# REFERENCES

Newton, C. and Chen, C. (1980). Second law analysis in cryogenic process. Energy Volume: 5, pp. 899-904.

Kanoğlu, M. (2002). Exergy analysis of multistage cascade refrigeration cycle used for natural gas liquefaction. International Journal of Energy Research, 26, 763-774

Remeljej, C.W. and Hoadley, A.F.A. (2004). An exergy analysis of small-scale liquefied natural gas liquefaction processes. Energy, 31, 2005-2019.

Gundersen, T., Aspelund, A. and Barton, P. (2009). An Overall of New Methodologies for the Design of Cryogenic process with an emphasis on LNG. Proceedings of the 1st Annual Gas Processing Symposium, 104-112.

Dhole, V.R. and Linnhoff, B. (1994). Overall Design of Low Temperature Processes. Computers Chemical Engineering, 18, S105-S111.

Marmolejo-Correa, D. and Gundersen, T. (2012). A comparison of exergy efficiency definitions with focus on low temperature processes. Energy, 44, 477-489.

Aspelund, A., Gundersen, T., Myklebust, J., Nowak, M.P. and Tomasgard, A. (2009). An optimization-simulation model for a simple LNG process. Computers and Chemical Engineering, 34, 1606-1617.

Alabdulkarem, A., Mortazavi, A., Hwang, Y., Radermacher, R. and Rogers, P. (2011). Optimization of propane pre-cooled mixed refrigerant LNG plant. Applied Thermal Engineering, 31, 091-1098.

Aspelund, A. and Gundersen, T. (2007). A new Process Synthesis Methodology utilizing Pressure Exergy in Subambient Processes. Procedding of the 17th European Symposium on Computer Aided Process Engineering, 24, 1133-1138 .

Mahabadipour, H. and Gharbi, H. (2013). Development and comparison of two expander cycles used in refrigeration system of olefin plant based on exergy analysis. Applied Thermal Engineering, 50, 771-780.

Vidal, A., Best, R., Rivero, R. and Cervantes, J. (2006). Analysis of a combined power and refrigeration cycle by the exergy method. Energy, 31, 3401-3414.

Marmolejo-Correa, D. and Gundersen, T. (2013). New Graphical Representation of Exergy Applied to Low Temperature Process Design. Industrial and Engineering Chemistry Research, 52, 7145-7156.

Marmolejo-Correa, D. and Gundersen, T. (2012). A new procedure for the design of LNG processes by combining Exergy and Pinch Analyses. Proceeding of the 25TH International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Perugia, Italy.

Marmolejo-Correa, D. and Gundersen, T. (2012). A new graphical representation of exergy applied to low temperature process design. Proceeding of the 11TH International Symposium on Process Systems Engineering, 2, 1180-1184, DOI: 10.1016/B978-0-444-59506-5.50067-5.

Marmolejo-Correa, D. and Gundersen, T. (2012). A new graphical exergy targeting representation for processes operating above and below ambient temperature. Proceeding of the 22nd European Symposium on Computer Aided Process Engineering, London, UK, 557-561.

Marmolejo-Correa, D. and Gundersen, T. (2011). Low Temperature Process Design: Challenges and Approaches for using Exergy Efficiencies. Proceeding of the 21st European Symposium on Computer Aided Process Engineering, 2, 1909-1913, DOI: 10.1016/B978-0-444-54298-4.50160-4.

Aspelund, A., Berstad, D.O., Gundersen, T. (2007). An Extended Pinch Analysis and Design procedure utilizing pressure based exergy for subambient cooling. Applied Thermal Engineering, 27(16), 2633-2649.

Linnhoff, B. and Dhole, V.R. (1992). Shaftwork targets for low-temperature process design. Chemical Engineering Science, 47(8), 2081-2091.

Yee, T.F., and Grossmann, I.E. (1990). Simultaneous optimization models for heat integration. II. Heat exchanger network synthesis. Computers and Chemical Engineering, 14(10), 1165-1184.

Linnhoff, B., Towsend, D.W., Boland, D., Hewitt, G.F., Thomas, B.E.A., Guy, A.R. and Marsland, R.H. (1982). A User Guide on Process Integration for the Efficient Use of Energy. The Institution of Chemical Engineers, Rugby.

Hackl, R. and Harvey, S. (2012). Total Site Analysis (TSA) and Exergy Analysis for Shaft Work and Associated Steam and Electricity Savings in Low Temperature Processes in Industrial Clusters. Chemical Engineering Transactions, 29, 73-78, DOI: 10.3303/CET1229013.

Pereira, C. and Lequisiga, D. (2014). Technical Evaluation of $C_3$-MR and Cascade Cycle on Natural Gas Liquefaction Process. International Journal of Chemical Engineering and Applications, 5, 451-456, DOI: 10.7763/IJCEA.2014.V5.427.

# APPENDICES

## Appendix A HEN Synthesis

```
SETS
        I         hot streams
/H1,H2,H3,H4,H5,H6,H7,H8,H9,H10,H11,H12,H13,H14,H15,H16,H17,H18/
        J         cold streams  / C1,C2,C3,C4,C5,C6,C7,C8,C9 /
        K         location      / firstlocation,location2*location26,lastlocation /
        CU        cold utility  / CU1,CU2,CU3,CU4,CU5,CU6,CU7,CU8,CU9,CU10/
;

SCALARS
        OMEGA             upper bound for heat exchange    /999999/
        GAMMA             upper bound for temperature difference /999999/
        EMAT              exchanger minimum approach temperature   /3/
        CHU               unit cost for hot utility     /1000/
        CF                fixed charge for exchangers   /99000/
        CW                unit cost for power consumption /200000/
;

PARAMETERS
TOUTH(I)  outlet temperature of cold stream
          /  H1    271.634
             H2    249.582
             H3    236.977
             H4    207.45
             H5    186.17
             H6    183.036
             H7    148.15
             H8    129.446
             H9    118.15
```

```
        H10    298.58
        H11    271.79
        H12    249.58
        H13    237.15
        H14    207.416
        H15    186.214
        H16    182.579
        H17    147.941
        H18    129.501      /
TINC(J)   inlet temperature of cold stream
/       C1     268.793
        C2     246.57
        C3     234.198
        C4     204.446
        C5     183.188
        C6     179.915
        C7     144.942
        C8     126.521
        C9     111.587     /
TOUTC(J)  outlet temperature of cold stream
/       C1     269.293
        C2     247.07
        C3     234.698
        C4     204.946
        C5     183.688
        C6     180.415
        C7     145.442
        C8     127.021
        C9     112.087       /
FH(I)     heat capacity of hot stream
/       H1     263.3583
        H2     272.9911
```

```
       H3     286.2356
       H4     351.4749
       H5     1480.733
       H6     1276.324
       H7     461.5032
       H8     374.2515
       H9     354.1076
       H10     22399
       H11     13446.61
       H12     12558.84
       H13     3152.466
       H14     2504.468
       H15     2901.974
       H16     1036.471
       H17     410.6263
       H18     149.4232       /
FC(J)     heat capacity of cold stream
/      C1     396200
       C2     320063
       C3     258800
       C4     221200
       C5     172800
       C6     65600
       C7     62400
       C8     23300
       C9     7830        /

FW(I,J)     heat capacity of work
TCUIN(CU) inlet temperature of cold utility
/      CU1     295
       CU2     268
       CU3     246
```

```
          CU4     234
          CU5     204
          CU6     183
          CU7     180
          CU8     145
          CU9     127
          CU10     111          /
TCUOUT(CU) outlet temperature of cold utility
/         CU1     300
          CU2     269
          CU3     247
          CU4     235
          CU5     205
          CU6     184
          CU7     181
          CU8     146
          CU9     128
          CU10     112          /
CCU(CU) unit cost for cold utility
/         CU1     22
          CU2     140
          CU3     160
          CU4     180
          CU5     300
          CU6     400
          CU7     450
          CU8     500
          CU9     600
          CU10     700          /

 ;

FW(I,J) =0;
FW('H10','C1') = 851.636;
```

```
          FW('H11','C2') = 621.772;
          FW('H12','C3') = 450.434;
          FW('H13','C4') = 388.078;
          FW('H14','C5') = 263.583;
          FW('H15','C6') = 88.14;
          FW('H16','C7') = 230.15;
          FW('H17','C8') = 55.29;
          FW('H18','C9') = 21.027;

VARIABLES
          TINH(I)        inlet temperature of hot stream
          O              objective function
          W              Shaft Work Requirement
;

POSITIVE VARIABLES
          dt(I,J,K)      temperature approach for match ij at the left of stage k
          dtcu(I,CU)     temperature approach for match hot stream i and cold utility
          dthu(J)        temperature approach for match cold stream j and hot utility
          q(I,J,K)       heat exchanged between hot stream i and cold stream j at
stage k
          qcu(I,CU)      heat exchanged between hot stream i and cold utility
          qhu(J)         heat exchanged between cold stream j and hot utility
          tH(I,K)        temperature of hot stream i at location k
          tC(J,K)        temperature of cold stream j at location k
;

BINARY VARIABLE
          z(I,J,K)       Binary variable of HEX Process to Process
          zcu(I,CU)      Binary variable of cold utility
          zhu(J)         Binary variable of hot utility
;
```

```
TINH.fx('H1') = 303.15;
TINH.fx('H2') = 271.634;
TINH.fx('H3') = 249.582;
TINH.fx('H4') = 236.977;
TINH.fx('H5') = 207.45;
TINH.fx('H6') = 186.17;
TINH.fx('H7') = 183.036;
TINH.fx('H8') = 148.15;
TINH.fx('H9') = 129.446;

TINH.lo('H10') = 299;
TINH.lo('H11') = 272;
TINH.lo('H12') = 250;
TINH.lo('H13') = 240;
TINH.lo('H14') = 208;
TINH.lo('H15') = 187;
TINH.lo('H16') = 183;
TINH.lo('H17') = 148;
TINH.lo('H18') = 130;

TINH.up('H10') = 308.951;
TINH.up('H11') = 285.491;
TINH.up('H12') = 260.839;
TINH.up('H13') = 281.75;
TINH.up('H14') = 248.822;
TINH.up('H15') = 198.068;
TINH.up('H16') = 232.016;
TINH.up('H17') = 184.059;
TINH.up('H18') = 162.963;
```

```
EQUATIONS
        OHB_H(I)          overall heat balance for each hot stream
        OHB_C(J)          overall heat balance for each cold stream
        SHB_H(I,K)       heat balance at each stage for hot stream
        SHB_C(J,K)       heat balance at each stage for cold stream
        TINHASSGN(I)  assignment of inlet temperature of hot stream i
        TINCASSGN(J)  assignment of inlet temperature of cold stream j
        FH1(I,K)          feasibility of temperature at each stage for hot stream
        FH2(I)            feasibility of temperature at last stage for hot stream
        FC1(J,K)          feasibility of temperature at each stage for cold stream
        FC2(J)            feasibility of temperature at first stage for cold stream
        HULOAD(I)         hot utility load
        CULOAD(J)         cold utility load
        HECOUNT1(I,J,K)    count heat exchanger
        HECOUNT2(I,CU)   count hot utility
        HECOUNT3(J)        count cold utility
        APPTEMPL(I,J,K)    approach temperature at the left of stage k
        APPTEMPR(I,J,K)    approach temperature at the right of stage k
        APPTEMPCU(I,CU) approach temperature at cold utility of hot stream i
        APPTEMPHU(J)       approach temperature at hot utility of cold stream j
        APPTEMPLIMIT(I,J,K)    limiting temperature approach
        APPTEMPCUMIN (I,CU)  approach temperature at cold utility
        CONSTMATCH      define match of cold utility
        CONSTMATCHC   define match of hot utility
        OBJFN               objective function
        SHAFTWORK        shaft work requirement
;

* Overall Energy balance........................................................
OHB_H(I) ..  (TINH(I)-TOUTH(I))*FH(I) =e=
SUM((J,K),q(I,J,K))+SUM(CU,qcu(I,CU));
OHB_C(J) ..  (TOUTC(J)-TINC(J))*FC(J) =e= SUM((I,K),q(I,J,K))+qhu(J);
```

```
* Heat balance at each stage..................................................
SHB_H(I,K)$(ORD(K) NE CARD(K)) .. (tH(I,K)-tH(I,K+1))*FH(I) =e=
SUM(J,q(I,J,K));
SHB_C(J,K)$(ORD(K) NE CARD(K)) .. (tC(J,K)-tC(J,K+1))*FC(J) =e=
SUM(I,q(I,J,K));

* Assignment Temperature......................................................
TINHASSGN(I) .. TINH(I) =e= tH(I,'firstlocation');
TINCASSGN(J) .. TINC(J) =e= tC(J,'lastlocation');

* Feasible Temperature........................................................
FH1(I,K)$(ORD(K) NE CARD(K)) .. tH(I,K) =g= tH(I,K+1);
FH2(I) .. TOUTH(I) =l= tH(I,'lastlocation');
FC1(J,K)$(ORD(K) NE CARD(K)) .. tC(J,K) =g= tC(J,K+1);
FC2(J) .. TOUTC(J) =g= tC(J,'firstlocation');

* Heat&Cold utility...........................................................
HULOAD(I) .. (tH(I,'lastlocation')-TOUTH(I))*FH(I) =e= SUM(CU,qcu(I,CU));
CULOAD(J) .. (TOUTC(J)-tC(J,'firstlocation'))*FC(J) =e= qhu(J);

* Counting existing heat exchanger at each stage...............................
HECOUNT1(I,J,K)$(ORD(K) NE CARD(K)) .. q(I,J,K)-OMEGA*z(I,J,K) =l= 0;
HECOUNT2(I,CU).. qcu(I,CU)-OMEGA*zcu(I,CU) =l= 0;
HECOUNT3(J) .. qhu(J)-OMEGA*zhu(J) =l= 0;

* Calculation of approach temperature..........................................
APPTEMPL(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =l= tH(I,K)-
tC(J,K)+GAMMA*(1-z(I,J,K));
APPTEMPR(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K+1) =l= tH(I,K+1)-
tC(J,K+1)+GAMMA*(1-z(I,J,K));
```

```
APPTEMPCU(I,CU).. dtcu(I,CU) =l= tH(I,'lastlocation')-
TCUOUT(CU)+GAMMA*(1-zcu(I,CU));
APPTEMPHU(J) .. dthu(J) =l= TOUTC(J)- tC(J,'firstlocation')+GAMMA*(1-
zhu(J));
APPTEMPLIMIT(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =g= EMAT;
APPTEMPCUMIN (I,CU) .. dtcu(I,CU) =g= EMAT;
CONSTMATCH.. SUM((I,CU),zcu(I,CU)) =l= 2;
CONSTMATCHC.. SUM((J),zhu(J)) =l= 0;

* Objective Function.........................................
OBJFN .. O =e=
SUM((I,CU),CCU(CU)*qcu(I,CU))+CHU*SUM(J,qhu(J))+CF*SUM((I,J,K),z(I,J,K
))+SUM((I,CU),CF*zcu(I,CU))+CF*SUM(J,zhu(J))+
CW*SUM((I,J),FW(I,J)*(TINH(I)-TOUTC(J)));
SHAFTWORK .. W =e= SUM((I,J),FW(I,J)*(TINH(I)-TOUTC(J))) ;
;
MODEL STAGEMODEL SYNHEAT model /ALL/ ;
SOLVE STAGEMODEL USING MIP MINIMISING O;
DISPLAY z.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,O.l,W.l,FW;
```

## Appendix B The Multistage Cascade Refrigeration of LNG Process Flowsheet and Stream Condition in PROII

**Table B1** The base case condition of multistage cascade refrigeration of LNG process

| | $T_s$ (°C) | $T_t$ (°C) | $P_s$ (atm) | $P_t$ (atm) | F (kg/s) |
|---|---|---|---|---|---|
| **H11** | 12.34 | -1.36 | 4.48 | 4.48 | 458.692 |
| **H12** | 8.6 | -1.36 | 16.5 | 16.5 | 332.718 |
| **H13** | 30 | -1.52 | 39.47 | 39.47 | 108.733 |
| **H14** | 35.8 | 25.43 | 9.5 | 9.5 | 652.143 |
| **H21** | -12.31 | -23.57 | 2.12 | 2.12 | 334.604 |
| **H22** | -1.36 | -23.63 | 16.5 | 16.5 | 332.718 |
| **H23** | -1.52 | -23.57 | 39.47 | 39.47 | 108.733 |
| **H31** | -23.63 | -36 | 16.5 | 16.5 | 332.718 |
| **H32** | -24.33 | -35.57 | 6.02 | 6.02 | 216.771 |
| **H33** | -23.57 | -36.17 | 39.47 | 39.47 | 108.733 |
| **H41** | -35.57 | -65.73 | 6.02 | 6.02 | 216.771 |
| **H42** | -36.17 | -65.7 | 39.47 | 39.47 | 108.733 |
| **H51** | -75.08 | -86.94 | 2.454 | 2.454 | 73.108 |
| **H52** | -41.13 | -86.9 | 35.5 | 35.5 | 136.283 |
| **H53** | -65.7 | -86.98 | 39.47 | 39.47 | 108.733 |
| **H61** | -86.9 | -90.57 | 35.5 | 35.5 | 136.283 |
| **H62** | -86.98 | -90.11 | 39.47 | 39.47 | 108.733 |
| **H71** | -89.09 | -125.21 | 9.402 | 9.402 | 29.39 |
| **H72** | -110.19 | -125 | 3.536 | 3.536 | 9.16 |
| **H73** | -90.11 | -125 | 39.47 | 39.47 | 108.733 |
| **H81** | -125 | -143.65 | 3.536 | 3.536 | 9.16 |
| **H82** | -125 | -143.7 | 39.47 | 39.47 | 108.733 |
| **H91** | -143.7 | -155 | 39.47 | 39.47 | 108.733 |
| **C1** | -4.36 | -4.36 | 4.08 | 4.08 | 652.143 |
| **C2** | -26.58 | -26.58 | 1.89 | 1.89 | 458.692 |
| **C3** | -38.95 | -38.95 | 1.15 | 1.15 | 334.604 |
| **C4** | -68.7 | -68.7 | 5.37 | 5.37 | 332.718 |
| **C5** | -89.96 | -89.9 | 2.12 | 2.12 | 216.771 |
| **C6** | -93.24 | -93.24 | 1.8 | 1.8 | 73.108 |
| **C7** | -128.21 | -128.21 | 8.15 | 8.15 | 136.283 |
| **C8** | -146.63 | -146.6 | 2.94 | 2.94 | 29.39 |
| **C9** | -161.56 | -161.56 | 1 | 1 | 9.16 |

**Table B2** The condition of multistage cascade refrigeration of LNG process from result of Shaft work targeting technique

| | $T_s$ (°C) | $T_t$ (°C) | $P_s$ (atm) | $P_t$ (atm) | F (kg/s) |
|---|---|---|---|---|---|
| **H11** | 12.351 | -1.373 | 4.48 | 4.48 | 425.756 |
| **H12** | 9.858 | -1.36 | 16.5 | 16.5 | 307.808 |
| **H13** | 30 | -1.36 | 39.47 | 39.47 | 108.733 |
| **H14** | 36.204 | 25.43 | 9.5 | 9.5 | 607.524 |
| **H21** | -12.301 | -23.563 | 2.12 | 2.12 | 309.773 |
| **H22** | -1.36 | -23.56 | 16.5 | 16.5 | 307.808 |
| **H23** | -1.36 | -23.55 | 39.47 | 39.47 | 108.733 |
| **H31** | -23.56 | -35.269 | 16.5 | 16.5 | 307.808 |
| **H32** | -22.799 | -36 | 6.02 | 6.02 | 198.524 |
| **H33** | -23.55 | -36 | 39.47 | 39.47 | 108.733 |
| **H41** | -36 | -65.734 | 6.02 | 6.02 | 198.524 |
| **H42** | -36 | -65.7 | 39.47 | 39.47 | 108.733 |
| **H51** | -50.197 | -86.936 | 2.454 | 2.454 | 84.691 |
| **H52** | -64.411 | -86.9 | 25 | 25 | 84.346 |
| **H53** | -65.7 | -86.93 | 39.47 | 39.47 | 108.733 |
| **H61** | -86.9 | -101.024 | 25 | 25 | 84.346 |
| **H62** | -86.93 | -101 | 39.47 | 39.47 | 108.733 |
| **H71** | -89.117 | -125.21 | 9.402 | 9.402 | 29.393 |
| **H72** | -115.271 | -125 | 3.536 | 3.536 | 9.043 |
| **H73** | -101 | -125 | 39.47 | 39.47 | 108.733 |
| **H81** | -125 | -143.66 | 3.536 | 3.536 | 9.043 |
| **H82** | -125 | -143.6 | 39.47 | 39.47 | 108.733 |
| **H91** | -143.6 | -155 | 39.47 | 39.47 | 108.733 |
| **C1** | -4.36 | -4.35 | 4.08 | 4.08 | 607.524 |
| **C2** | -26.58 | -26.57 | 1.89 | 1.89 | 425.756 |
| **C3** | -38.95 | -38.94 | 1.15 | 1.15 | 309.773 |
| **C4** | -68.7 | -68.7 | 5.37 | 5.37 | 307.808 |
| **C5** | -89.96 | -89.95 | 2.12 | 2.12 | 198.524 |
| **C6** | -104.028 | -104.018 | 1 | 1 | 84.691 |
| **C7** | -128.208 | -128.198 | 8.15 | 8.15 | 84.346 |
| **C8** | -146.63 | -146.62 | 2.94 | 2.94 | 29.393 |
| **C9** | -157.981 | -157.98 | 1.33 | 1.33 | 9.043 |

**Table B3** The condition of multistage cascade refrigeration of LNG process from result of the Extended Pinch Analysis and Design Methodology and novel exergy diagram

| | **$T_s$ (°C)** | **$T_t$ (°C)** | **$P_s$ (atm)** | **$P_t$ (atm)** | **F (kg/s)** |
|---|---|---|---|---|---|
| **H11** | 12.351 | -1.363 | 4.48 | 4.48 | 407.099 |
| **H12** | 0.674 | -1.36 | 14.78 | 14.78 | 275.825 |
| **H13** | 30 | -1.516 | 39.47 | 39.47 | 108.733 |
| **H14** | 35.932 | 25.43 | 9.5 | 9.5 | 561.128 |
| **H21** | -9.612 | -23.563 | 2.12 | 2.12 | 297.343 |
| **H22** | -1.36 | -23.681 | 14.78 | 14.78 | 275.825 |
| **H23** | -1.516 | -23.568 | 39.47 | 39.47 | 108.733 |
| **H31** | -23.681 | -39.011 | 14.78 | 14.78 | 275.825 |
| **H32** | -23.906 | -40.219 | 6.02 | 6.02 | 189.251 |
| **H33** | -23.568 | -38.882 | 39.47 | 39.47 | 108.733 |
| **H41** | -40.219 | -65.724 | 6.02 | 6.02 | 189.251 |
| **H42** | -38.882 | -65.7 | 39.47 | 39.47 | 108.733 |
| **H51** | -50.286 | -86.936 | 2.45 | 2.45 | 79.392 |
| **H52** | -65.443 | -86.9 | 25 | 25 | 77.968 |
| **H53** | -65.7 | -86.988 | 39.47 | 39.47 | 108.733 |
| **H61** | -86.9 | -101.024 | 25 | 25 | 77.968 |
| **H62** | -86.988 | -101.181 | 39.47 | 39.47 | 108.733 |
| **H71** | -89.122 | -125.21 | 9.402 | 9.402 | 27.722 |
| **H72** | -121.905 | -125 | 3.536 | 3.536 | 8.086 |
| **H73** | -101.181 | -125 | 39.47 | 39.47 | 108.733 |
| **H81** | -125 | -144.515 | 3.536 | 3.536 | 8.086 |
| **H82** | -125 | -143.704 | 39.47 | 39.47 | 108.733 |
| **H91** | -143.704 | -155.325 | 39.47 | 2.2 | 108.733 |
| **C1** | -4.36 | -4.36 | 4.08 | 4.08 | 561.128 |
| **C2** | -26.58 | -26.58 | 1.89 | 1.89 | 407.099 |
| **C3** | -42.19 | -42.19 | 1 | 1 | 297.343 |
| **C4** | -68.7 | -68.7 | 5.37 | 5.37 | 275.825 |
| **C5** | -89.96 | -89.96 | 2.12 | 2.12 | 189.251 |
| **C6** | -104.028 | -104.028 | 1 | 1 | 79.392 |
| **C7** | -128.208 | -128.208 | 8.15 | 8.15 | 77.968 |
| **C8** | -146.63 | -146.63 | 2.94 | 2.94 | 27.722 |
| **C9** | -157.032 | -157.032 | 1.43 | 1.43 | 8.086 |

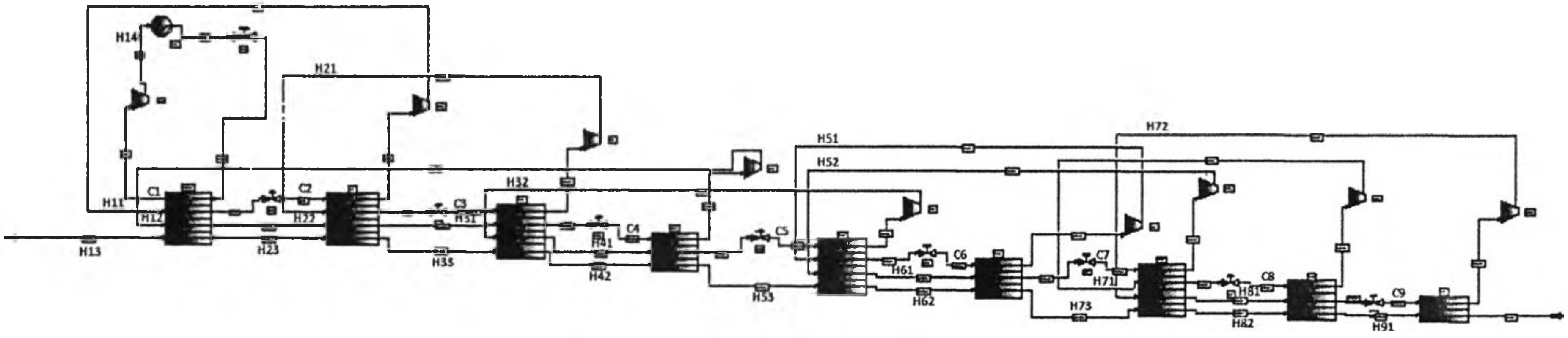

**Figure B1** The multistage cascade refrigeration of LNG process in PROII.

## Appendix C HEN Retrofit

### Model of HEN Retrofit for Case 1 (new exchangers ≥ 20)

```
SETS
        I       hot streams
/H1,H2,H3,H4,H5,H6,H7,H8,H9,H10,H11,H12,H13,H14,H15,H16,H17,H18/
        J       cold streams  / C1,C2,C3,C4,C5,C6,C7,C8,C9 /
        K       location     / firstlocation,location2*location26,lastlocation /
        CU      cold utility  / CU1,CU2,CU3,CU4,CU5,CU6,CU7,CU8,CU9,CU10/
;

SCALARS
        OMEGA           upper bound for heat exchange    /999999/
        GAMMA           upper bound for temperature difference /999999/
        EMAT            exchanger minimum approach temperature   /3/
        CHU             unit cost for hot utility    /1000/
        CF              fixed charge for exchangers   /99000000/
        CW              unit cost for power consumption /200000/
;

PARAMETERS
TOUTH(I)   outlet temperature of cold stream
          /  H1    271.634
             H2    249.582
             H3    236.977
             H4    207.45
             H5    186.17
             H6    183.036
             H7    148.15
             H8    129.446
             H9    118.15
```

```
      H10   298.58
      H11   271.79
      H12   249.58
      H13   237.15
      H14   207.416
      H15   186.214
      H16   182.579
      H17   147.941
      H18   129.501    /
TINC(J)  inlet temperature of cold stream
/     C1    268.793
      C2    246.57
      C3    234.198
      C4    204.446
      C5    183.188
      C6    179.915
      C7    144.942
      C8    126.521
      C9    111.587    /
TOUTC(J)  outlet temperature of cold stream
/     C1    269.293
      C2    247.07
      C3    234.698
      C4    204.946
      C5    183.688
      C6    180.415
      C7    145.442
      C8    127.021
      C9    112.087      /
FH(I)    heat capacity of hot stream
/     H1    263.3583
      H2    272.9911
```

```
         H3      286.2356
         H4      351.4749
         H5      1480.733
         H6      1276.324
         H7      461.5032
         H8      374.2515
         H9      354.1076
         H10     22399
         H11     13446.61
         H12     12558.84
         H13     3152.466
         H14     2504.468
         H15     2901.974
         H16     1036.471
         H17     410.6263
         H18     149.4232        /
FC(J)     heat capacity of cold stream
/        C1      396200
         C2      320063
         C3      258800
         C4      221200
         C5      172800
         C6      65600
         C7      62400
         C8      23300
         C9      7830       /

FW(I,J)     heat capacity of work
TCUIN(CU) inlet temperature of cold utility
/        CU1     295
         CU2     268
         CU3     246
```

```
      CU4      234
      CU5      204
      CU6      183
      CU7      180
      CU8      145
      CU9      127
      CU10      111        /
TCUOUT(CU) outlet temperature of cold utility
/     CU1      300
      CU2      269
      CU3      247
      CU4      235
      CU5      205
      CU6      184
      CU7      181
      CU8      146
      CU9      128
      CU10      112        /
CCU(CU) unit cost for cold utility
/     CU1      22
      CU2      140
      CU3      160
      CU4      180
      CU5      300
      CU6      400
      CU7      450
      CU8      500
      CU9      600
      CU10      700        /

;

FW(I,J) =0;
FW('H10','C1') = 851.636;
```

```
FW('H11','C2') = 621.772;
FW('H12','C3') = 450.434;
FW('H13','C4') = 388.078;
FW('H14','C5') = 263.583;
FW('H15','C6') = 88.14;
FW('H16','C7') = 230.15;
FW('H17','C8') = 55.29;
FW('H18','C9') = 21.027;

ex_z(I,J,K);
ex_z(I,J,K) = 0;
ex_z('H11','C1','firstlocation')= 1;
ex_z('H15','C1','firstlocation')= 1;
ex_z('H1','C1','firstlocation')= 1;
ex_z('H2','C2','location2')= 1;
ex_z('H12','C2','location2')= 1;
ex_z('H15','C2','location2')= 1;
ex_z('H17','C3','location3')= 1;
ex_z('H15','C3','location3')= 1;
ex_z('H3','C3','location3')= 1;
ex_z('H4','C4','location4')= 1;
ex_z('H17','C4','location4')= 1;
ex_z('H20','C5','location5')= 1;
ex_z('H18','C5','location5')= 1;
ex_z('H5','C5','location5')= 1;
ex_z('H6','C6','location6')= 1;
ex_z('H20','C6','location6')= 1;
ex_z('H7','C7','location7')= 1;
ex_z('H23','C7','location7')= 1;
ex_z('H21','C7','location7')= 1;
ex_z('H23','C8','location8')= 1;
ex_z('H8','C8','location8')= 1;
```

```
        ex_z('H9','C9','location9')= 1;

VARIABLES
        TINH(I)         inlet temperature of hot stream
        O               objective function
        W               Shaft Work Requirement
;

POSITIVE VARIABLES
        dt(I,J,K)       temperature approach for match ij at the left of stage k
        dtcu(I,CU)      temperature approach for match hot stream i and cold utility
        dthu(J)         temperature approach for match cold stream j and hot utility
        q(I,J,K)        heat exchanged between hot stream i and cold stream j at
stage k
        qcu(I,CU)       heat exchanged between hot stream i and cold utility
        qhu(J)          heat exchanged between cold stream j and hot utility
        tH(I,K)         temperature of hot stream i at location k
        tC(J,K)         temperature of cold stream j at location k
;

BINARY VARIABLE
        z(I,J,K)        Binary variable of HEX Process to Process
        zcu(I,CU)       Binary variable of cold utility
        zhu(J)          Binary variable of hot utility
;

TINH.fx('H1') = 303.15;
TINH.fx('H2') = 271.634;
TINH.fx('H3') = 249.582;
TINH.fx('H4') = 236.977;
TINH.fx('H5') = 207.45;
TINH.fx('H6') = 186.17;
```

```
TINH.fx('H7') = 183.036;
TINH.fx('H8') = 148.15;
TINH.fx('H9') = 129.446;

TINH.lo('H10') = 299;
TINH.lo('H11') = 272;
TINH.lo('H12') = 250;
TINH.lo('H13') = 240;
TINH.lo('H14') = 208;
TINH.lo('H15') = 187;
TINH.lo('H16') = 183;
TINH.lo('H17') = 148;
TINH.lo('H18') = 130;

TINH.up('H10') = 308.951;
TINH.up('H11') = 285.491;
TINH.up('H12') = 260.839;
TINH.up('H13') = 281.75;
TINH.up('H14') = 248.822;
TINH.up('H15') = 198.068;
TINH.up('H16') = 232.016;
TINH.up('H17') = 184.059;
TINH.up('H18') = 162.963;


EQUATIONS
      OHB_H(I)       overall heat balance for each hot stream
      OHB_C(J)       overall heat balance for each cold stream
      SHB_H(I,K)     heat balance at each stage for hot stream
      SHB_C(J,K)     heat balance at each stage for cold stream
      TINHASSGN(I)  assignment of inlet temperature of hot stream i
      TINCASSGN(J)  assignment of inlet temperature of cold stream j
```

```
        FH1(I,K)          feasibility of temperature at each stage for hot stream
        FH2(I)            feasibility of temperature at last stage for hot stream
        FC1(J,K)          feasibility of temperature at each stage for cold stream
        FC2(J)            feasibility of temperature at first stage for cold stream
        HULOAD(I)         hot utility load
        CULOAD(J)         cold utility load
        HECOUNT1(I,J,K)   count heat exchanger
        HECOUNT2(I,CU)   count hot utility
        HECOUNT3(J)       count cold utility
        APPTEMPL(I,J,K)   approach temperature at the left of stage k
        APPTEMPR(I,J,K)   approach temperature at the right of stage k
        APPTEMPCU(I,CU) approach temperature at cold utility of hot stream i
        APPTEMPHU(J)      approach temperature at hot utility of cold stream j
        APPTEMPLIMIT(I,J,K)    limiting temperature approach
        APPTEMPCUMIN (I,CU)  approach temperature at cold utility
        CONSTMATCH      define match of cold utility
        CONSTMATCHC     define match of hot utility
        newmatchz(I,J,K)
        OBJFN           objective function
        SHAFTWORK       shaft work requirement
;

* Overall Energy balance.......................................................
OHB_H(I) .. (TINH(I)-TOUTH(I))*FH(I) =e=
SUM((J,K),q(I,J,K))+SUM(CU,qcu(I,CU));
OHB_C(J) .. (TOUTC(J)-TINC(J))*FC(J) =e= SUM((I,K),q(I,J,K))+qhu(J);

* Heat balance at each stage..................................................
SHB_H(I,K)$(ORD(K)   NE   CARD(K))   ..   (tH(I,K)-tH(I,K+1))*FH(I)   =e=
SUM(J,q(I,J,K));
SHB_C(J,K)$(ORD(K)   NE   CARD(K))   ..   (tC(J,K)-tC(J,K+1))*FC(J)   =e=
SUM(I,q(I,J,K));
```

```
* Assignment Temperature.......................................................
TINHASSGN(I) .. TINH(I) =e= tH(I,'firstlocation');
TINCASSGN(J) .. TINC(J) =e= tC(J,'lastlocation');

* Feasible Temperature........................................................
FH1(I,K)$(ORD(K) NE CARD(K)) .. tH(I,K) =g= tH(I,K+1);
FH2(I) .. TOUTH(I) =l= tH(I,'lastlocation');
FC1(J,K)$(ORD(K) NE CARD(K)) .. tC(J,K) =g= tC(J,K+1);
FC2(J) .. TOUTC(J) =g= tC(J,'firstlocation');

* Heat&Cold utility..........................................................
HULOAD(I) .. (tH(I,'lastlocation')-TOUTH(I))*FH(I) =e= SUM(CU,qcu(I,CU));
CULOAD(J) .. (TOUTC(J)-tC(J,'firstlocation'))*FC(J) =e= qhu(J);

* Counting existing heat exchanger at each stage...............................
HECOUNT1(I,J,K)$(ORD(K) NE CARD(K)) .. q(I,J,K)-OMEGA*z(I,J,K) =l= 0;
HECOUNT2(I,CU).. qcu(I,CU)-OMEGA*zcu(I,CU) =l= 0;
HECOUNT3(J) .. qhu(J)-OMEGA*zhu(J) =l= 0;

* Calculation of approach temperature..........................................
APPTEMPL(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =l= tH(I,K)-
tC(J,K)+GAMMA*(1-z(I,J,K));
APPTEMPR(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K+1) =l= tH(I,K+1)-
tC(J,K+1)+GAMMA*(1-z(I,J,K));
APPTEMPCU(I,CU).. dtcu(I,CU) =l= tH(I,'lastlocation')-
TCUOUT(CU)+GAMMA*(1-zcu(I,CU));
APPTEMPHU(J) .. dthu(J) =l= TOUTC(J)- tC(J,'firstlocation')+GAMMA*(1-
zhu(J));
APPTEMPLIMIT(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =g= EMAT;
APPTEMPCUMIN (I,CU) .. dtcu(I,CU) =g= EMAT;
CONSTMATCH.. SUM((I,CU),zcu(I,CU)) =l= 2;
```

```
CONSTMATCHC.. SUM((J),zhu(J)) =l= 0;
CONSTMATCHHX.. SUM((I,J,K),newz(I,J,K)) =l= 20;
newmatchz(I,J,K)$(ORD(K) NE CARD(K)) .. newz(I,J,K) =E= z(I,J,K)-ex_z(I,J,K);

* Objective Function..........................................
OBJFN .. O =e=
SUM((I,CU),CCU(CU)*qcu(I,CU))+CHU*SUM(J,qhu(J))+CF*SUM((I,J,K),newz(I
,J,K))+SUM((I,CU),CF*zcu(I,CU))+CF*SUM(J,zhu(J))+
CW*SUM((I,J),FW(I,J)*(TINH(I)-TOUTC(J)));
SHAFTWORK .. W =e= SUM((I,J),FW(I,J)*(TINH(I)-TOUTC(J))) ;
;
MODEL STAGEMODEL SYNHEAT model /ALL/ ;
SOLVE STAGEMODEL USING MIP MINIMISING O;
DISPLAY z.l,ex_z,newz.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,O.l,W.l,FW;
```

**Model of HEN Retrofit for Case 2 (new exchangers ≥ 10)**

```
SETS
     I       hot streams
/H1,H2,H3,H4,H5,H6,H7,H8,H9,H10,H11,H12,H13,H14,H15,H16,H17,H18/
     J       cold streams  / C1,C2,C3,C4,C5,C6,C7,C8,C9 /
     K       location      / firstlocation,location2*location26,lastlocation /
     CU      cold utility  / CU1,CU2,CU3,CU4,CU5,CU6,CU7,CU8,CU9,CU10/
;

SCALARS
     OMEGA          upper bound for heat exchange   /999999/
     GAMMA          upper bound for temperature difference /999999/
     EMAT           exchanger minimum approach temperature   /3/
     CHU            unit cost for hot utility    /1000/
     CF             fixed charge for exchangers   /99000000/
     CW             unit cost for power consumption /200000/
```

**PARAMETERS**

```
TOUTH(I)   outlet temperature of cold stream
           /  H1    271.634
              H2    249.582
              H3    236.977
              H4    207.45
              H5    186.17
              H6    183.036
              H7    148.15
              H8    129.446
              H9    118.15
              H10   298.58
              H11   271.79
             H12    249.58
             H13    237.15
             H14    207.416
             H15    186.214
             H16    182.579
             H17    147.941
             H18    129.501     /
      TINC(J)   inlet temperature of cold stream
      /      C1     268.793
             C2     246.57
             C3     234.198
             C4     204.446
             C5     183.188
             C6     179.915
             C7     144.942
             C8     126.521
             C9     111.587     /
```

```
TOUTC(J)  outlet temperature of cold stream
/    C1     269.293
     C2     247.07
     C3     234.698
     C4     204.946
     C5     183.688
     C6     180.415
     C7     145.442
     C8     127.021
     C9     112.087      /
FH(I)    heat capacity of hot stream
/    H1     263.3583
     H2     272.9911
     H3     286.2356
     H4     351.4749
     H5     1480.733
     H6     1276.324
     H7     461.5032
     H8     374.2515
     H9     354.1076
     H10     22399
     H11     13446.61
     H12     12558.84
     H13     3152.466
     H14     2504.468
     H15     2901.974
     H16     1036.471
     H17     410.6263
     H18     149.4232      /
FC(J)    heat capacity of cold stream
/    C1     396200
     C2     320063
```

```
    C3    258800
    C4    221200
    C5    172800
    C6    65600
    C7    62400
    C8    23300
    C9    7830        /

FW(I,J)    heat capacity of work
TCUIN(CU) inlet temperature of cold utility
/     CU1     295
      CU2     268
      CU3     246
      CU4     234
      CU5     204
      CU6     183
      CU7     180
      CU8     145
      CU9     127
      CU10     111        /
TCUOUT(CU) outlet temperature of cold utility
/     CU1     300
      CU2     269
      CU3     247
      CU4     235
      CU5     205
      CU6     184
      CU7     181
      CU8     146
      CU9     128
      CU10     112        /
CCU(CU) unit cost for cold utility
```

```
/   CU1    22
    CU2    140
    CU3    160
    CU4    180
    CU5    300
    CU6    400
    CU7    450
    CU8    500
    CU9    600
    CU10    700      /

;

FW(I,J) =0;
FW('H10','C1') = 851.636;
FW('H11','C2') = 621.772;
FW('H12','C3') = 450.434;
FW('H13','C4') = 388.078;
FW('H14','C5') = 263.583;
FW('H15','C6') = 88.14;
FW('H16','C7') = 230.15;
FW('H17','C8') = 55.29;
FW('H18','C9') = 21.027;

ex_z(I,J,K);
ex_z(I,J,K) = 0;
ex_z('H11','C1','firstlocation')= 1;
ex_z('H15','C1','firstlocation')= 1;
ex_z('H1','C1','firstlocation')= 1;
ex_z('H2','C2','location2')= 1;
ex_z('H12','C2','location2')= 1;
ex_z('H15','C2','location2')= 1;
ex_z('H17','C3','location3')= 1;
ex_z('H15','C3','location3')= 1;
```

```
        ex_z('H3','C3','location3')= 1;
        ex_z('H4','C4','location4')= 1;
        ex_z('H17','C4','location4')= 1;
        ex_z('H20','C5','location5')= 1;
        ex_z('H18','C5','location5')= 1;
        ex_z('H5','C5','location5')= 1;
        ex_z('H6','C6','location6')= 1;
        ex_z('H20','C6','location6')= 1;
        ex_z('H7','C7','location7')= 1;
        ex_z('H23','C7','location7')= 1;
        ex_z('H21','C7','location7')= 1;
        ex_z('H23','C8','location8')= 1;
        ex_z('H8','C8','location8')= 1;
        ex_z('H9','C9','location9')= 1;

VARIABLES
        TINH(I)         inlet temperature of hot stream
        O               objective function
        W               Shaft Work Requirement
;

POSITIVE VARIABLES
        dt(I,J,K)       temperature approach for match ij at the left of stage k
        dtcu(I,CU)      temperature approach for match hot stream i and cold utility
        dthu(J)         temperature approach for match cold stream j and hot utility
        q(I,J,K)        heat exchanged between hot stream i and cold stream j at stage k
        qcu(I,CU)       heat exchanged between hot stream i and cold utility
        qhu(J)          heat exchanged between cold stream j and hot utility
        tH(I,K)         temperature of hot stream i at location k
        tC(J,K)         temperature of cold stream j at location k
;
```

```
BINARY VARIABLE
        z(I,J,K)            Binary variable of HEX Process to Process
        zcu(I,CU)           Binary variable of cold utility
        zhu(J)              Binary variable of hot utility
;

TINH.fx('H1') = 303.15;
TINH.fx('H2') = 271.634;
TINH.fx('H3') = 249.582;
TINH.fx('H4') = 236.977;
TINH.fx('H5') = 207.45;
TINH.fx('H6') = 186.17;
TINH.fx('H7') = 183.036;
TINH.fx('H8') = 148.15;
TINH.fx('H9') = 129.446;

TINH.lo('H10') = 299;
TINH.lo('H11') = 272;
TINH.lo('H12') = 250;
TINH.lo('H13') = 240;
TINH.lo('H14') = 208;
TINH.lo('H15') = 187;
TINH.lo('H16') = 183;
TINH.lo('H17') = 148;
TINH.lo('H18') = 130;

TINH.up('H10') = 308.951;
TINH.up('H11') = 285.491;
TINH.up('H12') = 260.839;
TINH.up('H13') = 281.75;
TINH.up('H14') = 248.822;
```

```
TINH.up('H15') = 198.068;
TINH.up('H16') = 232.016;
TINH.up('H17') = 184.059;
TINH.up('H18') = 162.963;


EQUATIONS
      OHB_H(I)          overall heat balance for each hot stream
      OHB_C(J)          overall heat balance for each cold stream
      SHB_H(I,K)       heat balance at each stage for hot stream
      SHB_C(J,K)       heat balance at each stage for cold stream
      TINHASSGN(I)  assignment of inlet temperature of hot stream i
      TINCASSGN(J)  assignment of inlet temperature of cold stream j
      FH1(I,K)          feasibility of temperature at each stage for hot stream
      FH2(I)            feasibility of temperature at last stage for hot stream
      FC1(J,K)          feasibility of temperature at each stage for cold stream
      FC2(J)            feasibility of temperature at first stage for cold stream
      HULOAD(I)         hot utility load
      CULOAD(J)         cold utility load
      HECOUNT1(I,J,K)    count heat exchanger
      HECOUNT2(I,CU)   count hot utility
      HECOUNT3(J)        count cold utility
      APPTEMPL(I,J,K)    approach temperature at the left of stage k
      APPTEMPR(I,J,K)    approach temperature at the right of stage k
      APPTEMPCU(I,CU) approach temperature at cold utility of hot stream i
      APPTEMPHU(J)       approach temperature at hot utility of cold stream j
      APPTEMPLIMIT(I,J,K)    limiting temperature approach
      APPTEMPCUMIN (I,CU)  approach temperature at cold utility
      CONSTMATCH      define match of cold utility
      CONSTMATCHC   define match of hot utility
      newmatchz(I,J,K)
      OBJFN                 objective function
```

```
        SHAFTWORK      shaft work requirement
;

* Overall Energy balance.....................................................
OHB_H(I) .. (TINH(I)-TOUTH(I))*FH(I) =e=
SUM((J,K),q(I,J,K))+SUM(CU,qcu(I,CU));
OHB_C(J) .. (TOUTC(J)-TINC(J))*FC(J) =e= SUM((I,K),q(I,J,K))+qhu(J);

* Heat balance at each stage..................................................
SHB_H(I,K)$(ORD(K) NE CARD(K)) .. (tH(I,K)-tH(I,K+1))*FH(I) =e=
SUM(J,q(I,J,K));
SHB_C(J,K)$(ORD(K) NE CARD(K)) .. (tC(J,K)-tC(J,K+1))*FC(J) =e=
SUM(I,q(I,J,K));

* Assignment Temperature.....................................................
TINHASSGN(I) .. TINH(I) =e= tH(I,'firstlocation');
TINCASSGN(J) .. TINC(J) =e= tC(J,'lastlocation');

* Feasible Temperature.......................................................
FH1(I,K)$(ORD(K) NE CARD(K)) .. tH(I,K) =g= tH(I,K+1);
FH2(I) .. TOUTH(I) =l= tH(I,'lastlocation');
FC1(J,K)$(ORD(K) NE CARD(K)) .. tC(J,K) =g= tC(J,K+1);
FC2(J) .. TOUTC(J) =g= tC(J,'firstlocation');

* Heat&Cold utility..........................................................
HULOAD(I) .. (tH(I,'lastlocation')-TOUTH(I))*FH(I) =e= SUM(CU,qcu(I,CU));
CULOAD(J) .. (TOUTC(J)-tC(J,'firstlocation'))*FC(J) =e= qhu(J);

* Counting existing heat exchanger at each stage..............................
HECOUNT1(I,J,K)$(ORD(K) NE CARD(K)) .. q(I,J,K)-OMEGA*z(I,J,K) =l= 0;
HECOUNT2(I,CU).. qcu(I,CU)-OMEGA*zcu(I,CU) =l= 0;
HECOUNT3(J) .. qhu(J)-OMEGA*zhu(J) =l= 0;
```

```
* Calculation of approach temperature...........................................
APPTEMPL(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =l= tH(I,K)-
tC(J,K)+GAMMA*(1-z(I,J,K));
APPTEMPR(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K+1) =l= tH(I,K+1)-
tC(J,K+1)+GAMMA*(1-z(I,J,K));
APPTEMPCU(I,CU).. dtcu(I,CU) =l= tH(I,'lastlocation')-
TCUOUT(CU)+GAMMA*(1-zcu(I,CU));
APPTEMPHU(J) .. dthu(J) =l= TOUTC(J)- tC(J,'firstlocation')+GAMMA*(1-
zhu(J));
APPTEMPLIMIT(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =g= EMAT;
APPTEMPCUMIN (I,CU) .. dtcu(I,CU) =g= EMAT;
CONSTMATCH.. SUM((I,CU),zcu(I,CU)) =l= 2;
CONSTMATCHC.. SUM((J),zhu(J)) =l= 0;
CONSTMATCHHX.. SUM((I,J,K),newz(I,J,K)) =l= 10;
newmatchz(I,J,K)$(ORD(K) NE CARD(K)) .. newz(I,J,K) =E= z(I,J,K)-ex_z(I,J,K);

* Objective Function...........................................
OBJFN .. O =e=
SUM((I,CU),CCU(CU)*qcu(I,CU))+CHU*SUM(J,qhu(J))+CF*SUM((I,J,K),newz(I
,J,K))+SUM((I,CU),CF*zcu(I,CU))+CF*SUM(J,zhu(J))+
CW*SUM((I,J),FW(I,J)*(TINH(I)-TOUTC(J)));
SHAFTWORK .. W =e= SUM((I,J),FW(I,J)*(TINH(I)-TOUTC(J))) ;
;
MODEL STAGEMODEL SYNHEAT model /ALL/ ;
SOLVE STAGEMODEL USING MIP MINIMISING O;
DISPLAY z.l,ex_z,newz.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,O.l,W.l,FW;
```

**Retrofitted HEN Model Validation by PROII**

The result from GAMS for case 1 (new exchangers ≥ 20) is validated with PROII by using the same match of exchanger because this result provides the optimal solution when compares case 1 (new exchangers $\geq$ 20) with case 2 (new exchangers $\geq$ 10). Figure C1 is illustrated the result of validation. Temperature and duty of streams are changed; additionally, three new cooling utilities are added in structure. The result of validation is 229,900 kW of cooling duty and 128,775.69 kW of shaft work requirement. There are errors of temperature, duty and phase change at target temperature of hot stream when compares with base case due to result from GAMS with assumption of heat capacity constant and without consideration of latent heat. In addition, Mathematical Programming does not include equation of thermodynamic. Although there are error of temperature, duty and phase change, the result from GAMS is validated by PROII, resulting in shaft work saving and cooling duty saving are about 10.62 % and 1.16 % from base case.

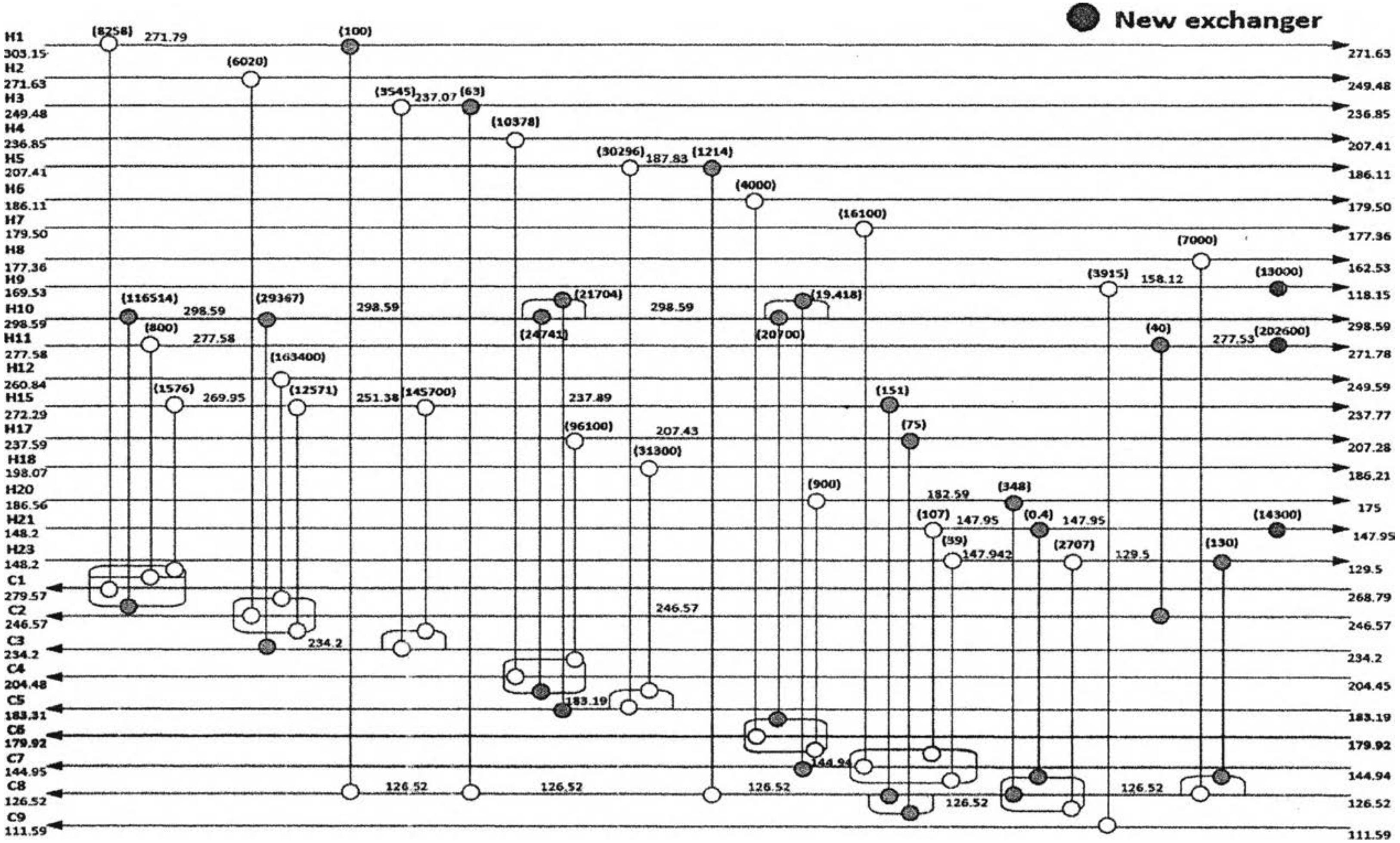

**Figure C1** The result of Retrofitted HEN of case 1 (new exchangers ≥ 20) validation from Mathematical programming.

## CURRICULUM VITAE

**Name:** Ms. Juthathip Thasai

**Date of Birth:** September 2, 1990

**Nationality:** Thai

**University Education:**

2009–2013 Bachelor of Engineering in Chemical Engineering, Department of Chemical Engineering, Faculty of Chemical Engineering, King Mongkut University of Technology North Bangkok, Bangkok, Thailand

**Work Experience:**

2012 Position: Trainee Technologist
Company name: PTT Global Chemical Plc.

**Proceedings:**

1. Thasai, J.; and Siemanond, K. (2015, April 21) Design and Optimization of Cryogenic Process. Proceedings of the 6th Research Symposium on Petrochemical and Materials Technology and the 21th PPC Symposium on Petroleum, Petrochemicals, and Polymers, Bangkok, Thailand.
2. Thasai, J.; and Siemanond, K. (2015, May 19-22) Combined Exergy-Pinch Analysis to Improve Cryogenic Process. Proceedings of the 12th International Conference on Chemical & Process Engineering (ICHEAP 12), Milan, Italy.