

## Linear Formulation for The Design of Shell-and-Tube Heat Exchangers Using the Bell-Delaware Method

Caroline de Oliveira Gonçalves<sup>a</sup>, André L.H. Costa<sup>a</sup>, Miguel Bagajewicz<sup>b</sup>

(a) Universidade do Estado do Rio de Janeiro

(b) University of Oklahoma

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## INTRODUCTION

Heat Exchanger Design



Considerable part of the investments  
in the process industry

## OBJECTIVE

Develop global optimization algorithm for cost minimization of shell and tube heat exchanger design using the Bell Delaware method

## OVERVIEW OF THE LITERATURE AND THE PRESENT WORK

- Works on heat exchanger design optimization:

- ✓ Heuristic approach
  - ✓ Stochastic approach
  - ✓ Mathematical Programming
- Local optimum

Proposal



Global optimum

## Basic structure of the proposed global optimization formulation

- **Variables:** project variables.
- **Constraints:** Bell Delaware method and associated limits.
- **Objective function:** minimization of heat exchanger area.

## METHODOLOGY

### Formulation strategy for global optimization

Equations in their original nonlinear form



Representation of design variables in the form of binary variables



Substitution of other variables from binary



Conversion to a linear formulation



Linear Formulation (MILP)

## DATA

| Variable                                       | Values                                                          |
|------------------------------------------------|-----------------------------------------------------------------|
| Outer tube diameter, $\widehat{pdte}_{sd}$ (m) | 0.01590, 0.01905, 0.02540                                       |
| Tube length, $\widehat{pL}_{sL}$ (m)           | 2.438, 3.658, 4.877, 6.096, 6.706                               |
| Number of baffles, $\widehat{pNb}_{sNb}$       | 7, 8, ... , 25                                                  |
| Number of tube passes, $\widehat{pNpt}_{sNpt}$ | 1, 2, 4, 6, 8                                                   |
| Tube pitch ratio, $\widehat{prp}_{srp}$        | 1.25, 1.33, 1.50                                                |
| Shell diameter, $\widehat{pDs}_{sDs}$ (m)      | 0.2050, 0.3048, 0.3366, 0.3874, 0.4382, 0.4890, 0.5398, 0.5906, |
|                                                | 0.6350, 0.6858, 0.7366, 0.7874, 0.8382, 0.8890, 0.9398, 0.9906, |
|                                                | 1.0668, 1.1430, 1.2192, 1.3716, 1.5240                          |
| Tube layout, $\widehat{play}_{slay}$           | 1 = triangular 30°, 2 = square 90°                              |
| Baffle cut ratio, $\widehat{pBc}_{sBc}$        | 0.20, 0.25, 0.30                                                |

## VALIDATION

### Against a Handbook model

| Variable                    | Handbook | Our revision | Our Numerical Model | Deviation (%) |
|-----------------------------|----------|--------------|---------------------|---------------|
| $h_i$ (W/m <sup>2</sup> °C) | 2133.50  | 2130.6418    | 2130.6418           | 0             |
| $h_s$ (W/m <sup>2</sup> °C) | 1252.00  | 1249.3178    | 1249.3178           | 0             |
| $\Delta P_c$ (kPa)          | 3.90     | 3.9173       | 3.9173              | 0.0011        |
| $\Delta P_w$ (kPa)          | 6.40     | 6.3726       | 6.3727              | 0.0007        |
| $\Delta P_e$ (kPa)          | 3.40     | 3.5014       | 3.5014              | 0.0011        |
| $\Delta P_s$ (kPa)          | 13.70    | 13.7915      | 13.7915             | 0.0009        |

## RESULTS

### EXAMPLE 1

| Variable                        | Shenoy's (1995)<br>solution | Shenoy (1995)<br>Rating using our<br>model | Ravagnani and<br>Caballero's (2007)<br>solution | Ravagnani and<br>Caballero (2007)<br>Rating using our<br>model | Our MILP model<br>Original available<br>pressure drops | Onishi et al.<br>(2013)<br>solution | Onishi et al.<br>(2013)<br>Rating using our<br>model | Our MILP model<br>Higher available<br>pressure drops |
|---------------------------------|-----------------------------|--------------------------------------------|-------------------------------------------------|----------------------------------------------------------------|--------------------------------------------------------|-------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Area (m <sup>2</sup> )          | 28.40                       | 28.40                                      | 38.52                                           | 38.52                                                          | 23.64                                                  | 28.89                               | 28.90                                                | 23.14                                                |
| <i>dte</i> (m)                  | 0.0191                      | 0.01910                                    | 0.01905                                         | 0.01905                                                        | 0.01905                                                | 0.01905                             | 0.01905                                              | 0.01590                                              |
| <i>dti</i> (m)                  | 0.0154                      | 0.01540                                    | 0.01660                                         | 0.01660                                                        | 0.01660                                                | 0.01660                             | 0.01660                                              | 0.01345                                              |
| <i>Ds</i> (m)                   | 0.549                       | 0.549                                      | 0.533                                           | 0.533                                                          | 0.387                                                  | 0.387                               | 0.387                                                | 0.387                                                |
| <i>lay</i>                      | Square                      | Square                                     | Square                                          | Square                                                         | Square                                                 | Square                              | Square                                               | Triangular                                           |
| <i>Npt</i>                      | 6                           | 6                                          | 2                                               | 2                                                              | 2                                                      | 2                                   | 2                                                    | 2                                                    |
| <i>rp</i>                       | 1.33                        | 1.33                                       | 1.33                                            | 1.33                                                           | 1.25                                                   | 1.33                                | 1.33                                                 | 1.50                                                 |
| <i>L</i> (m)                    | 1.286                       | 1.286                                      | 2.438                                           | 2.438                                                          | 2.438                                                  | 3.658                               | 3.658                                                | 2.438                                                |
| <i>Nb</i>                       | 6                           | 6                                          | 19                                              | 19                                                             | 7                                                      | 9                                   | 9                                                    | 9                                                    |
| <i>Ntt</i>                      | 368                         | 368                                        | 264                                             | 264                                                            | 162                                                    | 132                                 | 132                                                  | 190                                                  |
| <i>vt</i> (m/s)                 | -                           | 2.770                                      | 1.108                                           | 1.108                                                          | 1.805                                                  | 2.215                               | 2.215                                                | 2.344                                                |
| <i>vs</i> (m/s)                 | -                           | 0.668                                      | 1.162                                           | 0.980                                                          | 0.737                                                  | 0.517                               | 0.457                                                | 0.589                                                |
| <i>ht</i> (W/m <sup>2</sup> °C) | 8649.6                      | 10145.8                                    | 4087.1                                          | 5484.6                                                         | 8506.8                                                 | 7283.9                              | 10216.3                                              | 10989.2                                              |
| <i>hs</i> (W/m <sup>2</sup> °C) | 1364.5                      | 1321.4                                     | 1308.4                                          | 1418.4                                                         | 1700.3                                                 | 2096.0                              | 1249.0                                               | 1762.8                                               |
| $\Delta Pt$ (kPa)               | 42.000                      | 86.637                                     | 7.706                                           | 7.551                                                          | 18.540                                                 | 43.040                              | 36.738                                               | 36.249                                               |
| $\Delta Ps$ (kPa)               | 3.600                       | 3.195                                      | 7.000                                           | 10.434                                                         | 6.491                                                  | 10.000                              | 4.233                                                | 8.856                                                |

## RESULTS

### EXAMPLE 1

| Variable                        | Shenoy's (1995)<br>solution | Shenoy (1995)<br>Rating using our<br>model | Ravagnani and<br>Caballero's (2007)<br>solution | Ravagnani and<br>Caballero (2007)<br>Rating using our<br>model | Our MILP model<br>Original available<br>pressure drops | Onishi et al.<br>(2013)<br>solution | Onishi et al.<br>(2013)<br>Rating using our<br>model | Our MILP model<br>Higher available<br>pressure drops |
|---------------------------------|-----------------------------|--------------------------------------------|-------------------------------------------------|----------------------------------------------------------------|--------------------------------------------------------|-------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Area (m <sup>2</sup> )          | 28.40                       | 28.40                                      | 38.52                                           | 38.52                                                          | 23.64                                                  | 28.89                               | 28.90                                                | 23.14                                                |
| <i>dte</i> (m)                  | 0.01910                     | 0.01910                                    | 0.01905                                         | 0.01905                                                        | 0.01905                                                | 0.01905                             | 0.01905                                              | 0.01590                                              |
| <i>dti</i> (m)                  | 0.01540                     | 0.01540                                    | 0.01660                                         | 0.01660                                                        | 0.01660                                                | 0.01660                             | 0.01660                                              | 0.01345                                              |
| <i>Ds</i> (m)                   | 0.549                       | 0.549                                      | 0.533                                           | 0.533                                                          | 0.387                                                  | 0.387                               | 0.387                                                | 0.387                                                |
| <i>lay</i>                      | Square                      | Square                                     | Square                                          | Square                                                         | Square                                                 | Square                              | Square                                               | Triangular                                           |
| <i>Npt</i>                      | 6                           | 6                                          | 2                                               | 2                                                              | 2                                                      | 2                                   | 2                                                    | 2                                                    |
| <i>rp</i>                       | 1.33                        | 1.33                                       | 1.33                                            | 1.33                                                           | 1.25                                                   | 1.33                                | 1.33                                                 | 1.50                                                 |
| <i>L</i> (m)                    | 1.286                       | 1.286                                      | 2.438                                           | 2.438                                                          | 2.438                                                  | 3.658                               | 3.658                                                | 2.438                                                |
| <i>Nb</i>                       | 6                           | 6                                          | 19                                              | 19                                                             | 7                                                      | 9                                   | 9                                                    | 9                                                    |
| <i>Ntt</i>                      | 368                         | 368                                        | 264                                             | 264                                                            | 162                                                    | 132                                 | 132                                                  | 190                                                  |
| <i>vt</i> (m/s)                 | -                           | 2.770                                      | 1.108                                           | 1.108                                                          | 1.805                                                  | 2.215                               | 2.215                                                | 2.344                                                |
| <i>vs</i> (m/s)                 | -                           | 0.668                                      | 1.162                                           | 0.980                                                          | 0.737                                                  | 0.517                               | 0.457                                                | 0.589                                                |
| <i>ht</i> (W/m <sup>2</sup> °C) | 8649.6                      | 10145.8                                    | 4087.1                                          | 5484.6                                                         | 8506.8                                                 | 7283.9                              | 10216.3                                              | 10989.2                                              |
| <i>hs</i> (W/m <sup>2</sup> °C) | 1364.5                      | 1321.4                                     | 1308.4                                          | 1418.4                                                         | 1700.3                                                 | 2096.0                              | 1249.0                                               | 1762.8                                               |
| $\Delta Pt$ (kPa)               | 42.000                      | 86.637                                     | 7.706                                           | 7.551                                                          | 18.540                                                 | 43.040                              | 36.738                                               | 36.249                                               |
| $\Delta Ps$ (kPa)               | 3.600                       | 3.195                                      | 7.000                                           | 10.434                                                         | 6.491                                                  | 10.000                              | 4.233                                                | 8.856                                                |

## RESULTS

### EXAMPLE 1

| Variable                        | Shenoy's (1995)<br>solution | Shenoy (1995)<br>Rating using our<br>model | Ravagnani and<br>Caballero's (2007)<br>solution | Ravagnani and<br>Caballero (2007)<br>Rating using our<br>model | Our MILP model<br>Original available<br>pressure drops | Onishi et al.<br>(2013)<br>solution | Onishi et al.<br>(2013)<br>Rating using our<br>model | Our MILP model<br>Higher available<br>pressure drops |
|---------------------------------|-----------------------------|--------------------------------------------|-------------------------------------------------|----------------------------------------------------------------|--------------------------------------------------------|-------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Area (m <sup>2</sup> )          | 28.40                       | 28.40                                      | 38.52                                           | 38.52                                                          | 23.64                                                  | 28.89                               | 28.90                                                | 23.14                                                |
| <i>dte</i> (m)                  | 0.0191<br>0                 | 0.01910                                    | 0.01905                                         | 0.01905                                                        | 0.01905                                                | 0.01905                             | 0.01905                                              | 0.01590                                              |
| <i>dti</i> (m)                  | 0.0154<br>0                 | 0.01540                                    | 0.01660                                         | 0.01660                                                        | 0.01660                                                | 0.01660                             | 0.01660                                              | 0.01345                                              |
| <i>Ds</i> (m)                   | 0.549                       | 0.549                                      | 0.533                                           | 0.533                                                          | 0.387                                                  | 0.387                               | 0.387                                                | 0.387                                                |
| <i>lay</i>                      | Square                      | Square                                     | Square                                          | Square                                                         | Square                                                 | Square                              | Square                                               | Triangular                                           |
| <i>Npt</i>                      | 6                           | 6                                          | 2                                               | 2                                                              | 2                                                      | 2                                   | 2                                                    | 2                                                    |
| <i>rp</i>                       | 1.33                        | 1.33                                       | 1.33                                            | 1.33                                                           | 1.25                                                   | 1.33                                | 1.33                                                 | 1.50                                                 |
| <i>L</i> (m)                    | 1.286                       | 1.286                                      | 2.438                                           | 2.438                                                          | 2.438                                                  | 3.658                               | 3.658                                                | 2.438                                                |
| <i>Nb</i>                       | 6                           | 6                                          | 19                                              | 19                                                             | 7                                                      | 9                                   | 9                                                    | 9                                                    |
| <i>Ntt</i>                      | 368                         | 368                                        | 264                                             | 264                                                            | 162                                                    | 132                                 | 132                                                  | 190                                                  |
| <i>vt</i> (m/s)                 | -                           | 2.770                                      | 1.108                                           | 1.108                                                          | 1.805                                                  | 2.215                               | 2.215                                                | 2.344                                                |
| <i>vs</i> (m/s)                 | -                           | 0.668                                      | 1.162                                           | 0.980                                                          | 0.737                                                  | 0.517                               | 0.457                                                | 0.589                                                |
| <i>ht</i> (W/m <sup>2</sup> °C) | 8649.6                      | 10145.8                                    | 4087.1                                          | 5484.6                                                         | 8506.8                                                 | 7283.9                              | 10216.3                                              | 10989.2                                              |
| <i>hs</i> (W/m <sup>2</sup> °C) | 1364.5                      | 1321.4                                     | 1308.4                                          | 1418.4                                                         | 1700.3                                                 | 2096.0                              | 1249.0                                               | 1762.8                                               |
| $\Delta Pt$ (kPa)               | 42.000                      | 86.637                                     | 7.706                                           | 7.551                                                          | 18.540                                                 | 43.040                              | 36.738                                               | 36.249                                               |
| $\Delta Ps$ (kPa)               | 3.600                       | 3.195                                      | 7.000                                           | 10.434                                                         | 6.491                                                  | 10.000                              | 4.233                                                | 8.856                                                |

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### EXAMPLE 1

| Variable                        | Shenoy's (1995)<br>solution | Shenoy (1995)<br>Rating using our<br>model | Ravagnani and<br>Caballero's (2007)<br>solution | Ravagnani and<br>Caballero (2007)<br>Rating using our<br>model | Our MILP model<br>Original available<br>pressure drops | Onishi et al.<br>(2013)<br>solution | Onishi et al.<br>(2013)<br>Rating using our<br>model | Our MILP model<br>Higher available<br>pressure drops |
|---------------------------------|-----------------------------|--------------------------------------------|-------------------------------------------------|----------------------------------------------------------------|--------------------------------------------------------|-------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Area (m <sup>2</sup> )          | 28.40                       | 28.40                                      | 38.52                                           | 38.52                                                          | 23.64                                                  | 28.89                               | 28.90                                                | 23.14                                                |
| <i>dte</i> (m)                  | 0.01910                     | 0.01910                                    | 0.01905                                         | 0.01905                                                        | 0.01905                                                | 0.01905                             | 0.01905                                              | 0.01905                                              |
| <i>dti</i> (m)                  | 0.01540                     | 0.01540                                    | 0.01660                                         | 0.01660                                                        | 0.01660                                                | 0.01660                             | 0.01660                                              | 0.01345                                              |
| <i>Ds</i> (m)                   | 0.549                       | 0.549                                      | 0.533                                           | 0.533                                                          | 0.387                                                  | 0.387                               | 0.387                                                | 0.387                                                |
| <i>lay</i>                      | Square                      | Square                                     | Square                                          | Square                                                         | Square                                                 | Square                              | Square                                               | Triangular                                           |
| <i>Npt</i>                      | 6                           | 6                                          | 2                                               | 2                                                              | 2                                                      | 2                                   | 2                                                    | 2                                                    |
| <i>rp</i>                       | 1.33                        | 1.33                                       | 1.33                                            | 1.33                                                           | 1.25                                                   | 1.33                                | 1.33                                                 | 1.50                                                 |
| <i>L</i> (m)                    | 1.286                       | 1.286                                      | 2.438                                           | 2.438                                                          | 2.438                                                  | 3.658                               | 3.658                                                | 2.438                                                |
| <i>Nb</i>                       | 6                           | 6                                          | 19                                              | 19                                                             | 7                                                      | 9                                   | 9                                                    | 9                                                    |
| <i>Ntt</i>                      | 368                         | 368                                        | 264                                             | 264                                                            | 162                                                    | 132                                 | 132                                                  | 190                                                  |
| <i>vt</i> (m/s)                 | -                           | 2.770                                      | 1.108                                           | 1.108                                                          | 1.805                                                  | 2.215                               | 2.215                                                | 2.344                                                |
| <i>vs</i> (m/s)                 | -                           | 0.668                                      | 1.162                                           | 0.980                                                          | 0.737                                                  | 0.517                               | 0.457                                                | 0.589                                                |
| <i>ht</i> (W/m <sup>2</sup> °C) | 8649.6                      | 10145.8                                    | 4087.1                                          | 5484.6                                                         | 8506.8                                                 | 7283.9                              | 10216.3                                              | 10989.2                                              |
| <i>hs</i> (W/m <sup>2</sup> °C) | 1364.5                      | 1321.4                                     | 1308.4                                          | 1418.4                                                         | 1700.3                                                 | 2096.0                              | 1249.0                                               | 1762.8                                               |
| $\Delta Pt$ (kPa)               | 42.000                      | 86.637                                     | 7.706                                           | 7.551                                                          | 18.540                                                 | 43.040                              | 36.738                                               | 36.249                                               |
| $\Delta Ps$ (kPa)               | 3.600                       | 3.195                                      | 7.000                                           | 10.434                                                         | 6.491                                                  | 10.000                              | 4.233                                                | 8.856                                                |

## RESULTS

### EXAMPLE 2

| Variable                        | Mizutani et al.'s<br>(2003)<br>solution | Mizutani et al.<br>(2003)<br>Rating using our<br>model | Ravagnani and<br>Caballero's (2007)<br>solution | Ravagnani and<br>Caballero (2007)<br>Rating using our<br>model | Onishi et al. (2013)<br>solution | Onishi et al. (2013)<br>Rating using our<br>model | Our MILP Model |
|---------------------------------|-----------------------------------------|--------------------------------------------------------|-------------------------------------------------|----------------------------------------------------------------|----------------------------------|---------------------------------------------------|----------------|
| Total cost (\$/y)               | 5250.00                                 | 5279.56                                                | 5191.47                                         | 5137.78                                                        | 5134.21                          | 4853.40                                           | 3754.01        |
| Area cost (\$/y)                | 2826.00                                 | 2825.45                                                | 3663.23                                         | 3461.77                                                        | 3175.61                          | 3175.61                                           | 2510.14        |
| Pumping cost(\$/y)              | 2424.00                                 | 2454.11                                                | 1528.24                                         | 1676.02                                                        | 1958.59                          | 1677.79                                           | 1243.86        |
| Area (m <sup>2</sup> )          | 202.00                                  | 202.81                                                 | 286.15                                          | 286.15                                                         | 247.22                           | 247.22                                            | 165.95         |
| <i>dte</i> (m)                  | 0.01590                                 | 0.01590                                                | 0.01905                                         | 0.01905                                                        | 0.01905                          | 0.01905                                           | 0.01590        |
| <i>dti</i> (m)                  | 0.01260                                 | 0.01260                                                | 0.01570                                         | 0.01570                                                        | 0.01660                          | 0.01660                                           | 0.01255        |
| <i>Ds</i> (m)                   | 0.687                                   | 0.687                                                  | 0.838                                           | 0.838                                                          | 0.787                            | 0.787                                             | 0.591          |
| <i>lay</i>                      | Square                                  | Square                                                 | Square                                          | Square                                                         | Square                           | Square                                            | Square         |
| <i>Npt</i>                      | 2                                       | 2                                                      | 2                                               | 2                                                              | 2                                | 2                                                 | 1              |
| <i>rp</i>                       | 1.25                                    | 1.25                                                   | 1.33                                            | 1.33                                                           | 1.33                             | 1.33                                              | 1.33           |
| <i>L</i> (m)                    | 4.877                                   | 4.877                                                  | 6.706                                           | 6.706                                                          | 6.706                            | 6.706                                             | 6.096          |
| <i>Nb</i>                       | 8                                       | 8                                                      | 18                                              | 18                                                             | 17                               | 17                                                | 12             |
| <i>Ntt</i>                      | 832                                     | 832                                                    | 713                                             | 713                                                            | 616                              | 616                                               | 545            |
| <i>vt</i> (m/s)                 | -                                       | 1.334                                                  | 1.003                                           | 1.003                                                          | 1.039                            | 1.039                                             | 1.027          |
| <i>vs</i> (m/s)                 | -                                       | 0.467                                                  | 0.500                                           | 0.447                                                          | 0.500                            | 0.449                                             | 0.512          |
| <i>ht</i> (W/m <sup>2</sup> °C) | 6480.0                                  | 7400.0                                                 | 4186.2                                          | 5599.4                                                         | 4356.7                           | 5743.4                                            | 5846.7         |
| <i>hs</i> (W/m <sup>2</sup> °C) | 1829.0                                  | 1951.7                                                 | 1516.5                                          | 1558.8                                                         | 1880.2                           | 1591.6                                            | 1972.0         |
| $\Delta Pt$ (kPa)               | 22.676                                  | 23.553                                                 | 13.404                                          | 14.701                                                         | 15.921                           | 14.729                                            | 8.650          |
| $\Delta Ps$ (kPa)               | 7.494                                   | 6.558                                                  | 6.445                                           | 7.065                                                          | 10.609                           | 7.049                                             | 9.467          |

## RESULTS

### EXAMPLE 2

| Variable                        | Mizutani et al.'s<br>(2003)<br>solution | Mizutani et al.<br>(2003)<br>Rating using our<br>model | Ravagnani and<br>Caballero's (2007)<br>solution | Ravagnani and<br>Caballero (2007)<br>Rating using our<br>model | Onishi et al. (2013)<br>solution | Onishi et al. (2013)<br>Rating using our<br>model | Our MILP Model |
|---------------------------------|-----------------------------------------|--------------------------------------------------------|-------------------------------------------------|----------------------------------------------------------------|----------------------------------|---------------------------------------------------|----------------|
| Total cost (\$/y)               | 5250.00                                 | 5279.56                                                | 5191.47                                         | 5137.78                                                        | 5134.21                          | 4853.40                                           | 3754.01        |
| Area cost (\$/y)                | 2826.00                                 | 2825.45                                                | 3663.23                                         | 3461.77                                                        | 3175.61                          | 3175.61                                           | 2510.14        |
| Pumping cost(\$/y)              | 2424.00                                 | 2454.11                                                | 1528.24                                         | 1676.02                                                        | 1958.59                          | 1677.79                                           | 1243.86        |
| Area (m <sup>2</sup> )          | 202.00                                  | 202.81                                                 | 286.15                                          | 286.15                                                         | 247.22                           | 247.22                                            | 165.95         |
| <i>dte</i> (m)                  | 0.01590                                 | 0.01590                                                | 0.01905                                         | 0.01905                                                        | 0.01905                          | 0.01905                                           | 0.01590        |
| <i>dti</i> (m)                  | 0.01260                                 | 0.01260                                                | 0.01570                                         | 0.01570                                                        | 0.01660                          | 0.01660                                           | 0.01255        |
| <i>Ds</i> (m)                   | 0.687                                   | 0.687                                                  | 0.838                                           | 0.838                                                          | 0.787                            | 0.787                                             | 0.591          |
| <i>lay</i>                      | Square                                  | Square                                                 | Square                                          | Square                                                         | Square                           | Square                                            | Square         |
| <i>Npt</i>                      | 2                                       | 2                                                      | 2                                               | 2                                                              | 2                                | 2                                                 | 1              |
| <i>rp</i>                       | 1.25                                    | 1.25                                                   | 1.33                                            | 1.33                                                           | 1.33                             | 1.33                                              | 1.33           |
| <i>L</i> (m)                    | 4.877                                   | 4.877                                                  | 6.706                                           | 6.706                                                          | 6.706                            | 6.706                                             | 6.096          |
| <i>Nb</i>                       | 8                                       | 8                                                      | 18                                              | 18                                                             | 17                               | 17                                                | 12             |
| <i>Ntt</i>                      | 832                                     | 832                                                    | 713                                             | 713                                                            | 616                              | 616                                               | 545            |
| <i>vt</i> (m/s)                 | -                                       | 1.334                                                  | 1.003                                           | 1.003                                                          | 1.039                            | 1.039                                             | 1.027          |
| <i>vs</i> (m/s)                 | -                                       | 0.467                                                  | 0.500                                           | 0.447                                                          | 0.500                            | 0.449                                             | 0.512          |
| <i>ht</i> (W/m <sup>2</sup> °C) | 6480.0                                  | 7400.0                                                 | 4186.2                                          | 5599.4                                                         | 4356.7                           | 5743.4                                            | 5846.7         |
| <i>hs</i> (W/m <sup>2</sup> °C) | 1829.0                                  | 1951.7                                                 | 1516.5                                          | 1558.8                                                         | 1880.2                           | 1591.6                                            | 1972.0         |
| $\Delta Pt$ (kPa)               | 22.676                                  | 23.553                                                 | 13.404                                          | 14.701                                                         | 15.921                           | 14.729                                            | 8.650          |
| $\Delta Ps$ (kPa)               | 7.494                                   | 6.558                                                  | 6.445                                           | 7.065                                                          | 10.609                           | 7.049                                             | 9.467          |

## CONCLUSION

This approach rendered significantly better results than the literature MINLP approaches.

## FUTURE WORK

- Investigation of an alternative objective function considering, for example, the total mass of the heat exchanger
- Apply the linear formulation to a train of exchangers in series
- Inclusion of design uncertainties in optimization.