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# APPENDICES

## Appendix A Retrofit Design of Heat Exchanger Network (HEN) by Optimization Model (GAMS)

**Source code of GAMS: Above pinch at pinch of Light Crude**

```
SETS
     I  hot streams /I1,I2,I3,I4,I5,I6/
     J  cold streams /J1,J2/
     K  Stage no. /K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11/;

PARAMETER TINI(I)
/I1=274.7096301,I2=321.1748182,I3=234.3976629,I4=273.171406,I5=326.4004111
,I6=341.7349314/

TOUTI(I)/I1=201.1734,I2=232.22,I3=201.1734,I4=201.1734,I5=201.1734,I6=201.1
734/
       TINJ(J) /J1=166.5257,J2=166.6421787/
       TOUTJ(J)/J1=170,J2=370/
       FI(I)  /I1=69.913,I2=98.604,I3=67.762,I4=49.644,I5=59.981,I6=135.328/
       FJ(J)  /J1=434.319,J2=585.628/
       EMAT  /34.6477/
       OMEGA /10000000/
       TAL  /10000000/;

VARIABLES
     dt(I,J,K) Approach temperature
     dtcu(I)  Approach temperature between cold utility and hot stream
     dthu(J)  Approach temperature between hot utility and cold stream
     q(I,J,K)  heat exchanged between hot I and cold J
     qcu(I)   heat exchanged between cold utility and hot I
```

qhu(J) heat exchanged between hot utility and cold J

ti(I,K) temp of hot stream i at hot end of stage k

tj(J,K) temp of cold stream j at hot end of stage k

z(I,J,K) exchanger matching between hot I and cold J at stage k

zcu(I) cold utility matching with hot I

zhu(J) hot utility matching with cold J

ZZ total energy and matching

qcs, qhs

ddt(I,J,K) Real Approach Temperature

;

POSITIVE VARIABLE dt(I,J,K),dtcu(I),dthu(J),q(I,J,K),qcu(I),qhu(J),ti(I,K),
tj(J,K);

BINARY VARIABLES z(I,J,K),zcu(I),zhu(J);

EQUATIONS

MINU objective function minimize utilities and matching

HOTI(I) heat balance in hot streams I

COLDJ(J) heat balance in cold stream J

HOTK1(I) heat balance of hot at stage K1

HOTK2(I) heat balance of hot at stage K2

HOTK3(I) heat balance of hot at stage K3

HOTK4(I) heat balance of hot at stage K4

HOTK5(I) heat balance of hot at stage K5

HOTK6(I) heat balance of hot at stage K6

HOTK7(I) heat balance of hot at stage K7

HOTK8(I) heat balance of hot at stage K8

HOTK9(I) heat balance of hot at stage K9

HOTK10(I) heat balance of hot at stage K10

COLDK1(J) heat balance of cold at stage K1

COLDK2(J) heat balance of cold at stage K2

COLDK3(J) heat balance of cold at stage K3

COLDK4(J) heat balance of cold at stage K4

COLDK5(J) heat balance of cold at stage K5

COLDK6(J) heat balance of cold at stage K6

COLDK7(J) heat balance of cold at stage K7

COLDK8(J) heat balance of cold at stage K8

COLDK9(J) heat balance of cold at stage K9

COLDK10(J) heat balance of cold at stage K10

TINHOT(I) hot temp in

TINCOLD(J) cold temp in

FEHOTK1(I) feasibility of hot temp at stage K1

FEHOTK2(I) feasibility of hot temp at stage K2

FEHOTK3(I) feasibility of hot temp at stage K3

FEHOTK4(I) feasibility of hot temp at stage K4

FEHOTK5(I) feasibility of hot temp at stage K5

FEHOTK6(I) feasibility of hot temp at stage K6

FEHOTK7(I) feasibility of hot temp at stage K7

FEHOTK8(I) feasibility of hot temp at stage K8

FEHOTK9(I) feasibility of hot temp at stage K9

FEHOTK10(I) feasibility of hot temp at stage K10

FECOLDK1(J) feasibility of cold temp at stage K1

FECOLDK2(J) feasibility of cold temp at stage K2

FECOLDK3(J) feasibility of cold temp at stage K3

FECOLDK4(J) feasibility of cold temp at stage K4

FECOLDK5(J) feasibility of cold temp at stage K5

FECOLDK6(J) feasibility of cold temp at stage K6

FECOLDK7(J) feasibility of cold temp at stage K7

FECOLDK8(J) feasibility of cold temp at stage K8

FECOLDK9(J) feasibility of cold temp at stage K9

FECOLDK10(J) feasibility of cold temp at stage K10

FEHOTOUT(I) feasibility of hot temp out

FECOLDOUT(J) feasibility of cold temp out

HOTU(I) hot utility load

COLDU(J) cold utility load

LogicK1(I,J) Logical constraint at stage k1

LogicK2(I,J) Logical constraint at stage k2

LogicK3(I,J) Logical constraint at stage k3

LogicK4(I,J) Logical constraint at stage k4

LogicK5(I,J) Logical constraint at stage k5

LogicK6(I,J) Logical constraint at stage k6

LogicK7(I,J) Logical constraint at stage k7

LogicK8(I,J) Logical constraint at stage k8

LogicK9(I,J) Logical constraint at stage k9

LogicK10(I,J) Logical constraint at stage k10

LogicHOT(J) Logical constraint hot utility

LogicCOLD(I) Logical constraint cold utility

ApproK1(I,J) approach temp at stage k1

AApproK1(I,J) the other approach temp at stage k1

ApproK2(I,J) approach temp at stage k2

AApproK2(I,J) the other approach temp at stage k2

ApproK3(I,J) approach temp at stage k3

AApproK3(I,J) the other approach temp at stage k3

ApproK4(I,J) approach temp at stage k4

AApproK4(I,J) the other approach temp at stage k4

ApproK5(I,J) approach temp at stage k5

```
    AApproK5(I,J) the other approach temp at stage k5
    ApproK6(I,J)  approach temp at stage k6
    AApproK6(I,J) the other approach temp at stage k6
    ApproK7(I,J)  approach temp at stage k3
    AApproK7(I,J) the other approach temp at stage k7
    ApproK8(I,J)  approach temp at stage k4
    AApproK8(I,J) the other approach temp at stage k8
    ApproK9(I,J)  approach temp at stage k5
    AApproK9(I,J) the other approach temp at stage k9
    ApproK10(I,J)  approach temp at stage k6
    AApproK10(I,J) the other approach temp at stage k10

    EMATdt(I,J,K) EMAT constraint

    dtreal(I,J,K)

qcsum, qhsum

con1
con5
con8
;
MINU      .. ZZ =E= SUM((I,J,K),z(I,J,K))+ SUM((I,J,K),q(I,J,K))
;

HOTI(I)   .. (TINI(I)-TOUTI(I))*FI(I)=E= SUM((J,K),q(I,J,K))+qcu(I);
COLDJ(J)  .. (TOUTJ(J)-TINJ(J))*FJ(J)=E= SUM((I,K),q(I,J,K))+qhu(J);

HOTK1(I)  .. (ti(I,'K1')-ti(I,'K2'))*FI(I)=E= SUM(J,q(I,J,'K1'));
HOTK2(I)  .. (ti(I,'K2')-ti(I,'K3'))*FI(I)=E= SUM(J,q(I,J,'K2'));
HOTK3(I)  .. (ti(I,'K3')-ti(I,'K4'))*FI(I)=E= SUM(J,q(I,J,'K3'));
HOTK4(I)  .. (ti(I,'K4')-ti(I,'K5'))*FI(I)=E= SUM(J,q(I,J,'K4'));
```

```
HOTK5(I)   .. (ti(I,'K5')-ti(I,'K6'))*FI(I)=E= SUM(J,q(I,J,'K5'));
HOTK6(I)   .. (ti(I,'K6')-ti(I,'K7'))*FI(I)=E= SUM(J,q(I,J,'K6'));
HOTK7(I)   .. (ti(I,'K7')-ti(I,'K8'))*FI(I)=E= SUM(J,q(I,J,'K7'));
HOTK8(I)   .. (ti(I,'K8')-ti(I,'K9'))*FI(I)=E= SUM(J,q(I,J,'K8'));
HOTK9(I)   .. (ti(I,'K9')-ti(I,'K10'))*FI(I)=E= SUM(J,q(I,J,'K9'));
HOTK10(I)   .. (ti(I,'K10')-ti(I,'K11'))*FI(I)=E= SUM(J,q(I,J,'K10'));

COLDK1(J)  .. (tj(J,'K1')-tj(J,'K2'))*FJ(J)=E= SUM(I,q(I,J,'K1'));
COLDK2(J)  .. (tj(J,'K2')-tj(J,'K3'))*FJ(J)=E= SUM(I,q(I,J,'K2'));
COLDK3(J)  .. (tj(J,'K3')-tj(J.'K4'))*FJ(J)=E= SUM(I,q(I,J,'K3'));
COLDK4(J)  .. (tj(J,'K4')-tj(J,'K5'))*FJ(J)=E= SUM(I,q(I,J,'K4'));
COLDK5(J)  .. (tj(J,'K5')-tj(J,'K6'))*FJ(J)=E= SUM(I,q(I,J,'K5'));
COLDK6(J)  .. (tj(J,'K6')-tj(J,'K7'))*FJ(J)=E= SUM(I,q(I,J,'K6'));
COLDK7(J)  .. (tj(J,'K7')-tj(J,'K8'))*FJ(J)=E= SUM(I,q(I,J,'K7'));
COLDK8(J)  .. (tj(J,'K8')-tj(J,'K9'))*FJ(J)=E= SUM(I,q(I,J,'K8'));
COLDK9(J)  .. (tj(J,'K9')-tj(J,'K10'))*FJ(J)=E= SUM(I,q(I,J,'K9'));
COLDK10(J)  .. (tj(J,'K10')-tj(J,'K11'))*FJ(J)=E= SUM(I,q(I,J,'K10'));

TINHOT(I)  .. TINI(I) =E= ti(I,'K1');
TINCOLD(J) .. TINJ(J) =E= tj(J,'K11');

FEHOTK1(I) .. ti(I,'K1') =G= ti(I,'K2');
FEHOTK2(I) .. ti(I,'K2') =G= ti(I,'K3');
FEHOTK3(I) .. ti(I,'K3') =G= ti(I,'K4');
FEHOTK4(I) .. ti(I,'K4') =G= ti(I,'K5');
FEHOTK5(I) .. ti(I,'K5') =G= ti(I,'K6');
FEHOTK6(I) .. ti(I,'K6') =G= ti(I,'K7');
FEHOTK7(I) .. ti(I,'K7') =G= ti(I,'K8');
FEHOTK8(I) .. ti(I,'K8') =G= ti(I,'K9');
FEHOTK9(I) .. ti(I,'K9') =G= ti(I,'K10');
FEHOTK10(I) .. ti(I,'K10') =G= ti(I,'K11');
```

```
FECOLDK1(J).. tj(J,'K1') =G= tj(J,'K2');
FECOLDK2(J).. tj(J,'K2') =G= tj(J,'K3');
FECOLDK3(J).. tj(J,'K3') =G= tj(J,'K4');
FECOLDK4(J).. tj(J,'K4') =G= tj(J,'K5');
FECOLDK5(J).. tj(J,'K5') =G= tj(J,'K6');
FECOLDK6(J).. tj(J,'K6') =G= tj(J,'K7');
FECOLDK7(J).. tj(J,'K7') =G= tj(J,'K8');
FECOLDK8(J).. tj(J,'K8') =G= tj(J,'K9');
FECOLDK9(J).. tj(J,'K9') =G= tj(J,'K10');
FECOLDK10(J).. tj(J,'K10') =G= tj(J,'K11');

FEHOTOUT(I) .. TOUTI(I) =L= ti(I,'K11');
FECOLDOUT(J).. TOUTJ(J) =G= tj(J,'K1');

HOTU(I)  .. (ti(I,'K11')-TOUTI(I))*FI(I) =E= qcu(I);
COLDU(J) .. (TOUTJ(J)-tj(j,'K1'))*FJ(J) =E= qhu(J);

LogicK1(I,J).. q(I,J,'K1')-OMEGA*z(I,J,'K1') =L= 0;
LogicK2(I,J).. q(I,J,'K2')-OMEGA*z(I,J,'K2') =L= 0;
LogicK3(I,J).. q(I,J,'K3')-OMEGA*z(I,J,'K3') =L= 0;
LogicK4(I,J).. q(I,J,'K4')-OMEGA*z(I,J,'K4') =L= 0;
LogicK5(I,J).. q(I,J,'K5')-OMEGA*z(I,J,'K5') =L= 0;
LogicK6(I,J).. q(I,J,'K6')-OMEGA*z(I,J,'K6') =L= 0;
LogicK7(I,J).. q(I,J,'K7')-OMEGA*z(I,J,'K7') =L= 0;
LogicK8(I,J).. q(I,J,'K8')-OMEGA*z(I,J,'K8') =L= 0;
LogicK9(I,J).. q(I,J,'K9')-OMEGA*z(I,J,'K9') =L= 0;
LogicK10(I,J).. q(I,J,'K10')-OMEGA*z(I,J,'K10') =L= 0;

LogicHOT(J) .. qhu(J)-OMEGA*zhu(J) =L= 0;
LogicCOLD(I).. qcu(I)-OMEGA*zcu(I) =L= 0;

ApproK1(I,J) .. dt(I,J,'K1') =L= (ti(I,'K1')-tj(J,'K1'))+TAL*(1-z(I,J,'K1'));
```

```
AApproK1(I,J).. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K1'));
ApproK2(I,J) .. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K2'));
AApproK2(I,J).. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K2'));
ApproK3(I,J) .. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K3'));
AApproK3(I,J).. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K3'));
ApproK4(I,J) .. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K4'));
AApproK4(I,J).. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J.'K5'))+TAL*(1-z(I,J.'K4'));
ApproK5(I,J) .. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J,'K5'))+TAL*(1-z(I,J,'K5'));
AApproK5(I,J).. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K5'));
ApproK6(I.J) .. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K6'));
AApproK6(I,J).. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K6'));
ApproK7(I,J) .. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K7'));
AApproK7(I,J).. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K7'));
ApproK8(I,J) .. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K8'));
AApproK8(I,J).. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K8'));
ApproK9(I,J) .. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K9'));
AApproK9(I,J).. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I,J,'K9'));
ApproK10(I,J) .. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I,J,'K10'));
AApproK10(I,J).. dt(I,J,'K11') =L= (ti(I,'K11')-tj(J,'K11'))+TAL*(1-z(I,J,'K10'));

EMATdt(I,J,K) .. dt(I,J,K)  =G= EMAT;
dtreal(I,J,K) .. ddt(I,J,K)  =E= ti(I,K)-tj(J,K);

qcsum   ..   qcs =e= sum(i,qcu(i));
qhsum   ..   qhs =e= sum(j,qhu(j));

con1 .. qcs =e= 0;
con5 .. sum(j,z('I2',j,'k10'))=e= 0;
con8 .. sum(i,z(i,'J2','k10'))=e= 0;


MODEL TSHIP /ALL/ ;
```

```
SOLVE TSHIP USING MIP MINIMIZING ZZ;
DISPLAY z.L,q.L,qcu.L,qcs.L,qhu.L,qhs.L,ZZ.L,dt.L,ddt.L,ti.L,tj.L;
```

**Source code of GAMS: Above pinch at nonpinch of Light Crude**

```
SETS
    I  hot streams /I1,I2,I3,I4.I5,I6/
    J  cold streams /J1,J2/
    K  Stage no. /K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11/;
PARAMETER TINI(I)
/I1=274.7096301,I2=321.1748182,I3=234.3976629,I4=273.171406,I5=326.4004111
,I6=341.7349314/

TOUTI(I)/I1=204.732,I2=232.22,I3=204.648,I4=204.732,I5=207.283,I6=204.732/
    TINJ(J) /J1=170,J2=166.6421787/
    TOUTJ(J)/J1=170,J2=370/
    FI(I)  /I1=69.913,I2=98.604,I3=67.762,I4=49.644,I5=59.981,I6=135.328/
    FJ(J)  /J1=434.319,J2=585.628/
    EMAT  /5/
    OMEGA /10000000/
    TAL  /10000000/;

VARIABLES
    dt(I,J,K) Approach temperature
    dtcu(I)   Approach temperature between cold utility and hot stream
    dthu(J)   Approach temperature between hot utility and cold stream
    q(I,J,K)  heat exchanged between hot I and cold J
    qcu(I)    heat exchanged between cold utility and hot I
    qhu(J)    heat exchanged between hot utility and cold J
    ti(I,K)   temp of hot stream i at hot end of stage k
    tj(J,K)   temp of cold stream j at hot end of stage k
    z(I,J,K)  exchanger matching between hot I and cold J at stage k
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    zcu(I)    cold utility matching with hot I
    zhu(J)    hot utility matching with cold J
    ZZ        total energy and matching
    qcs, qhs
    ddt(I,J,K) Real Approach Temperature
;

POSITIVE VARIABLE dt(I,J,K),dtcu(I),dthu(J),q(I,J,K),qcu(I),qhu(J),ti(I,K),
            tj(J,K);
BINARY VARIABLES  z(I,J,K),zcu(I),zhu(J);

EQUATIONS
    MINU       objective function minimize utilities and matching
    HOTI(I)    heat balance in hot streams I
    COLDJ(J)   heat balance in cold stream J

    HOTK1(I)    heat balance of hot  at stage K1
    HOTK2(I)    heat balance of hot  at stage K2
    HOTK3(I)    heat balance of hot  at stage K3
    HOTK4(I)    heat balance of hot  at stage K4
    HOTK5(I)    heat balance of hot  at stage K5
    HOTK6(I)    heat balance of hot  at stage K6
    HOTK7(I)    heat balance of hot  at stage K7
    HOTK8(I)    heat balance of hot  at stage K8
    HOTK9(I)    heat balance of hot  at stage K9
    HOTK10(I)   heat balance of hot  at stage K10

    COLDK1(J)   heat balance of cold  at stage K1
    COLDK2(J)   heat balance of cold  at stage K2
    COLDK3(J)   heat balance of cold  at stage K3
    COLDK4(J)   heat balance of cold  at stage K4
    COLDK5(J)   heat balance of cold  at stage K5
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COLDK6(J) heat balance of cold at stage K6

COLDK7(J) heat balance of cold at stage K7

COLDK8(J) heat balance of cold at stage K8

COLDK9(J) heat balance of cold at stage K9

COLDK10(J) heat balance of cold at stage K10

TINHOT(I) hot temp in

TINCOLD(J) cold temp in

FEHOTK1(I) feasibility of hot temp at stage K1

FEHOTK2(I) feasibility of hot temp at stage K2

FEHOTK3(I) feasibility of hot temp at stage K3

FEHOTK4(I) feasibility of hot temp at stage K4

FEHOTK5(I) feasibility of hot temp at stage K5

FEHOTK6(I) feasibility of hot temp at stage K6

FEHOTK7(I) feasibility of hot temp at stage K7

FEHOTK8(I) feasibility of hot temp at stage K8

FEHOTK9(I) feasibility of hot temp at stage K9

FEHOTK10(I) feasibility of hot temp at stage K10

FECOLDK1(J) feasibility of cold temp at stage K1

FECOLDK2(J) feasibility of cold temp at stage K2

FECOLDK3(J) feasibility of cold temp at stage K3

FECOLDK4(J) feasibility of cold temp at stage K4

FECOLDK5(J) feasibility of cold temp at stage K5

FECOLDK6(J) feasibility of cold temp at stage K6

FECOLDK7(J) feasibility of cold temp at stage K7

FECOLDK8(J) feasibility of cold temp at stage K8

FECOLDK9(J) feasibility of cold temp at stage K9

FECOLDK10(J) feasibility of cold temp at stage K10

FEHOTOUT(I) feasibility of hot temp out

FECOLDOUT(J) feasibility of cold temp out

HOTU(I) hot utility load
COLDU(J) cold utility load

LogicK1(I,J) Logical constraint at stage k1
LogicK2(I,J) Logical constraint at stage k2
LogicK3(I,J) Logical constraint at stage k3
LogicK4(I,J) Logical constraint at stage k4
LogicK5(I,J) Logical constraint at stage k5
LogicK6(I,J) Logical constraint at stage k6
LogicK7(I,J) Logical constraint at stage k7
LogicK8(I,J) Logical constraint at stage k8
LogicK9(I,J) Logical constraint at stage k9
LogicK10(I,J) Logical constraint at stage k10

LogicHOT(J) Logical constraint hot utility
LogicCOLD(I) Logical constraint cold utility

ApproK1(I,J) approach temp at stage k1
AApproK1(I,J) the other approach temp at stage k1
ApproK2(I,J) approach temp at stage k2
AApproK2(I,J) the other approach temp at stage k2
ApproK3(I,J) approach temp at stage k3
AApproK3(I,J) the other approach temp at stage k3
ApproK4(I,J) approach temp at stage k4
AApproK4(I,J) the other approach temp at stage k4
ApproK5(I,J) approach temp at stage k5
AApproK5(I,J) the other approach temp at stage k5
ApproK6(I,J) approach temp at stage k6
AApproK6(I,J) the other approach temp at stage k6
ApproK7(I,J) approach temp at stage k3

AApproK7(I,J) the other approach temp at stage k7

ApproK8(I,J) approach temp at stage k4

AApproK8(I,J) the other approach temp at stage k8

ApproK9(I,J) approach temp at stage k5

AApproK9(I,J) the other approach temp at stage k9

ApproK10(I,J) approach temp at stage k6

AApproK10(I,J) the other approach temp at stage k10

EMATdt(I,J,K) EMAT constraint

dtreal(I,J,K)

HOTNOSPLITTING1K1
HOTNOSPLITTING2K1
HOTNOSPLITTING3K1
HOTNOSPLITTING4K1
HOTNOSPLITTING5K1
HOTNOSPLITTING6K1

HOTNOSPLITTING1K2
HOTNOSPLITTING2K2
HOTNOSPLITTING3K2
HOTNOSPLITTING4K2
HOTNOSPLITTING5K2
HOTNOSPLITTING6K2

HOTNOSPLITTING1K3
HOTNOSPLITTING2K3
HOTNOSPLITTING3K3
HOTNOSPLITTING4K3
HOTNOSPLITTING5K3
HOTNOSPLITTING6K3

HOTNOSPLITTING1K4
HOTNOSPLITTING2K4
HOTNOSPLITTING3K4
HOTNOSPLITTING4K4
HOTNOSPLITTING5K4
HOTNOSPLITTING6K4

HOTNOSPLITTING1K5
HOTNOSPLITTING2K5
HOTNOSPLITTING3K5
HOTNOSPLITTING4K5
HOTNOSPLITTING5K5
HOTNOSPLITTING6K5

HOTNOSPLITTING1K6
HOTNOSPLITTING2K6
HOTNOSPLITTING3K6
HOTNOSPLITTING4K6
HOTNOSPLITTING5K6
HOTNOSPLITTING6K6

HOTNOSPLITTING1K7
HOTNOSPLITTING2K7
HOTNOSPLITTING3K7
HOTNOSPLITTING4K7
HOTNOSPLITTING5K7
HOTNOSPLITTING6K7

HOTNOSPLITTING1K8
HOTNOSPLITTING2K8
HOTNOSPLITTING3K8

HOTNOSPLITTING4K8
HOTNOSPLITTING5K8
HOTNOSPLITTING6K8

HOTNOSPLITTING1K9
HOTNOSPLITTING2K9
HOTNOSPLITTING3K9
HOTNOSPLITTING4K9
HOTNOSPLITTING5K9
HOTNOSPLITTING6K9

HOTNOSPLITTING1K10
HOTNOSPLITTING2K10
HOTNOSPLITTING3K10
HOTNOSPLITTING4K10
HOTNOSPLITTING5K10
HOTNOSPLITTING6K10

*COLDNOSPLITTING1K1
COLDNOSPLITTING2K1

*COLDNOSPLITTING1K2
COLDNOSPLITTING2K2

*COLDNOSPLITTING1K3
COLDNOSPLITTING2K3

*COLDNOSPLITTING1K4
COLDNOSPLITTING2K4

*COLDNOSPLITTING1K5
COLDNOSPLITTING2K5

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*COLDNOSPLITTING1K6
COLDNOSPLITTING2K6

*COLDNOSPLITTING1K7
COLDNOSPLITTING2K7

*COLDNOSPLITTING1K8
COLDNOSPLITTING2K8

*COLDNOSPLITTING1K9
COLDNOSPLITTING2K9

*COLDNOSPLITTING1K10
COLDNOSPLITTING2K10

qcsum, qhsum

con1
;
MINU      .. ZZ =E= SUM((I,J,K),z(I,J,K))+ SUM((I,J,K),q(I,J,K))
;

HOTI(I)   .. (TINI(I)-TOUTI(I))*FI(I)=E= SUM((J,K),q(I,J,K))+qcu(I);
COLDJ(J)  .. (TOUTJ(J)-TINJ(J))*FJ(J)=E= SUM((I,K),q(I,J,K))+qhu(J);

HOTK1(I)  .. (ti(I,'K1')-ti(I,'K2'))*FI(I)=E= SUM(J,q(I,J,'K1'));
HOTK2(I)  .. (ti(I,'K2')-ti(I,'K3'))*FI(I)=E= SUM(J,q(I,J,'K2'));
HOTK3(I)  .. (ti(I,'K3')-ti(I,'K4'))*FI(I)=E= SUM(J,q(I,J,'K3'));
HOTK4(I)  .. (ti(I,'K4')-ti(I,'K5'))*FI(I)=E= SUM(J,q(I,J,'K4'));
HOTK5(I)  .. (ti(I,'K5')-ti(I,'K6'))*FI(I)=E= SUM(J,q(I,J,'K5'));
HOTK6(I)  .. (ti(I,'K6')-ti(I,'K7'))*FI(I)=E= SUM(J,q(I,J,'K6'));
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```
HOTK7(I)  .. (ti(I,'K7')-ti(I,'K8'))*FI(I)=E= SUM(J,q(I,J,'K7'));
HOTK8(I)  .. (ti(I,'K8')-ti(I,'K9'))*FI(I)=E= SUM(J,q(I,J,'K8'));
HOTK9(I)  .. (ti(I,'K9')-ti(I,'K10'))*FI(I)=E= SUM(J,q(I,J,'K9'));
HOTK10(I)  .. (ti(I,'K10')-ti(I,'K11'))*FI(I)=E= SUM(J,q(I,J,'K10'));

COLDK1(J)  .. (tj(J,'K1')-tj(J,'K2'))*FJ(J)=E= SUM(I,q(I,J,'K1'));
COLDK2(J)  .. (tj(J,'K2')-tj(J,'K3'))*FJ(J)=E= SUM(I,q(I,J,'K2'));
COLDK3(J)  .. (tj(J,'K3')-tj(J,'K4'))*FJ(J)=E= SUM(I,q(I,J,'K3'));
COLDK4(J)  .. (tj(J,'K4')-tj(J,'K5'))*FJ(J)=E= SUM(I,q(I,J,'K4'));
COLDK5(J)  .. (tj(J,'K5')-tj(J,'K6'))*FJ(J)=E= SUM(I,q(I,J,'K5'));
COLDK6(J)  .. (tj(J,'K6')-tj(J,'K7'))*FJ(J)=E= SUM(I,q(I,J,'K6'));
COLDK7(J)  .. (tj(J,'K7')-tj(J,'K8'))*FJ(J)=E= SUM(I,q(I,J,'K7'));
COLDK8(J)  .. (tj(J,'K8')-tj(J,'K9'))*FJ(J)=E= SUM(I,q(I,J,'K8'));
COLDK9(J)  .. (tj(J,'K9')-tj(J,'K10'))*FJ(J)=E= SUM(I,q(I,J,'K9'));
COLDK10(J)  .. (tj(J,'K10')-tj(J,'K11'))*FJ(J)=E= SUM(I,q(I,J,'K10'));

TINHOT(I)  .. TINI(I) =E= ti(I,'K1');
TINCOLD(J) .. TINJ(J) =E= tj(J,'K11');

FEHOTK1(I) .. ti(I,'K1') =G= ti(I,'K2');
FEHOTK2(I) .. ti(I,'K2') =G= ti(I,'K3');
FEHOTK3(I) .. ti(I,'K3') =G= ti(I,'K4');
FEHOTK4(I) .. ti(I,'K4') =G= ti(I,'K5');
FEHOTK5(I) .. ti(I,'K5') =G= ti(I,'K6');
FEHOTK6(I) .. ti(I,'K6') =G= ti(I,'K7');
FEHOTK7(I) .. ti(I,'K7') =G= ti(I,'K8');
FEHOTK8(I) .. ti(I,'K8') =G= ti(I,'K9');
FEHOTK9(I) .. ti(I,'K9') =G= ti(I,'K10');
FEHOTK10(I) .. ti(I,'K10') =G= ti(I,'K11');

FECOLDK1(J).. tj(J,'K1') =G= tj(J,'K2');
FECOLDK2(J).. tj(J,'K2') =G= tj(J,'K3');
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FECOLDK3(J).. tj(J,'K3') =G= tj(J,'K4');
FECOLDK4(J).. tj(J,'K4') =G= tj(J,'K5');
FECOLDK5(J).. tj(J,'K5') =G= tj(J,'K6');
FECOLDK6(J).. tj(J,'K6') =G= tj(J,'K7');
FECOLDK7(J).. tj(J,'K7') =G= tj(J,'K8');
FECOLDK8(J).. tj(J,'K8') =G= tj(J,'K9');
FECOLDK9(J).. tj(J,'K9') =G= tj(J,'K10');
FECOLDK10(J).. tj(J,'K10') =G= tj(J,'K11');

FEHOTOUT(I) .. TOUTI(I) =L= ti(I,'K11');
FECOLDOUT(J).. TOUTJ(J) =G= tj(J,'K1');

HOTU(I)  .. (ti(I,'K11')-TOUTI(I))*FI(I) =E= qcu(I);
COLDU(J) .. (TOUTJ(J)-tj(j,'K1'))*FJ(J) =E= qhu(J);

LogicK1(I,J).. q(I,J,'K1')-OMEGA*z(I,J,'K1') =L= 0;
LogicK2(I,J).. q(I,J,'K2')-OMEGA*z(I,J,'K2') =L= 0;
LogicK3(I,J).. q(I,J,'K3')-OMEGA*z(I,J,'K3') =L= 0;
LogicK4(I,J).. q(I,J,'K4')-OMEGA*z(I,J,'K4') =L= 0;
LogicK5(I,J).. q(I,J,'K5')-OMEGA*z(I,J,'K5') =L= 0;
LogicK6(I,J).. q(I,J,'K6')-OMEGA*z(I,J,'K6') =L= 0;
LogicK7(I,J).. q(I,J,'K7')-OMEGA*z(I,J,'K7') =L= 0;
LogicK8(I,J).. q(I,J,'K8')-OMEGA*z(I,J,'K8') =L= 0;
LogicK9(I,J).. q(I,J,'K9')-OMEGA*z(I,J,'K9') =L= 0;
LogicK10(I,J).. q(I,J,'K10')-OMEGA*z(I,J,'K10') =L= 0;

LogicHOT(J) .. qhu(J)-OMEGA*zhu(J) =L= 0;
LogicCOLD(I).. qcu(I)-OMEGA*zcu(I) =L= 0;

ApproK1(I,J) .. dt(I,J,'K1') =L= (ti(I,'K1')-tj(J,'K1'))+TAL*(1-z(I,J,'K1'));
AApproK1(I,J).. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K1'));
ApproK2(I,J) .. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K2'));
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AApproK2(I,J).. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K2'));
ApproK3(I,J) .. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K3'));
AApproK3(I,J).. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K3'));
ApproK4(I,J) .. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K4'));
AApproK4(I,J).. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J,'K5'))+TAL*(1-z(I,J,'K4'));
ApproK5(I,J) .. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J,'K5'))+TAL*(1-z(I,J,'K5'));
AApproK5(I,J).. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K5'));
ApproK6(I,J) .. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K6'));
AApproK6(I,J).. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K6'));
ApproK7(I,J) .. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K7'));
AApproK7(I,J).. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K7'));
ApproK8(I,J) .. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K8'));
AApproK8(I,J).. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K8'));
ApproK9(I,J) .. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K9'));
AApproK9(I,J).. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I,J,'K9'));
ApproK10(I,J) .. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I,J,'K10'));
AApproK10(I,J).. dt(I,J,'K11') =L= (ti(I,'K11')-tj(J,'K11'))+TAL*(1-z(I,J,'K10'));

EMATdt(I,J,K) .. dt(I,J,K)  =G= EMAT;
dtreal(I,J,K) .. ddt(I,J,K)  =E= ti(I,K)-tj(J,K);

HOTNOSPLITTING1K1..sum(J,z('I1',J,'K1')) =L= 1;
HOTNOSPLITTING2K1..sum(J,z('I2',J,'K1')) =L= 1;
HOTNOSPLITTING3K1..sum(J,z('I3',J,'K1')) =L= 1;
HOTNOSPLITTING4K1..sum(J,z('I4',J,'K1')) =L= 1;
HOTNOSPLITTING5K1..sum(J,z('I5',J,'K1')) =L= 1;
HOTNOSPLITTING6K1..sum(J,z('I6',J,'K1')) =L= 1;

HOTNOSPLITTING1K2..sum(J,z('I1',J,'K2')) =L= 1;
HOTNOSPLITTING2K2..sum(J,z('I2',J,'K2')) =L= 1;
HOTNOSPLITTING3K2..sum(J,z('I3',J,'K2')) =L= 1;
HOTNOSPLITTING4K2..sum(J,z('I4',J,'K2')) =L= 1;
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HOTNOSPLITTING5K2..sum(J.z('I5',J,'K2')) =L= 1;
HOTNOSPLITTING6K2..sum(J,z('I6',J,'K2')) =L= 1;

HOTNOSPLITTING1K3..sum(J,z('I1',J,'K3')) =L= 1;
HOTNOSPLITTING2K3..sum(J,z('I2',J,'K3')) =L= 1;
HOTNOSPLITTING3K3..sum(J,z('I3',J,'K3')) =L= 1;
HOTNOSPLITTING4K3..sum(J.z('I4',J,'K3')) =L= 1;
HOTNOSPLITTING5K3..sum(J,z('I5',J,'K3')) =L= 1;
HOTNOSPLITTING6K3..sum(J.z('I6',J,'K3')) =L= 1;

HOTNOSPLITTING1K4..sum(J.z('I1',J,'K4')) =L= 1;
HOTNOSPLITTING2K4..sum(J,z('I2',J,'K4')) =L= 1;
HOTNOSPLITTING3K4..sum(J,z('I3',J,'K4')) =L= 1;
HOTNOSPLITTING4K4..sum(J,z('I4',J,'K4')) =L= 1;
HOTNOSPLITTING5K4..sum(J,z('I5',J,'K4')) =L= 1;
HOTNOSPLITTING6K4..sum(J.z('I6',J,'K4')) =L= 1;

HOTNOSPLITTING1K5..sum(J,z('I1',J,'K5')) =L= 1;
HOTNOSPLITTING2K5..sum(J,z('I2',J,'K5')) =L= 1;
HOTNOSPLITTING3K5..sum(J,z('I3',J,'K5')) =L= 1;
HOTNOSPLITTING4K5..sum(J,z('I4',J,'K5')) =L= 1;
HOTNOSPLITTING5K5..sum(J,z('I5',J,'K5')) =L= 1;
HOTNOSPLITTING6K5..sum(J,z('I6',J,'K5')) =L= 1;

HOTNOSPLITTING1K6..sum(J,z('I1',J,'K6')) =L= 1;
HOTNOSPLITTING2K6..sum(J,z('I2'.J,'K6')) =L= 1;
HOTNOSPLITTING3K6..sum(J,z('I3',J,'K6')) =L= 1;
HOTNOSPLITTING4K6..sum(J,z('I4'.J,'K6')) =L= 1;
HOTNOSPLITTING5K6..sum(J,z('I5',J,'K6')) =L= 1;
HOTNOSPLITTING6K6..sum(J,z('I6',J,'K6')) =L= 1;

HOTNOSPLITTING1K7..sum(J,z('I1',J,'K7')) =L= 1;
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HOTNOSPLITTING2K7..sum(J,z('I2',J,'K7')) =L= 1;
HOTNOSPLITTING3K7..sum(J,z('I3',J,'K7')) =L= 1;
HOTNOSPLITTING4K7..sum(J,z('I4',J,'K7')) =L= 1;
HOTNOSPLITTING5K7..sum(J,z('I5',J,'K7')) =L= 1;
HOTNOSPLITTING6K7..sum(J,z('I6',J,'K7')) =L= 1;

HOTNOSPLITTING1K8..sum(J,z('I1',J,'K8')) =L= 1;
HOTNOSPLITTING2K8..sum(J,z('I2',J,'K8')) =L= 1;
HOTNOSPLITTING3K8..sum(J,z('I3',J,'K8')) =L= 1;
HOTNOSPLITTING4K8..sum(J,z('I4',J,'K8')) =L= 1;
HOTNOSPLITTING5K8..sum(J,z('I5',J,'K8')) =L= 1;
HOTNOSPLITTING6K8..sum(J,z('I6',J,'K8')) =L= 1;

HOTNOSPLITTING1K9..sum(J,z('I1',J,'K9')) =L= 1;
HOTNOSPLITTING2K9..sum(J,z('I2',J,'K9')) =L= 1;
HOTNOSPLITTING3K9..sum(J,z('I3',J,'K9')) =L= 1;
HOTNOSPLITTING4K9..sum(J,z('I4',J,'K9')) =L= 1;
HOTNOSPLITTING5K9..sum(J,z('I5',J,'K9')) =L= 1;
HOTNOSPLITTING6K9..sum(J,z('I6',J,'K9')) =L= 1;

HOTNOSPLITTING1K10..sum(J,z('I1',J,'K10')) =L= 1;
HOTNOSPLITTING2K10..sum(J,z('I2',J,'K10')) =L= 1;
HOTNOSPLITTING3K10..sum(J,z('I3',J,'K10')) =L= 1;
HOTNOSPLITTING4K10..sum(J,z('I4',J,'K10')) =L= 1;
HOTNOSPLITTING5K10..sum(J,z('I5',J,'K10')) =L= 1;
HOTNOSPLITTING6K10..sum(J,z('I6',J,'K10')) =L= 1;

*COLDNOSPLITTING1K1..sum(I,z(I,'J1','K1')) =L= 1;
COLDNOSPLITTING2K1..sum(I,z(I,'J2','K1')) =L= 2;

*COLDNOSPLITTING1K2..sum(I,z(I,'J1','K2')) =L= 1;
COLDNOSPLITTING2K2..sum(I,z(I,'J2','K2')) =L= 2;
```

```
*COLDNOSPLITTING1K3..sum(I,z(I,'J1','K3')) =L= 1;
COLDNOSPLITTING2K3..sum(I,z(I,'J2','K3')) =L= 2;

*COLDNOSPLITTING1K4..sum(I,z(I,'J1','K4')) =L= 1;
COLDNOSPLITTING2K4..sum(I,z(I,'J2','K4')) =L= 2;

*COLDNOSPLITTING1K5..sum(I,z(I,'J1','K5')) =L= 1;
COLDNOSPLITTING2K5..sum(I,z(I,'J2','K5')) =L= 2;
*COLDNOSPLITTING1K6..sum(I,z(I,'J1','K6')) =L= 1;
COLDNOSPLITTING2K6..sum(I,z(I,'J2','K6')) =L= 2;

*COLDNOSPLITTING1K7..sum(I,z(I,'J1','K7')) =L= 1;
COLDNOSPLITTING2K7..sum(I,z(I,'J2','K7')) =L= 2;

*COLDNOSPLITTING1K8..sum(I,z(I,'J1','K8')) =L= 1;
COLDNOSPLITTING2K8..sum(I,z(I,'J2','K8')) =L= 2;

*COLDNOSPLITTING1K9..sum(I,z(I,'J1','K9')) =L= 1;
COLDNOSPLITTING2K9..sum(I,z(I,'J2','K9')) =L= 2;

*COLDNOSPLITTING1K10..sum(I,z(I,'J1','K10')) =L= 1;
COLDNOSPLITTING2K10..sum(I,z(I,'J2','K10')) =L= 2;

qcsum  ..  qcs =e= sum(i,qcu(i));
qhsum  ..  qhs =e= sum(j,qhu(j));

con1 .. qcs =e= 0;

MODEL TSHIP /ALL/ ;
SOLVE TSHIP USING MIP MINIMIZING ZZ;
DISPLAY z.L,q.L,qcu.L,qcs.L,qhu.L,qhs.L,ZZ.L,dt.L,ddt.L,ti.L,tj.L;
```

**Source code of GAMS: Below pinch at pinch of Light Crude**

```
I  hot streams /H1,H2,H3,H4,H5,H6,H7/
J  cold streams /C1,C2/
K  Stage no. /K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11/;

PARAMETER TINI(I)
/H1=201.1734,H2=201.1734,H3=32.22,H4=201.1734,H5=201.1734,H6=201.1734,H
7=201.1734/
    TOUTI(I)/H1=104.44,H2=148.89,H3=30,H4=30,H5=30,H6=30,H7=30/
    TINJ(J) /C1=25,C2=125/
    TOUTJ(J)/C1=125,C2=166.5257/
    FI(I)
/H1=121.021,H2=69.913,H3=105.221,H4=67.762,H5=49.644,H6=59.981,H7=135.3
28/
    FJ(J)  /C1=380.575,C2=434.319/
    EMAT  /34.6477/
    OMEGA /10000000/
    TAL  /10000000/;

VARIABLES
  dt(I,J,K) Approach temperature
  dtcu(I)  Approach temperature between cold utility and hot stream
  dthu(J)  Approach temperature between hot utility and cold stream
  q(I,J,K)  heat exchanged between hot I and cold J
  qcu(I)   heat exchanged between cold utility and hot I
  qhu(J)   heat exchanged between hot utility and cold J
  ti(I,K)  temp of hot stream i at hot end of stage k
  tj(J,K)  temp of cold stream j at hot end of stage k
  z(I,J,K)  exchanger matching between hot I and cold J at stage k
  zcu(I)   cold utility matching with hot I
```

```
    zhu(J)    hot utility matching with cold J
    ZZ        total energy and matching
    qcs, qhs
    ddt(I,J,K) Real Approach Temperature
;

POSITIVE VARIABLE dt(I,J,K),dtcu(I),dthu(J),q(I,J,K),qcu(I),qhu(J),ti(I,K),
            tj(J,K);
BINARY VARIABLES  z(I,J,K),zcu(I),zhu(J);

EQUATIONS
    MINU       objective function minimize utilities and matching

    HOTI(I)    heat balance in hot streams I
    COLDJ(J)   heat balance in cold stream J

    HOTK1(I)    heat balance of hot  at stage K1
    HOTK2(I)    heat balance of hot  at stage K2
    HOTK3(I)    heat balance of hot  at stage K3
    HOTK4(I)    heat balance of hot  at stage K4
    HOTK5(I)    heat balance of hot  at stage K5
    HOTK6(I)    heat balance of hot  at stage K6
    HOTK7(I)    heat balance of hot  at stage K7
    HOTK8(I)    heat balance of hot  at stage K8
    HOTK9(I)    heat balance of hot  at stage K9
    HOTK10(I)    heat balance of hot  at stage K10

    COLDK1(J)    heat balance of cold  at stage K1
    COLDK2(J)    heat balance of cold  at stage K2
    COLDK3(J)    heat balance of cold  at stage K3
    COLDK4(J)    heat balance of cold  at stage K4
    COLDK5(J)    heat balance of cold  at stage K5
```

COLDK6(J) heat balance of cold at stage K6

COLDK7(J) heat balance of cold at stage K7

COLDK8(J) heat balance of cold at stage K8

COLDK9(J) heat balance of cold at stage K9

COLDK10(J) heat balance of cold at stage K10

TINHOT(I) hot temp in

TINCOLD(J) cold temp in

FEHOTK1(I) feasibility of hot temp at stage K1

FEHOTK2(I) feasibility of hot temp at stage K2

FEHOTK3(I) feasibility of hot temp at stage K3

FEHOTK4(I) feasibility of hot temp at stage K4

FEHOTK5(I) feasibility of hot temp at stage K5

FEHOTK6(I) feasibility of hot temp at stage K6

FEHOTK7(I) feasibility of hot temp at stage K7

FEHOTK8(I) feasibility of hot temp at stage K8

FEHOTK9(I) feasibility of hot temp at stage K9

FEHOTK10(I) feasibility of hot temp at stage K10

FECOLDK1(J) feasibility of cold temp at stage K1

FECOLDK2(J) feasibility of cold temp at stage K2

FECOLDK3(J) feasibility of cold temp at stage K3

FECOLDK4(J) feasibility of cold temp at stage K4

FECOLDK5(J) feasibility of cold temp at stage K5

FECOLDK6(J) feasibility of cold temp at stage K6

FECOLDK7(J) feasibility of cold temp at stage K7

FECOLDK8(J) feasibility of cold temp at stage K8

FECOLDK9(J) feasibility of cold temp at stage K9

FECOLDK10(J) feasibility of cold temp at stage K10

FEHOTOUT(I) feasibility of hot temp out
FECOLDOUT(J) feasibility of cold temp out

HOTU(I) hot utility load
COLDU(J) cold utility load

LogicK1(I,J) Logical constraint at stage k1
LogicK2(I,J) Logical constraint at stage k2
LogicK3(I,J) Logical constraint at stage k3
LogicK4(I,J) Logical constraint at stage k4
LogicK5(I,J) Logical constraint at stage k5
LogicK6(I,J) Logical constraint at stage k6
LogicK7(I,J) Logical constraint at stage k7
LogicK8(I,J) Logical constraint at stage k8
LogicK9(I,J) Logical constraint at stage k9
LogicK10(I,J) Logical constraint at stage k10

LogicHOT(J) Logical constraint hot utility
LogicCOLD(I) Logical constraint cold utility

ApproK1(I,J) approach temp at stage k1
AApproK1(I,J) the other approach temp at stage k1
ApproK2(I,J) approach temp at stage k2
AApproK2(I,J) the other approach temp at stage k2
ApproK3(I,J) approach temp at stage k3
AApproK3(I,J) the other approach temp at stage k3
ApproK4(I,J) approach temp at stage k4
AApproK4(I,J) the other approach temp at stage k4
ApproK5(I,J) approach temp at stage k5
AApproK5(I,J) the other approach temp at stage k5
ApproK6(I,J) approach temp at stage k6
AApproK6(I,J) the other approach temp at stage k6

```
     ApproK7(I,J)  approach temp at stage k3
     AApproK7(I,J) the other approach temp at stage k7
     ApproK8(I,J)  approach temp at stage k4
     AApproK8(I,J) the other approach temp at stage k8
     ApproK9(I,J)  approach temp at stage k5
     AApproK9(I,J) the other approach temp at stage k9
     ApproK10(I,J)  approach temp at stage k6
     AApproK10(I,J) the other approach temp at stage k10

     EMATdt(I,J,K) EMAT constraint

     dtreal(I,J,K)



qcsum, qhsum

con2
con3
;

MINU      .. ZZ =E= SUM((I,J,K),z(I,J,K))+ SUM((I,J,K),q(I,J,K))
;
HOTI(I)    .. (TINI(I)-TOUTI(I))*FI(I)=E= SUM((J,K),q(I,J,K))+qcu(I);
COLDJ(J)   .. (TOUTJ(J)-TINJ(J))*FJ(J)=E= SUM((I,K),q(I,J,K))+qhu(J);

HOTK1(I)   .. (ti(I,'K1')-ti(I,'K2'))*FI(I)=E= SUM(J,q(I,J,'K1'));
HOTK2(I)   .. (ti(I,'K2')-ti(I,'K3'))*FI(I)=E= SUM(J,q(I,J,'K2'));
HOTK3(I)   .. (ti(I,'K3')-ti(I,'K4'))*FI(I)=E= SUM(J,q(I,J,'K3'));
HOTK4(I)   .. (ti(I,'K4')-ti(I,'K5'))*FI(I)=E= SUM(J,q(I,J,'K4'));
HOTK5(I)   .. (ti(I,'K5')-ti(I,'K6'))*FI(I)=E= SUM(J,q(I,J,'K5'));
HOTK6(I)   .. (ti(I,'K6')-ti(I,'K7'))*FI(I)=E= SUM(J,q(I,J,'K6'));
HOTK7(I)   .. (ti(I,'K7')-ti(I,'K8'))*FI(I)=E= SUM(J,q(I,J,'K7'));
```

```
HOTK8(I)  .. (ti(I,'K8')-ti(I,'K9'))*FI(I)=E= SUM(J,q(I,J,'K8'));
HOTK9(I)  .. (ti(I,'K9')-ti(I,'K10'))*FI(I)=E= SUM(J,q(I,J,'K9'));
HOTK10(I)  .. (ti(I,'K10')-ti(I,'K11'))*FI(I)=E= SUM(J,q(I,J,'K10'));

COLDK1(J)  .. (tj(J,'K1')-tj(J,'K2'))*FJ(J)=E= SUM(I,q(I,J,'K1'));
COLDK2(J)  .. (tj(J,'K2')-tj(J,'K3'))*FJ(J)=E= SUM(I,q(I,J,'K2'));
COLDK3(J)  .. (tj(J,'K3')-tj(J,'K4'))*FJ(J)=E= SUM(I,q(I,J,'K3'));
COLDK4(J)  .. (tj(J,'K4')-tj(J,'K5'))*FJ(J)=E= SUM(I,q(I,J,'K4'));
COLDK5(J)  .. (tj(J,'K5')-tj(J,'K6'))*FJ(J)=E= SUM(I,q(I,J,'K5'));
COLDK6(J)  .. (tj(J,'K6')-tj(J,'K7'))*FJ(J)=E= SUM(I,q(I,J,'K6'));
COLDK7(J)  .. (tj(J,'K7')-tj(J,'K8'))*FJ(J)=E= SUM(I,q(I,J,'K7'));
COLDK8(J)  .. (tj(J,'K8')-tj(J,'K9'))*FJ(J)=E= SUM(I,q(I,J,'K8'));
COLDK9(J)  .. (tj(J,'K9')-tj(J,'K10'))*FJ(J)=E= SUM(I,q(I,J,'K9'));
COLDK10(J)  .. (tj(J,'K10')-tj(J,'K11'))*FJ(J)=E= SUM(I,q(I,J,'K10'));

TINHOT(I)  .. TINI(I) =E= ti(I,'K1');
TINCOLD(J) .. TINJ(J) =E= tj(J,'K11');

FEHOTK1(I) .. ti(I,'K1') =G= ti(I,'K2');
FEHOTK2(I) .. ti(I,'K2') =G= ti(I,'K3');
FEHOTK3(I) .. ti(I,'K3') =G= ti(I,'K4');
FEHOTK4(I) .. ti(I,'K4') =G= ti(I,'K5');
FEHOTK5(I) .. ti(I,'K5') =G= ti(I,'K6');
FEHOTK6(I) .. ti(I,'K6') =G= ti(I,'K7');
FEHOTK7(I) .. ti(I,'K7') =G= ti(I,'K8');
FEHOTK8(I) .. ti(I,'K8') =G= ti(I,'K9');
FEHOTK9(I) .. ti(I,'K9') =G= ti(I,'K10');
FEHOTK10(I) .. ti(I,'K10') =G= ti(I,'K11');

FECOLDK1(J).. tj(J,'K1') =G= tj(J,'K2');
FECOLDK2(J).. tj(J,'K2') =G= tj(J,'K3');
FECOLDK3(J).. tj(J,'K3') =G= tj(J,'K4');
```

```
FECOLDK4(J).. tj(J,'K4') =G= tj(J,'K5');
FECOLDK5(J).. tj(J,'K5') =G= tj(J,'K6');
FECOLDK6(J).. tj(J,'K6') =G= tj(J,'K7');
FECOLDK7(J).. tj(J,'K7') =G= tj(J,'K8');
FECOLDK8(J).. tj(J,'K8') =G= tj(J,'K9');
FECOLDK9(J).. tj(J,'K9') =G= tj(J,'K10');
FECOLDK10(J).. tj(J,'K10') =G= tj(J,'K11');

FEHOTOUT(I) .. TOUTI(I) =L= ti(I,'K11');
FECOLDOUT(J).. TOUTJ(J) =G= tj(J,'K1');

HOTU(I)  .. (ti(I,'K11')-TOUTI(I))*FI(I) =E= qcu(I);
COLDU(J) .. (TOUTJ(J)-tj(j,'K1'))*FJ(J) =E= qhu(J);

LogicK1(I,J).. q(I,J,'K1')-OMEGA*z(I,J,'K1') =L= 0;
LogicK2(I,J).. q(I,J,'K2')-OMEGA*z(I,J,'K2') =L= 0;
LogicK3(I,J).. q(I,J,'K3')-OMEGA*z(I,J,'K3') =L= 0;
LogicK4(I,J).. q(I,J,'K4')-OMEGA*z(I,J,'K4') =L= 0;
LogicK5(I,J).. q(I,J,'K5')-OMEGA*z(I,J,'K5') =L= 0;
LogicK6(I,J).. q(I,J,'K6')-OMEGA*z(I,J,'K6') =L= 0;
LogicK7(I,J).. q(I,J,'K7')-OMEGA*z(I,J,'K7') =L= 0;
LogicK8(I,J).. q(I,J,'K8')-OMEGA*z(I,J,'K8') =L= 0;
LogicK9(I,J).. q(I,J,'K9')-OMEGA*z(I,J,'K9') =L= 0;
LogicK10(I,J).. q(I,J,'K10')-OMEGA*z(I,J,'K10') =L= 0;

LogicHOT(J) .. qhu(J)-OMEGA*zhu(J) =L= 0;
LogicCOLD(I).. qcu(I)-OMEGA*zcu(I) =L= 0;

ApproK1(I,J) .. dt(I,J,'K1') =L= (ti(I,'K1')-tj(J,'K1'))+TAL*(1-z(I,J,'K1'));
AApproK1(I,J).. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K1'));
ApproK2(I,J) .. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K2'));
AApproK2(I,J).. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K2'));
```

```
ApproK3(I,J) .. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K3'));
AApproK3(I,J).. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K3'));
ApproK4(I,J) .. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K4'));
AApproK4(I,J).. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J,'K5'))+TAL*(1-z(I,J,'K4'));
ApproK5(I,J) .. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J,'K5'))+TAL*(1-z(I,J,'K5'));
AApproK5(I,J).. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K5'));
ApproK6(I,J) .. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K6'));
AApproK6(I,J).. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K6'));
ApproK7(I,J) .. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K7'));
AApproK7(I,J).. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K7'));
ApproK8(I,J) .. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K8'));
AApproK8(I,J).. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K8'));
ApproK9(I,J) .. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K9'));
AApproK9(I,J).. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I,J,'K9'));
ApproK10(I,J) .. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I,J,'K10'));
AApproK10(I,J).. dt(I,J,'K11') =L= (ti(I,'K11')-tj(J,'K11'))+TAL*(1-z(I,J,'K10'));

EMATdt(I,J,K) .. dt(I,J,K)  =G= EMAT;
dtreal(I,J,K) .. ddt(I,J,K)  =E= ti(I,K)-tj(J,K);

qcsum   ..  qcs =e= sum(i,qcu(i));
qhsum   ..  qhs =e= sum(j,qhu(j));

con2 .. sum((i,j),z(i,j,'k1'))=e= 4;
con3 .. qhs =e= 0;

MODEL TSHIP /ALL/ ;
SOLVE TSHIP USING MIP MINIMIZING ZZ;
DISPLAY z.L,q.L,qcu.L,qcs.L,qhu.L,qhs.L,ZZ.L,dt.L,ddt.L,ti.L,tj.L;
```

**Source code of GAMS: Below pinch at nonpinch of Light Crude**

```
SETS
     I   hot streams /I1,I2,I3,I4,I5,I6,I7/
     J   cold streams /J1,J2/
     K   Stage no. /K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11/;

PARAMETER TINI(I)
/I1=159.648,I2=159.648,I3=32.22,I4=201.1734,I5=159.648,I6=159.648,I7=160.129/
       TOUTI(I)/I1=104.44,I2=148.89,I3=30,I4=30,I5=30,I6=30,I7=30/
       TINJ(J) /J1=25,J2=125/
       TOUTJ(J)/J1=125,J2=125/
       FI(I)
/I1=121.021,I2=69.913,I3=105.221,I4=67.762,I5=49.644,I6=59.981,I7=135.328/
       FJ(J)   /J1=380.575,J2=434.319/
       EMAT  /5/
       OMEGA /10000000/
       TAL  /10000000/;

VARIABLES
     dt(I,J,K) Approach temperature
     dtcu(I)   Approach temperature between cold utility and hot stream
     dthu(J)   Approach temperature between hot utility and cold stream
     q(I,J,K)  heat exchanged between hot I and cold J
     qcu(I)    heat exchanged between cold utility and hot I
     qhu(J)    heat exchanged between hot utility and cold J
     ti(I,K)   temp of hot stream i at hot end of stage k
     tj(J,K)   temp of cold stream j at hot end of stage k
     z(I,J,K)  exchanger matching between hot I and cold J at stage k
     zcu(I)    cold utility matching with hot I
     zhu(J)    hot utility matching with cold J
     ZZ        total energy and matching
     qcs, qhs
     ddt(I,J,K) Real Approach Temperature
```

```
;

POSITIVE VARIABLE dt(I,J,K),dtcu(I),dthu(J),q(I,J,K),qcu(I),qhu(J),ti(I,K),
           tj(J,K);
BINARY VARIABLES  z(I,J,K),zcu(I),zhu(J);

EQUATIONS
   MINU       objective function minimize utilities and matching

   HOTI(I)    heat balance in hot streams I
   COLDJ(J)    heat balance in cold stream J

   HOTK1(I)     heat balance of hot  at stage K1
   HOTK2(I)     heat balance of hot  at stage K2
   HOTK3(I)     heat balance of hot  at stage K3
   HOTK4(I)     heat balance of hot  at stage K4
   HOTK5(I)     heat balance of hot  at stage K5
   HOTK6(I)     heat balance of hot  at stage K6
   HOTK7(I)     heat balance of hot  at stage K7
   HOTK8(I)     heat balance of hot  at stage K8
   HOTK9(I)     heat balance of hot  at stage K9
   HOTK10(I)     heat balance of hot  at stage K10

   COLDK1(J)    heat balance of cold  at stage K1
   COLDK2(J)    heat balance of cold  at stage K2
   COLDK3(J)    heat balance of cold  at stage K3
   COLDK4(J)    heat balance of cold  at stage K4
   COLDK5(J)    heat balance of cold  at stage K5
   COLDK6(J)    heat balance of cold  at stage K6
   COLDK7(J)    heat balance of cold  at stage K7
   COLDK8(J)    heat balance of cold  at stage K8
   COLDK9(J)    heat balance of cold  at stage K9
```

COLDK10(J) heat balance of cold at stage K10

TINHOT(I) hot temp in

TINCOLD(J) cold temp in

FEHOTK1(I) feasibility of hot temp at stage K1

FEHOTK2(I) feasibility of hot temp at stage K2

FEHOTK3(I) feasibility of hot temp at stage K3

FEHOTK4(I) feasibility of hot temp at stage K4

FEHOTK5(I) feasibility of hot temp at stage K5

FEHOTK6(I) feasibility of hot temp at stage K6

FEHOTK7(I) feasibility of hot temp at stage K7

FEHOTK8(I) feasibility of hot temp at stage K8

FEHOTK9(I) feasibility of hot temp at stage K9

FEHOTK10(I) feasibility of hot temp at stage K10

FECOLDK1(J) feasibility of cold temp at stage K1

FECOLDK2(J) feasibility of cold temp at stage K2

FECOLDK3(J) feasibility of cold temp at stage K3

FECOLDK4(J) feasibility of cold temp at stage K4

FECOLDK5(J) feasibility of cold temp at stage K5

FECOLDK6(J) feasibility of cold temp at stage K6

FECOLDK7(J) feasibility of cold temp at stage K7

FECOLDK8(J) feasibility of cold temp at stage K8

FECOLDK9(J) feasibility of cold temp at stage K9

FECOLDK10(J) feasibility of cold temp at stage K10

FEHOTOUT(I) feasibility of hot temp out

FECOLDOUT(J) feasibility of cold temp out

HOTU(I) hot utility load

COLDU(J) cold utility load

LogicK1(I,J) Logical constraint at stage k1

LogicK2(I,J) Logical constraint at stage k2

LogicK3(I,J) Logical constraint at stage k3

LogicK4(I,J) Logical constraint at stage k4

LogicK5(I,J) Logical constraint at stage k5

LogicK6(I,J) Logical constraint at stage k6

LogicK7(I,J) Logical constraint at stage k7

LogicK8(I,J) Logical constraint at stage k8

LogicK9(I,J) Logical constraint at stage k9

LogicK10(I,J) Logical constraint at stage k10

LogicHOT(J) Logical constraint hot utility

LogicCOLD(I) Logical constraint cold utility

ApproK1(I,J) approach temp at stage k1

AApproK1(I,J) the other approach temp at stage k1

ApproK2(I,J) approach temp at stage k2

AApproK2(I,J) the other approach temp at stage k2

ApproK3(I,J) approach temp at stage k3

AApproK3(I,J) the other approach temp at stage k3

ApproK4(I,J) approach temp at stage k4

AApproK4(I,J) the other approach temp at stage k4

ApproK5(I,J) approach temp at stage k5

AApproK5(I,J) the other approach temp at stage k5

ApproK6(I,J) approach temp at stage k6

AApproK6(I,J) the other approach temp at stage k6

ApproK7(I,J) approach temp at stage k3

AApproK7(I,J) the other approach temp at stage k7

ApproK8(I,J) approach temp at stage k4

AApproK8(I,J) the other approach temp at stage k8

ApproK9(I,J) approach temp at stage k5

AApproK9(I,J) the other approach temp at stage k9
ApproK10(I,J) approach temp at stage k6
AApproK10(I,J) the other approach temp at stage k10

EMATdt(I,J,K) EMAT constraint

dtreal(I,J,K)

COLDNOSPLITTING1K1
COLDNOSPLITTING2K1

COLDNOSPLITTING1K2
COLDNOSPLITTING2K2

COLDNOSPLITTING1K3
COLDNOSPLITTING2K3
COLDNOSPLITTING1K4
COLDNOSPLITTING2K4

COLDNOSPLITTING1K5
COLDNOSPLITTING2K5

COLDNOSPLITTING1K6
COLDNOSPLITTING2K6

COLDNOSPLITTING1K7
COLDNOSPLITTING2K7

COLDNOSPLITTING1K8
COLDNOSPLITTING2K8

COLDNOSPLITTING1K9

```
COLDNOSPLITTING2K9

COLDNOSPLITTING1K10
COLDNOSPLITTING2K10

qcsum, qhsum

con3
;

MINU      .. ZZ =E= SUM((I,J,K),z(I,J,K))+ SUM((I,J,K),q(I,J,K))
;
HOTI(I)   .. (TINI(I)-TOUTI(I))*FI(I)=E= SUM((J,K),q(I,J,K))+qcu(I);
COLDJ(J)  .. (TOUTJ(J)-TINJ(J))*FJ(J)=E= SUM((I,K),q(I,J,K))+qhu(J);

HOTK1(I)  .. (ti(I,'K1')-ti(I,'K2'))*FI(I)=E= SUM(J,q(I,J,'K1'));
HOTK2(I)  .. (ti(I,'K2')-ti(I,'K3'))*FI(I)=E= SUM(J,q(I,J,'K2'));
HOTK3(I)  .. (ti(I,'K3')-ti(I,'K4'))*FI(I)=E= SUM(J,q(I,J,'K3'));
HOTK4(I)  .. (ti(I,'K4')-ti(I,'K5'))*FI(I)=E= SUM(J,q(I,J,'K4'));
HOTK5(I)  .. (ti(I,'K5')-ti(I,'K6'))*FI(I)=E= SUM(J,q(I,J,'K5'));
HOTK6(I)  .. (ti(I,'K6')-ti(I,'K7'))*FI(I)=E= SUM(J,q(I,J,'K6'));
HOTK7(I)  .. (ti(I,'K7')-ti(I,'K8'))*FI(I)=E= SUM(J,q(I,J,'K7'));
HOTK8(I)  .. (ti(I,'K8')-ti(I,'K9'))*FI(I)=E= SUM(J,q(I,J,'K8'));
HOTK9(I)  .. (ti(I,'K9')-ti(I,'K10'))*FI(I)=E= SUM(J,q(I,J,'K9'));
HOTK10(I) .. (ti(I,'K10')-ti(I,'K11'))*FI(I)=E= SUM(J,q(I,J,'K10'));

COLDK1(J) .. (tj(J,'K1')-tj(J,'K2'))*FJ(J)=E= SUM(I,q(I,J,'K1'));
COLDK2(J) .. (tj(J,'K2')-tj(J,'K3'))*FJ(J)=E= SUM(I,q(I,J,'K2'));
COLDK3(J) .. (tj(J,'K3')-tj(J,'K4'))*FJ(J)=E= SUM(I,q(I,J,'K3'));
COLDK4(J) .. (tj(J,'K4')-tj(J,'K5'))*FJ(J)=E= SUM(I,q(I,J,'K4'));
COLDK5(J) .. (tj(J,'K5')-tj(J,'K6'))*FJ(J)=E= SUM(I,q(I,J,'K5'));
COLDK6(J) .. (tj(J,'K6')-tj(J,'K7'))*FJ(J)=E= SUM(I,q(I,J,'K6'));
```

```
COLDK7(J)  .. (tj(J,'K7')-tj(J,'K8'))*FJ(J)=E= SUM(I,q(I,J,'K7'));
COLDK8(J)  .. (tj(J,'K8')-tj(J,'K9'))*FJ(J)=E= SUM(I,q(I,J,'K8'));
COLDK9(J)  .. (tj(J,'K9')-tj(J,'K10'))*FJ(J)=E= SUM(I,q(I,J,'K9'));
COLDK10(J)  .. (tj(J,'K10')-tj(J,'K11'))*FJ(J)=E= SUM(I,q(I,J,'K10'));

TINHOT(I)  .. TINI(I) =E= ti(I,'K1');
TINCOLD(J) .. TINJ(J) =E= tj(J,'K11');

FEHOTK1(I) .. ti(I,'K1') =G= ti(I,'K2');
FEHOTK2(I) .. ti(I,'K2') =G= ti(I,'K3');
FEHOTK3(I) .. ti(I,'K3') =G= ti(I,'K4');
FEHOTK4(I) .. ti(I,'K4') =G= ti(I,'K5');
FEHOTK5(I) .. ti(I,'K5') =G= ti(I,'K6');
FEHOTK6(I) .. ti(I,'K6') =G= ti(I,'K7');
FEHOTK7(I) .. ti(I,'K7') =G= ti(I,'K8');
FEHOTK8(I) .. ti(I,'K8') =G= ti(I,'K9');
FEHOTK9(I) .. ti(I,'K9') =G= ti(I,'K10');
FEHOTK10(I) .. ti(I,'K10') =G= ti(I,'K11');

FECOLDK1(J).. tj(J,'K1') =G= tj(J,'K2');
FECOLDK2(J).. tj(J,'K2') =G= tj(J,'K3');
FECOLDK3(J).. tj(J,'K3') =G= tj(J,'K4');
FECOLDK4(J).. tj(J,'K4') =G= tj(J,'K5');
FECOLDK5(J).. tj(J,'K5') =G= tj(J,'K6');
FECOLDK6(J).. tj(J,'K6') =G= tj(J,'K7');
FECOLDK7(J).. tj(J,'K7') =G= tj(J,'K8');
FECOLDK8(J).. tj(J,'K8') =G= tj(J,'K9');
FECOLDK9(J).. tj(J,'K9') =G= tj(J,'K10');
FECOLDK10(J).. tj(J,'K10') =G= tj(J,'K11');

FEHOTOUT(I) .. TOUTI(I) =L= ti(I,'K11');
FECOLDOUT(J).. TOUTJ(J) =G= tj(J,'K1');
```

```
HOTU(I) .. (ti(I,'K11')-TOUTI(I))*FI(I) =E= qcu(I);
COLDU(J) .. (TOUTJ(J)-tj(j,'K1'))*FJ(J) =E= qhu(J);

LogicK1(I,J).. q(I,J,'K1')-OMEGA*z(I,J,'K1') =L= 0;
LogicK2(I,J).. q(I,J,'K2')-OMEGA*z(I,J,'K2') =L= 0;
LogicK3(I,J).. q(I,J,'K3')-OMEGA*z(I,J,'K3') =L= 0;
LogicK4(I,J).. q(I,J,'K4')-OMEGA*z(I,J,'K4') =L= 0;
LogicK5(I,J).. q(I,J,'K5')-OMEGA*z(I,J,'K5') =L= 0;
LogicK6(I,J).. q(I,J,'K6')-OMEGA*z(I,J,'K6') =L= 0;
LogicK7(I,J).. q(I,J,'K7')-OMEGA*z(I,J,'K7') =L= 0;
LogicK8(I,J).. q(I,J,'K8')-OMEGA*z(I,J,'K8') =L= 0;
LogicK9(I,J).. q(I,J,'K9')-OMEGA*z(I,J,'K9') =L= 0;
LogicK10(I,J).. q(I,J,'K10')-OMEGA*z(I,J,'K10') =L= 0;

LogicHOT(J) .. qhu(J)-OMEGA*zhu(J) =L= 0;
LogicCOLD(I).. qcu(I)-OMEGA*zcu(I) =L= 0;

ApproK1(I,J) .. dt(I,J,'K1') =L= (ti(I,'K1')-tj(J,'K1'))+TAL*(1-z(I,J,'K1'));
AApproK1(I,J).. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K1'));
ApproK2(I,J) .. dt(I,J,'K2') =L= (ti(I,'K2')-tj(J,'K2'))+TAL*(1-z(I,J,'K2'));
AApproK2(I,J).. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K2'));
ApproK3(I,J) .. dt(I,J,'K3') =L= (ti(I,'K3')-tj(J,'K3'))+TAL*(1-z(I,J,'K3'));
AApproK3(I,J).. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K3'));
ApproK4(I,J) .. dt(I,J,'K4') =L= (ti(I,'K4')-tj(J,'K4'))+TAL*(1-z(I,J,'K4'));
AApproK4(I,J).. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J,'K5'))+TAL*(1-z(I,J,'K4'));
ApproK5(I,J) .. dt(I,J,'K5') =L= (ti(I,'K5')-tj(J,'K5'))+TAL*(1-z(I,J,'K5'));
AApproK5(I,J).. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K5'));
ApproK6(I,J) .. dt(I,J,'K6') =L= (ti(I,'K6')-tj(J,'K6'))+TAL*(1-z(I,J,'K6'));
AApproK6(I,J).. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K6'));
ApproK7(I,J) .. dt(I,J,'K7') =L= (ti(I,'K7')-tj(J,'K7'))+TAL*(1-z(I,J,'K7'));
AApproK7(I,J).. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K7'));
```

```
ApproK8(I,J) .. dt(I,J,'K8') =L= (ti(I,'K8')-tj(J,'K8'))+TAL*(1-z(I,J,'K8'));
AApproK8(I,J).. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K8'));
ApproK9(I,J) .. dt(I,J,'K9') =L= (ti(I,'K9')-tj(J,'K9'))+TAL*(1-z(I,J,'K9'));
AApproK9(I,J).. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I,J,'K9'));
ApproK10(I,J) .. dt(I,J,'K10') =L= (ti(I,'K10')-tj(J,'K10'))+TAL*(1-z(I.J,'K10'));
AApproK10(I,J).. dt(I,J,'K11') =L= (ti(I,'K11')-tj(J,'K11'))+TAL*(1-z(I,J,'K10'));

EMATdt(I,J,K) .. dt(I,J,K)  =G= EMAT;
dtreal(I,J,K) .. ddt(I,J,K)  =E= ti(I,K)-tj(J,K);

COLDNOSPLITTING1K1..sum(I,z(I,'J1','K1')) =L= 2;
COLDNOSPLITTING2K1..sum(I,z(I,'J2','K1')) =L= 2;

COLDNOSPLITTING1K2..sum(I,z(I,'J1','K2')) =L= 2;
COLDNOSPLITTING2K2..sum(I,z(I,'J2','K2')) =L= 2;

COLDNOSPLITTING1K3..sum(I,z(I,'J1','K3')) =L= 2;
COLDNOSPLITTING2K3..sum(I,z(I,'J2','K3')) =L= 2;

COLDNOSPLITTING1K4..sum(I,z(I,'J1','K4')) =L= 2;
COLDNOSPLITTING2K4..sum(I,z(I,'J2','K4')) =L= 2;

COLDNOSPLITTING1K5..sum(I,z(I,'J1','K5')) =L= 2;
COLDNOSPLITTING2K5..sum(I,z(I,'J2','K5')) =L= 2;

COLDNOSPLITTING1K6..sum(I,z(I,'J1','K6')) =L= 2;
COLDNOSPLITTING2K6..sum(I,z(I,'J2','K6')) =L= 2;

COLDNOSPLITTING1K7..sum(I,z(I,'J1','K7')) =L= 2;
COLDNOSPLITTING2K7..sum(I,z(I.'J2','K7')) =L= 2;

COLDNOSPLITTING1K8..sum(I,z(I,'J1','K8')) =L= 2;
```

```
COLDNOSPLITTING2K8..sum(I,z(I,'J2','K8')) =L= 2;

COLDNOSPLITTING1K9..sum(I,z(I,'J1','K9')) =L= 2;
COLDNOSPLITTING2K9..sum(I,z(I,'J2','K9')) =L= 2;

COLDNOSPLITTING1K10..sum(I,z(I,'J1','K10')) =L= 2;
COLDNOSPLITTING2K10..sum(I,z(I,'J2','K10')) =L= 2;

qcsum  ..  qcs =e= sum(i,qcu(i));
qhsum  ..  qhs =e= sum(j,qhu(j));

con3 .. qhs =e= 0;

MODEL TSHIP /ALL/ ;
SOLVE TSHIP USING MIP MINIMIZING ZZ;
DISPLAY z.L,q.L,qcu.L,qcs.L,qhu.L,qhs.L,ZZ.L,dt.L,ddt.L,ti.L,tj.L;
```

## Appendix B Cost Calculation for Retrofit Design of Heat Exchanger Network (HEN)

**Example of Medium Crude retrofitted cost calculation**

- Plant life time (n) = 5
- Rate of interest (i) = 0.1
- Costs of hot utilities = 0.4431 cent/MJ
- Costs of cold utilities = 0.0222 cent/MJ

**Table 1B** Utility cost calculation of Medium Crude retrofitted case

| | Utility used (MJ/yr) | | | |
|---|---|---|---|---|
| **Utility** | **Base case** | **Retrofit** | **Utility saved (MJ/yr)** | **Utility saving cost (/yr)** |
| **Hot Utility** | 2650534394 | 1967478709 | 683055685 | 3026620 |
| **Cold Utility** | 1253747139 | 571382662 | 682364477 | 151485 |
| **Total** | **3904281533** | **2538861370** | | 3178105 |

**Utility Saving cost$_i$ = [(Hot utility used of base case – Hot utility used of retrofit case)*Cost of hot utility]+ [(Cold utility used of base case – Cold utility used of retrofit case)*Cost of cold utility]**

= [(2650534391-1967478709)*0.4431]+[(1253747139-571382662)*0.0222]

= 2889186 ($/year)

**Table 2B** Utility Saving Cost of each year and Total Utility Saving Cost for 5 years life time

| Year | Utility Saving ($) |
|---|---|
| 1 | 2889186 |
| 2 | 2626533 |
| 3 | 2387757 |
| 4 | 2170688 |
| 5 | 1973353 |
| **Total** | 12047517 |

**Total Investment Cost calculation**

- Exchanger (\$) = 8,600 + [670×Area$^{0.83}$ (m$^2$)]
- Area addition (\$) = 4,300 + [1476× Added Area$^{0.83}$ (m$^2$)]
- Area reduction (\$) = 4,300 + [9× Reduced Area$^{0.83}$ (m$^2$)]
- New shell (\$) = 8,600 + [1476×Area of shell $^{0.83}$(m$^2$)]
- Splitting cost = 20,000 \$
- Relocation cost = 25,000 \$

**Table 3B** Results of relocation of retrofitted design of Medium Crude

| | Retrofit Design(relocation) |
|---|---|
| | **Medium Crude** |
| no.of new exchanger | 10 |
| Area of new exchanger | 3445.49 |
| no. of used existing exchanger | 9 |
| Added Area | 3.6 |
| Removed area | 471.21 |
| no.of new shell | 1 |
| Area of new shell | 555.35 |
| Investment cost (5 years life time) | 1,042,097 |

**Total Investment Cost (\$) = {[no. of New Exchanger×8,600] + [670×Area$^{0.83}$ (m$^2$)]}+ { [no. of Used Existing Exchanger×4,300 ]+ [1476× Added Area$^{0.83}$ (m$^2$)]+ [9× Reduced Area$^{0.83}$ (m$^2$)]}+{[no. of New Shell× 8,600 ]+ 1476×Area of shell $^{0.83}$(m$^2$)]}+Splitting Cost+Relocation Cost**

= {[10×8,600] + [670×3445.49$^{0.83}$ (m$^2$)]}+{[9 ×4,300 ]+ [1476× 3.6$^{0.83}$ (m$^2$)]} + [9× 471.21$^{0.83}$ (m$^2$)]}+ {[1×8,600] + [1476×555.35$^{0.83}$ (m$^2$)]}+20,000+25,000

= 1,042,097 \$

**Net Present Value (NPV) calculation**

$$NPV = \sum_{t=1}^{n\ years} \left( \frac{Utility\ saving\ cost_i}{(1 + Annual\ interest\ rate)^i} \right) - Total\ investment\ cost$$

$= 12,047,517-1,042,097$

$= 11,005,420$ \$

# CURRICULUM VITAE

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| | | |
|---|---|---|
| 2009 | Position: | Student Internship |
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**Presentations:**

1. Bongkoch, Y. and Kitipat, S. (2012, April 24) Retrofit of Crude Preheat Train under Different Kinds of Crude Oils. Paper presented at the 3rd Research Symposium on Petrochemical and Materials Technology and the 18th PPC Symposium on Petroleum, Petrochemicals, and Polymers, Bangkok, Thailand.