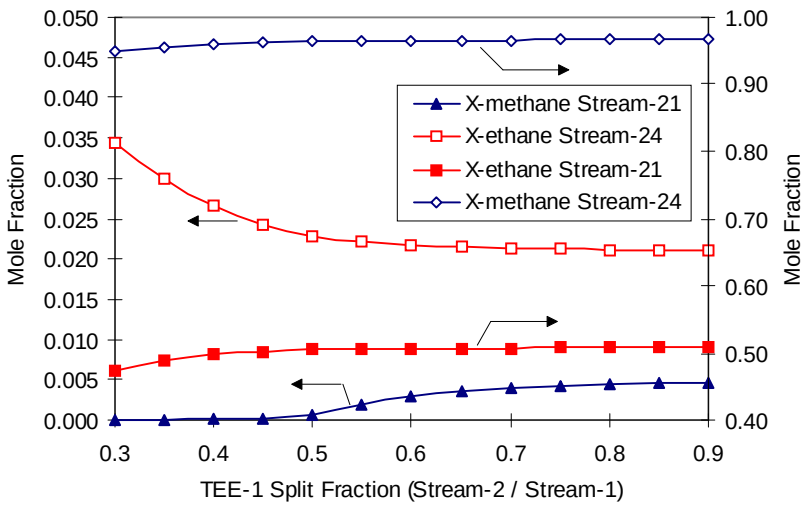


Figure 12. Mole fractions of ethane and methane in the residue and product streams as a function of TEE-1 split fraction.

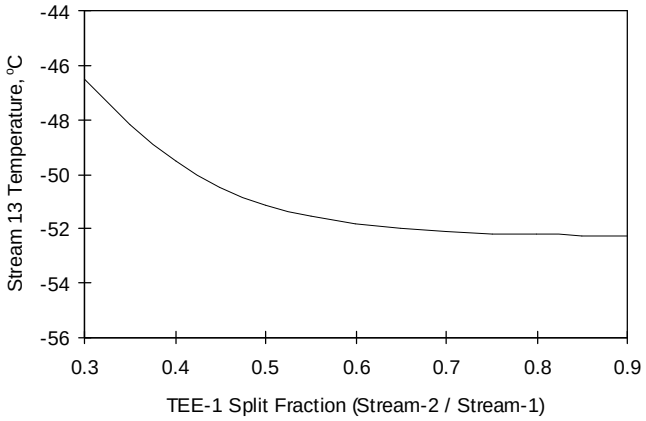


Figure 13. Temperature of the HEN outlet (natural-gas stream entering the main TEP) as a function of TEE-1 split fraction.

Fig. 13 shows the temperature of the HEN outlet (Stream 13), which is the chilled natural-gas stream entering the expander side of the TEP, as a function of TEE-1 split. The dependence is highly non-linear for split fractions less than about 0.6. Since there is a one-to-one correspondence between the temperature of Stream 13 and the ethane recovery, the dependencies of the ethane recovery and HEN-outlet temperature on TEE-1 split are very similar. This implies that the ethane-recovery and methane-rejection levels can be controlled with TEE-1 split manipulations.

TEE-2 Split Fraction:

Fig. 14 shows the ethane recovery and methane rejection as a function of TEE-2 split (nominal value was 0.75 as given in Table 1). The ethane recovery and methane rejection are insensitive to TEE-2 split-fraction variations and thus TEE-2 split cannot be

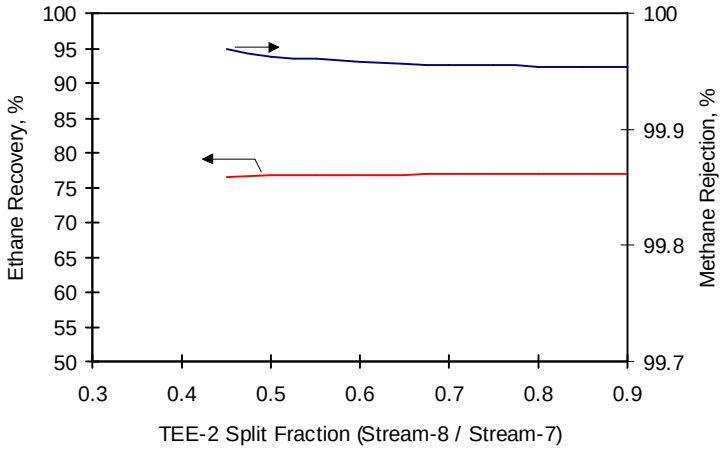


Figure 14. Ethane recovery and methane rejection as a function of TEE-2 split fraction.

used effectively for the control. Similarly, Fig. 15 shows the mole fractions of ethane and methane in the residue and product streams as a function of TEE-2 split. The mole fractions are also insensitive to TEE-2 split-fraction variations and thus TEE-2 split cannot be used for the composition control as well. Although not shown here, the temperature of the HEN outlet (Stream 13) is also insensitive, as expected, to TEE-2 split manipulations.

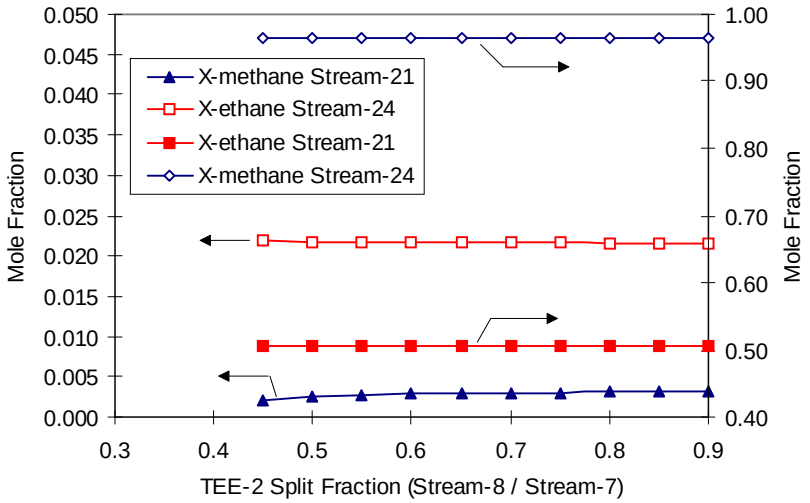


Figure 15. Mole fractions of ethane and methane in the residue and product streams as a function of TEE-2 split fraction.

BP-1 Bypass Fraction:

Fig. 16 shows the ethane recovery and methane rejection as a function of BP-1 bypass fraction (nominal value was 0.2 as given in Table 1). The ethane recovery can be controlled via BP-1 bypass manipulation. The methane rejection becomes insensitive to BP-1 bypass manipulations for bypass fractions greater than about 0.25.

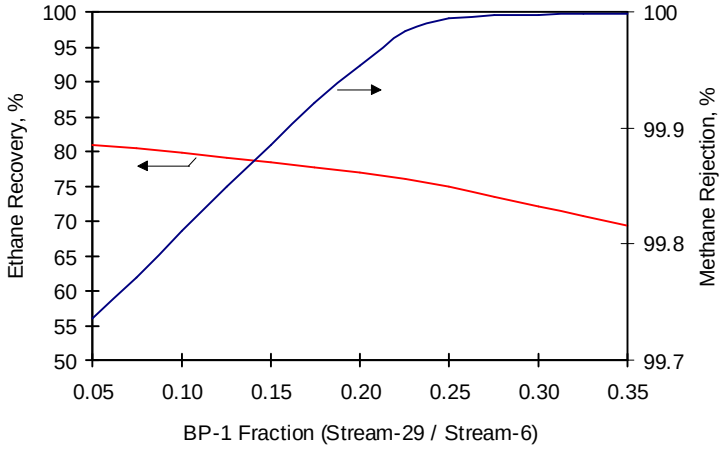


Figure 16. Ethane recovery and methane rejection as a function of BP-1 bypass fraction.

Fig. 17 shows the mole fractions of ethane and methane in the residue and product streams as a function of BP-1 bypass fraction. The mole fraction of methane in the product (Stream 21) becomes negligible for bypass fractions greater than about 0.25. Furthermore, the mole fraction of ethane in the product is almost constant for bypass fractions less than about 0.2. Therefore, the nominal BP-1 bypass fraction of 0.2 seems to be optimal considering both the ethane-recovery and

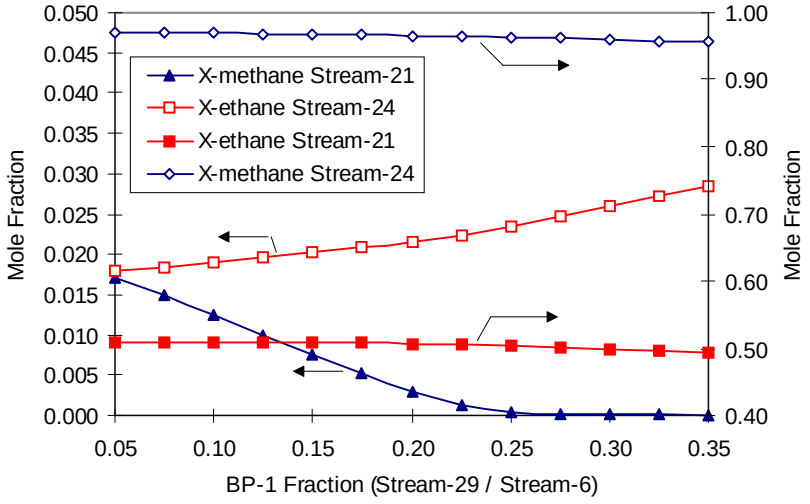


Figure 17. Mole fractions of ethane and methane in the residue and product streams as a function of the BP-1 bypass fraction.

methane-rejection levels in the product stream. The methane mole fraction in the residue (Stream 24) is not very sensitive to BP-1 bypass fraction. However, the ethane mole fraction increases appreciably with increasing BP-1 bypass; indicating the increasing loss of ethane in the residue for higher BP-1 bypass fractions.

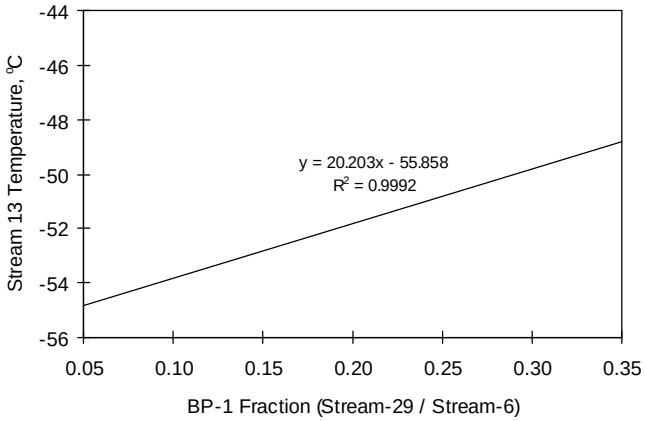


Figure 18. Temperature of the HEN outlet (natural-gas stream entering the main TEP) as a function of BP-1 bypass fraction.

Fig. 18 shows the temperature of the HEN outlet (Stream 13), which is the chilled natural-gas stream entering the expander side of the TEP, as a function of BP-1 bypass fraction. The dependence is perfectly linear. Since there is a one-to-one correspondence between the temperature of Stream 13 and the ethane recovery, the dependencies of the ethane recovery and HEN-outlet temperature on BP-1 bypass are very similar. This implies that ethane-recovery/methane-rejection levels can be controlled with BP-1 bypass manipulations.

BP-2 Bypass Fraction:

Fig. 19 shows the ethane recovery and methane rejection as a function of BP-2 bypass fraction (nominal value was 0.2 as given in Table 1). The ethane recovery can be controlled via BP-2 bypass manipulation; although not as effective as with the BP-1 bypass. Contrary to BP-1 bypass, the methane rejection is sensitive to BP-2 bypass manipulations throughout the entire range of BP-2 bypass.

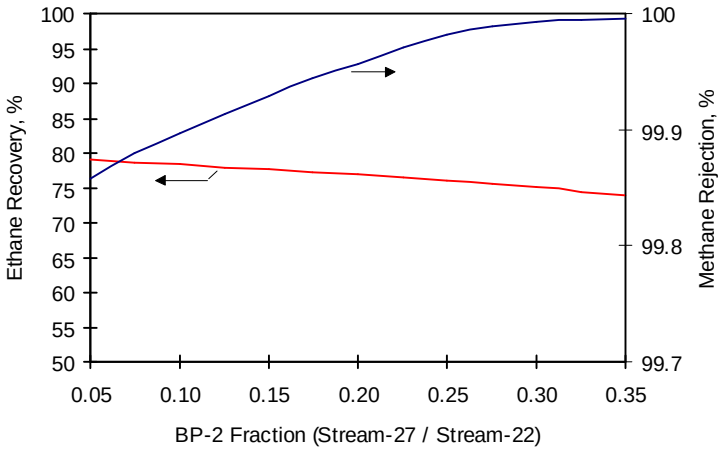


Figure 19. Ethane recovery and methane rejection as a function of BP-2 bypass fraction.

Fig. 20 shows the mole fractions of ethane and methane in the residue and product streams as a function of BP-2 bypass fraction. The mole fraction of methane in the product (Stream 21) becomes negligible for bypass fractions greater than about 0.3. Furthermore, the mole fraction of ethane in the product is almost

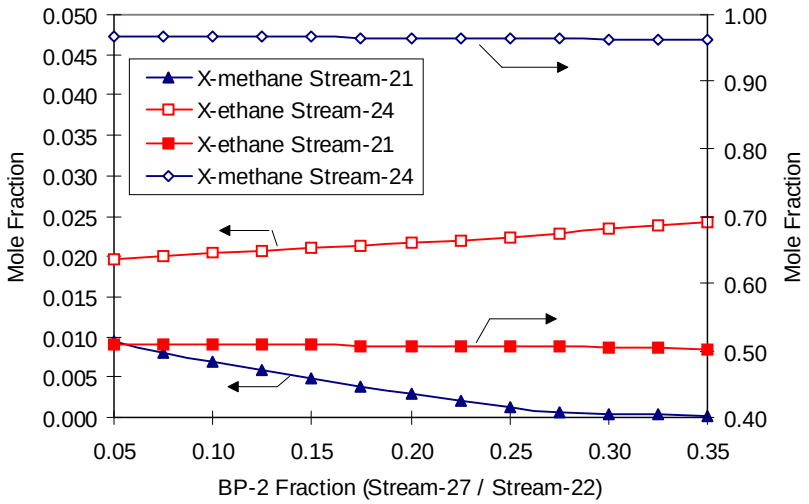


Figure 20. Mole fractions of ethane and methane in the residue and product streams as a function of BP-2 bypass fraction.

constant throughout the entire BP-2 bypass range. Therefore, BP-2 bypass fraction seems to be an insignificant variable for the control of the ethane recovery although it has an effect on the methane rejection. The methane mole fraction in the residue (Stream 24) is not very sensitive to BP-2 bypass. Furthermore, the ethane mole fraction increases not very appreciably (as compared to the effect of the BP-1 bypass) with increasing BP-2 bypass fractions; indicating the relatively insignificant loss of ethane in the residue for higher BP-2 bypass fractions.

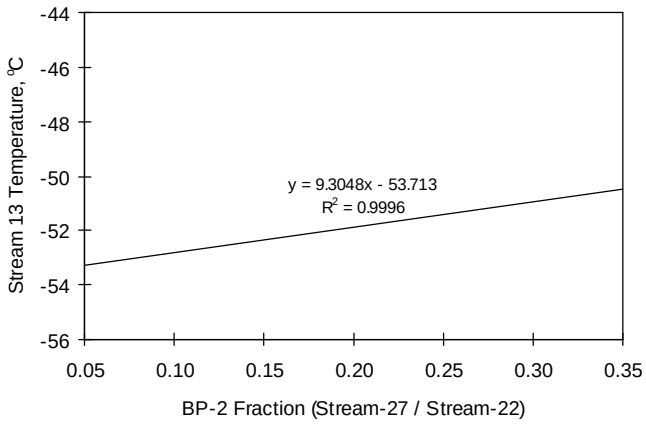


Figure 21. Temperature of the HEN outlet (natural-gas stream entering the main TEP) as a function of BP-2 bypass fraction.

Fig. 21 shows the temperature of the HEN outlet (Stream 13), which is the chilled natural-gas stream entering the expander side of the TEP, as a function of BP-2 bypass fraction. The dependence is perfectly linear; however, the slope is not as steep as that for the BP-1 bypass. Since there is a one-to-one correspondence between the temperature of Stream 13 and the ethane recovery, the dependencies of the ethane recovery and HEN-outlet temperature on BP-2 bypass are very similar. This implies that the ethane-recovery/methane-rejection levels can be controlled with BP-2 bypass manipulations. However, since the effect of BP-2 bypass manipulations are less significant than those of the BP-1 bypass, BP-1 bypass should be preferred over BP-2 bypass.

Comparison of the Effects of the Manipulated Variables over Normalized Ranges:

Figs. 22-25 show the effects of the manipulated variables (TEE-1 and TEE-2 split fractions, and BP-1 and BP-2 bypass fractions) on ethane recovery, methane rejection, and on mole fractions of methane and ethane in the residue and product streams when the ranges of the manipulated variables are normalized within their lower and upper limits. In Figs. 22-25, the point of intersection of the curves corresponds to the nominal values of the manipulated variables (Table 1).

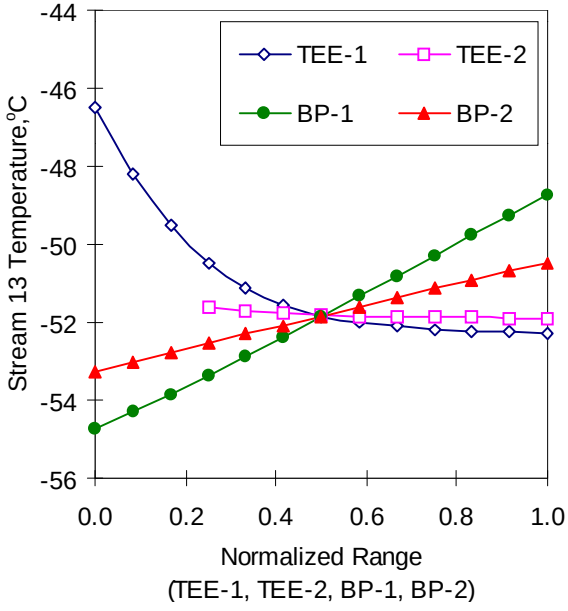


Figure 22. Temperature of the HEN outlet as a function of the normalized range of the manipulated variables.

Fig. 22 shows that TEE-2 split has almost no effect on the HEN outlet temperature (and hence on the ethane recovery). TEE-1 split has a non-linear and significant effect only in the normalized range 0-0.6. BP-1 bypass has a linear and significant effect which is valid throughout the entire range. The effect of BP-2 bypass is less than that of BP-1. Therefore, the control of the HEN outlet temperature should be done with TEE-1 split fraction for higher temperatures of Stream 13, and as the temperature decreases, for example towards -52°C,

the control should be done with BP-1 bypass manipulations. Fig. 23 shows that TEE-2 split has almost no effect on the ethane recovery. TEE-1 split has a non-linear and significant effect only in the normalized range 0.6-1. BP-1 bypass has a more linear and significant effect which is valid throughout the entire range. The effect of BP-2 bypass is less than that of BP-1. Therefore, the control of the ethane recovery should be done with TEE-1 split for lower ethane-recovery levels, and as the recovery increases, for example towards 75%, the control should be done with BP-1 bypass manipulations. Fig. 24 shows that TEE-2 split has almost no effect on the ethane mole fraction in the product stream. TEE-1 split has a very non-linear and significant effect only in the normalized range 0-0.6. BP-1 bypass has a more linear and significant effect especially in the normalized range 0.2-1. The effect of the BP-2 bypass is less than that of BP-1. Therefore, the control of the ethane mole fraction should be done with TEE-1 split for lower ethane-mole-fraction levels, and as the mole fraction increases, for example towards 0.5, the control should be done with BP-1 bypass manipulations. Fig. 25 shows that TEE-2 split has almost no effect on the methane rejection. TEE-1 split has a significant effect only in the normalized range 0.3-0.6. BP-1 bypass has the most significant and nearly linear effect in the normalized range 0-0.6. The effect of BP-2 bypass is less than that of BP-1. Therefore, the control of the methane rejection should be done with BP-1 bypass manipulations.

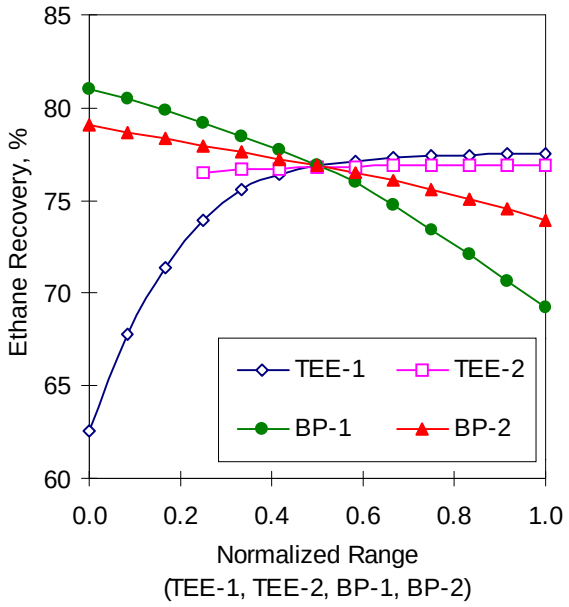


Figure 23. Ethane recovery as a function of the normalized range of the manipulated variables.

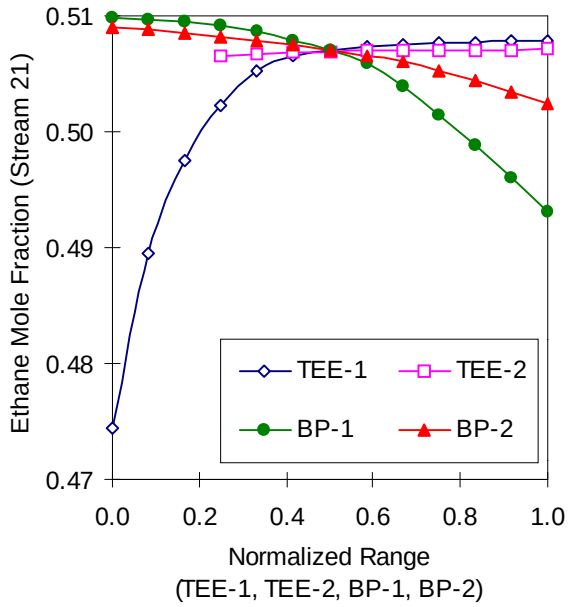


Figure 24. Ethane mole fraction as a function of the normalized range of the manipulated variables.

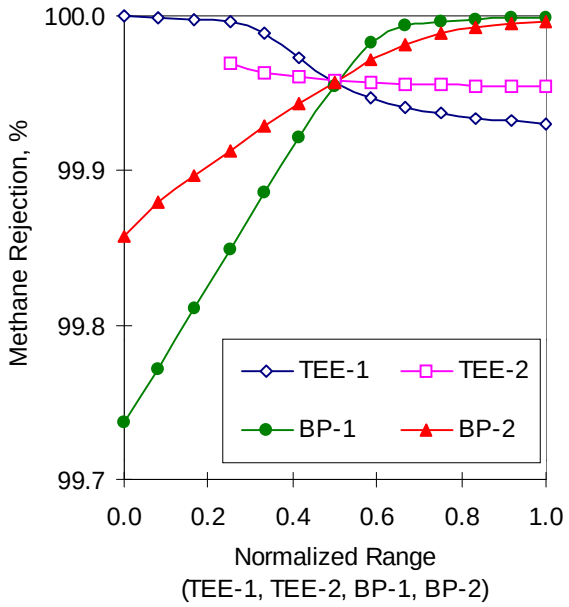


Figure 25. Methane rejection as a function of the normalized range of the manipulated variables.

Steady-State Optimal Control

The steady-state control problem was defined as follows: *When there is a disturbance in the natural-gas feed-stream condition(s), keep the ethane recovery at its desired level by using the manipulated variables in the HEN of the TEP.*

The three manipulated variables were selected as the TEE-1 split fraction (X_1), BP-1 bypass fraction (X_2), and BP-2 bypass fraction (X_3). TEE-2 was not included in the manipulated variables since its effect on ethane recovery was concluded to be negligible compared to those of the other three. The nominal values of these manipulated variables had been listed in Table 1. The desired level of ethane recovery, R, (ethane recovery set point) was selected as R^{set} = 76.9%, which is the recovery at the base-case operating conditions that were listed in Table 2.

The optimization problem, solved using the HYSYS's optimizer, was posed as follows (minimization of the norm of the ethane-recovery deviation from its set point subject to manipulated-variable bounds):

$$\begin{aligned} &\underset{X_1, X_2, X_3}{\text{minimize}} \left\| R - R^{set} \right\| \\ &\text{s.t.} \quad 0.20 \le X_1 \le 0.90 \\ &\qquad\quad 0.05 \le X_2 \le 0.35 \\ &\qquad\quad 0.05 \le X_3 \le 0.35 \end{aligned} \tag{1}$$

Table 3 lists the three disturbance scenarios and the corresponding uncontrolled response (ethane recovery level and HEN outlet temperature) of the TEP, and Table 4 lists the optimal values of the manipulated variables that keep the ethane-recovery level at its set point for each disturbance scenario.

Table 3. Disturbance scenarios and the corresponding uncontrolled response of the TEP.

Disturbance Scenario	Ethane Recovery	HEN Outlet Temperature
+15°C upset in feed temperature (from 35°C to 50°C)	64.9%	–47.2°C
+10 atm upset in feed pressure (from 60 atm to 70 atm)	82.6%	–49.3°C
–5°C upset in feed temperature (from 35°C to 30°C) and +10 atm upset in feed pressure (from 60 atm to 70 atm)	84.1%	–50.7°C

Table 4. Optimal values of the manipulated variables corresponding to disturbance scenarios.

Disturbance Scenario	TEE-1 split ratio	BP-1 bypass fraction	BP-2 bypass fraction
+15°C upset in feed temperature (from 35°C to 50°C)	0.9000	0.0728	0.1155
+10 atm upset in feed pressure (from 60 atm to 70 atm)	0.3094	0.2169	0.2247
–5°C upset in feed temperature (from 35°C to 30°C) and +10 atm upset in feed pressure (from 60 atm to 70 atm)	0.2486	0.2189	0.2244

Flexibility

The flexibility was defined as follows: *The maximum (limiting) magnitude of disturbance in the natural-gas feed-stream condition(s) such that the ethane recovery can be kept at its desired level via the manipulated variables in the HEN of the TEP.*

The manipulated variables were the TEE-1 split fraction (X_1), BP-1 bypass fraction (X_2), and BP-2 bypass fraction (X_3). The desired level of ethane recovery, R, (ethane recovery set point) was $R^{set} = 76.9\%$.

The flexibility problem, solved using the HYSYS's optimizer, was posed as the following optimization problem (maximization of the disturbance magnitude, d, subject to ethane-recovery-set-point equality constraint and subject to manipulated-variable bounds): Two disturbance variables, d, were studied; the natural-gas feed stream temperature and pressure.

$$\begin{aligned} &\underset{X_1, X_2, X_3}{\text{maximize}} && d \\ &\text{s.t.} && R - R^{set} = 0 \\ & && 0.20 \le X_1 \le 0.90 \\ & && 0.05 \le X_2 \le 0.35 \\ & && 0.05 \le X_3 \le 0.35 \end{aligned} \tag{2}$$

Table 4 shows the maximum and minimum values of the feed-stream temperature and pressure that can be tolerated while keeping the ethane recovery at its set point via the manipulated variables in the HEN.

Table 4. Flexibility of the TEP to feed temperature and pressure variations.

Disturbance Scenario	TEE-1 split ratio	BP-1 bypass fraction	BP-2 bypass fraction
Maximum feed temperature = 53.3°C	0.9	0.05	0.05
Minimum feed temperature = 10.1°C	0.2	0.35	0.35
Maximum feed pressure = 83.2 atm	0.2	0.35	0.35
Minimum feed pressure = 50.2 atm	0.9	0.05	0.05

Table 4 shows that the TEP can be operated at 76.9% ethane-recovery level, via the three manipulated variables in the HEN, as long as the natural-gas feed temperature is between $10.1 \le T(^oC) \le 53.3$ (when the feed pressure is at its 60 atm nominal value) and as long as the natural-gas feed pressure is between $50.2 \le P(atm) \le 83.2$ (when the feed temperature is at its 35°C nominal value).

Additional Comments

In the literature, the synthesis, design, and flexibility analysis of HENs are done as independent from the main process to which the HEN is attached. The analyses are mostly based on the fixed (mean) values of stream properties (density, heat capacity, etc) and heat-transfer coefficients. However, these properties are generally strong functions of temperature and pressure; especially for plants like the TEP where extreme temperatures and pressures involved result in strong non-ideal/non-linear phase-equilibria/physical-property behavior.

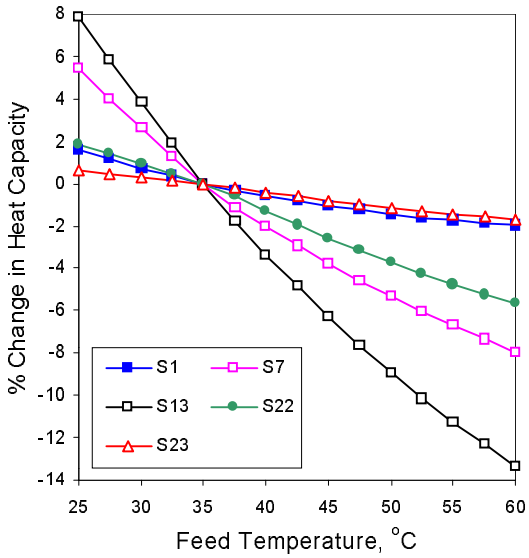


Figure 26. Deviation in heat capacities of some HEN streams with feed temperature.

Here, with Figs. 26-28, we demonstrate the variations in heat capacities of Streams 1, 7, 13, 22, and 23 in the HEN of the TEP as a function of the natural-gas feed temperature, feed pressure, and TEE-1 split ratio. Significant variations in heat capacities are observed around the nominal values of the x-axis variables (intersection of the curves). Clearly, any HEN synthesis, design, and flexibility analysis based on the nominal values of parameters would yield erroneous results for complex plants like the TEP.

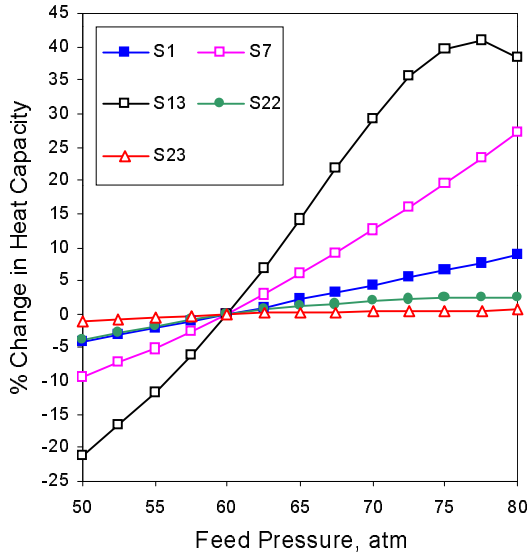


Figure 27. Deviation in heat capacities of some HEN streams with feed pressure.

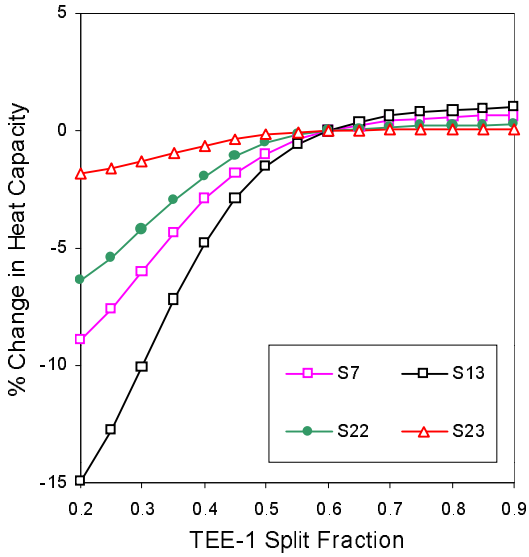


Figure 28. Deviation in heat capacities of some HEN streams with TEE-1 split ratio.

Conclusions

A Turbo-Expander Plant (TEP) is investigated with emphasis on its Heat-Exchanger Network (HEN) that strongly interacts with the TEP. In the analyses, the process flowsheet simulator HYSYS was used with its optimization capability. Bypass streams around heat exchangers were added to increase flexibility and disturbance-rejection ability of the HEN. Together with the bypasses, the split fractions in the HEN were used as the manipulated variables in investigating the

flexibility and steady-state optimizing-control of the TEP. The emphasis was given to the assessment of flexibility of the process in maintaining desired level of ethane recovery under natural-gas feed-stream temperature and pressure disturbances. The heat-exchanger bypasses and split fraction as the manipulated variables were able to control the ethane recovery at its set point for wide range of natural-gas feed-stream temperature and pressure disturbances. It was shown that, for the TEP, any HEN synthesis, design, and flexibility analysis based on the nominal values of physical properties would yield erroneous results due to significant variations in heat capacities around the nominal operating conditions.

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