Retrofit of Mass Exchange Networks Using Pinch Technology

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The purpose of this article is to demonstrate that the Pinch Technology approach for the retrofit of heat exchange networks (HENs) may be successfully applied to the retrofit of mass exchange networks (MENs). This has three main features: the determination of retrofit targets (both for utility savings and capital investment), the generation of a savings-investment curve (for a range of minimum composition differences) which leads to the choice of a particular set of targets, and design of a network to meet the chosen targets.

El-Halwagi and Manousiouthakis (1989) first used the analogy between heat and mass transfer to apply Pinch Technology to the synthesis of MENs. They showed how specifying the minimum composition difference ε (analogous to the minimum approach temperature in HENs) locates the mass-transfer pinch and allows a target for the minimum flow rate of mass-separating agent (MSA) required by a network to be determined. This is analogous to the energy targeting procedure for HEN synthesis (Linnhoff et al., 1982). They showed that, in order to achieve the MSA targets in designing a network, there should be no transfer of mass across the pinch.

We recently presented a method to determine capital cost targets for MENs which is analogous to that for HENs except that the driving forces and design procedures are fundamentally different (Hallale and Fraser, 1998a,b; 2000a,b). For mass exchange, the driving force involves equilibrium relationships, and the design of mass exchangers is more complex than heat exchangers. This work allows capital and operating costs to be traded off in order to optimize the total cost ahead of design. It was also shown that proper use of available driving force is required to approach the capital cost targets.

Note, however, that all of the above-mentioned work has been aimed at grassroots designs. Based on these successful applications of HEN approaches to grassroots MEN design, this article explores the postulate that the approach used in retrofit of HENs may be successfully applied to retrofit of MENs. In addition to the grassroots techniques described above, the work of Tjoe and Linnhoff (1986) will form the basis for this approach.

It should be noted that the traditional capital-operating trade-off used for grassroots designs (Hallale and Fraser, 2000c,d) is not meaningful for retrofit. The aim in a retrofit is generally to achieve the best savings in operating costs, subject to a minimum payback period or a maximum capital expenditure.

Retrofit Example

The coke-oven gas sweetening process presented by El-Halwagi and Manousiouthakis (1989) is the example used to test our hypothesis. The objective of the process is the removal of H_2S from two rich streams: coke-oven gas (R_1) and the tail gas from a Claus unit (R_2). Rich stream data are given in Table 1. Two lean streams are used: aqueous ammonia (S_1, which is available from within the process) and chilled methanol (S_2, which is purchased from outside). Data for the lean streams are shown in Table 2. Both MSA costs and equipment costs are taken from Papalexandri et al. (1994). The mass exchangers used are all sieve tray columns costing $4,552 per equilibrium stage per year, with a 5-year annualization. Assuming that this is an installed cost gives a capital cost of $22,760 per equilibrium stage. Mass transfer of H_2S is governed by the following equilibrium relations

$$S_1: y = 1.45 x_1 \quad S_2: y = 0.26 x_2$$

Figure 1 shows an existing plant design for the problem. This is based on a grassroots design by Papalexandri et al. (1994). The objective is to retrofit this plant in order to reduce the operating costs. As is common in industry, a payback period less than or equal to six months is required. Operating cost savings can best be achieved by reducing the use of the external MSA (S_2 in this case). This is because the internal MSA (S_1) is less expensive (see Table 2). Internal MSAs are generally cheaper and may even be available for free (El-Halwagi, 1997).

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Table 1. Rich Stream Data for Coke-Oven Gas Sweetening Process

Stream	G_i (kg/s)	y^s (Mass Fraction)	y^t (Mass Fraction)
R_1 (Coke-oven gas)	0.9	0.070	0.0003
R_2 (Claus tail gas)	0.1	0.051	0.0001

Retrofit Targeting

We will now apply the HEN retrofit method of Tjoe and Linnhoff (1986) to this example, using the established grass-roots methods for MENs to determine utility (MSA) targets and equipment cost targets.

The method of Tjoe and Linnhoff starts by varying the minimum approach temperature to obtain a series of minimum energy targets and the equivalent minimum heat-transfer area targets. These are then plotted on an area-energy diagram, together with the plant's installed area and energy usage.

Next, a retrofit path is constructed from the plant's current position, either assuming a constant ratio between plant operation and the target curve, or by allowing the retrofit to have an ideal incremental area—energy usage which allows it to approach the target curve (see Ahmad and Polley, 1990). For each point on this retrofit curve, the extra area added is converted to a capital investment and the energy saved is converted to a savings in operating cost. This then gives a savings-investment diagram, which shows the ideal utility savings possible for a particular capital investment.

In MEN retrofit the savings-investment curve is developed from the analog of the area-energy plot, which is a size-load plot. This shows total mass exchanger size vs. the mass load on the external MSA. Note that the mass load is used and not the external MSA flow rate. This is because mass load, and not MSA flow rate, is the proper analog of the utility energy requirement in HENs. The MSA load target can be converted to a flow rate target by using the supply and maximum compositions specified for the MSA.

The MSA load target is found using the method of El-Halwagi and Manousiouthakis (1989). The mass exchanger size can be determined by the number of stages or the height of packing, depending on the type of equipment being used, using the method of Hallale and Fraser (1998a,b). In this example, all exchangers are tray columns and the relevant size parameter is the number of stages, so a stages-load plot is developed.

To do this, we need to determine targets for the minimum number of stages for a network at a given value of ε. This is done using the y-x composite curve plot (Hallale and Fraser, 1998a). The plot consists of a composite operating line and the mass-transfer equilibrium line. Because there are two nonoverlapping MSAs in this problem, Figure 2 shows each one on its own plot. Notice how, unlike the traditional composite curves of Pinch Technology, both axes show compositions. This representation allows the number of stages target for a given ε value to be stepped-off in a conventional McCabe-Thiele construction, as shown in Figure 2.

Carrying out the targeting for MSA load and number of stages over a range of ε values provides the stages-load diagram (Figure 3), which plots the stages target vs. the MSA load target. Note that the repetitive targeting calculations were readily automated using a spreadsheet.

Table 2. Lean Stream Data for Coke-Oven Gas Sweetening Process

Stream	L_j^c (kg/s)	x^s (Mass Fraction)	x^c (Mass Fraction)	Supply Cost ($/yr)/(kg/s)
S_1 (Aqueous ammonia)	2.3	0.0006	0.031	117,360
S_2 (Chilled methanol)	∞	0.0002	0.0035	176,040

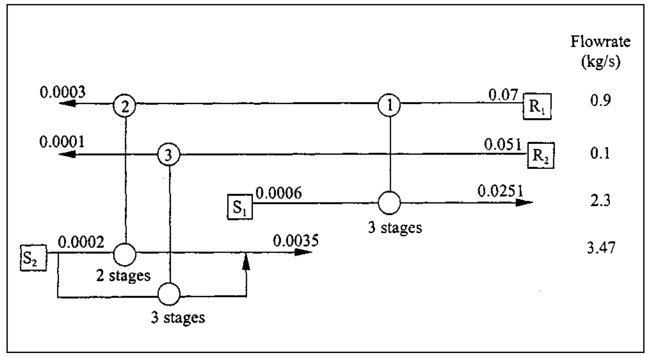

Figure 1. Existing process for coke-oven gas example.

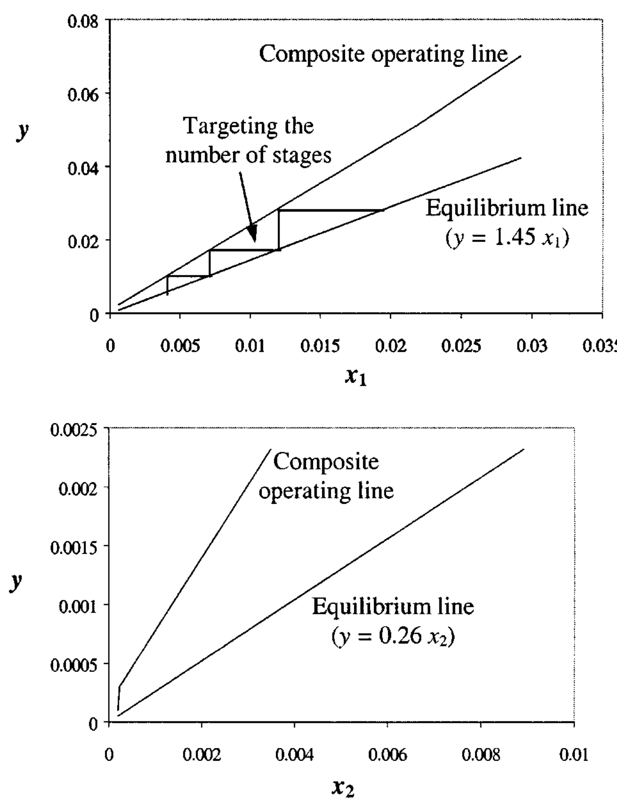

Figure 2. The y-x composite curve plot for the coke-oven gas example, showing each MSA separately.

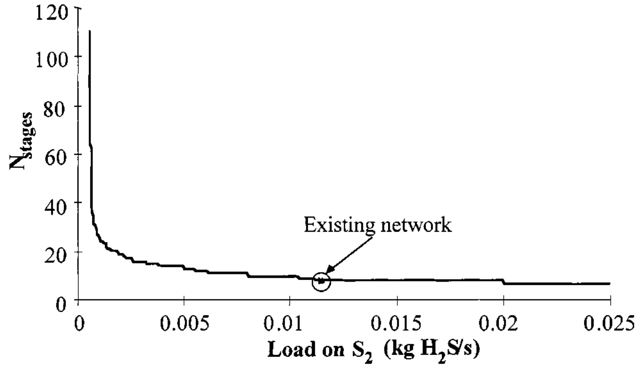

Figure 3. Stages-load diagram for the coke-oven gas example.

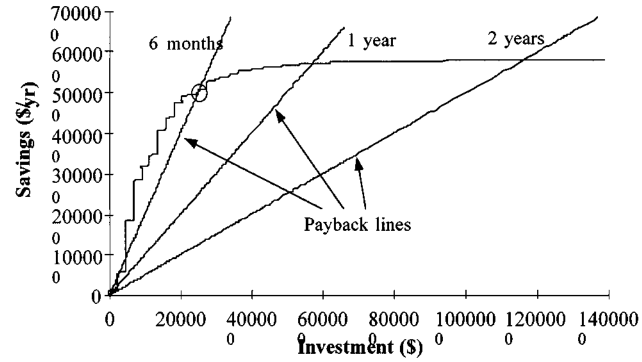

Figure 4. Savings-investment curve for the coke-oven gas example.

The existing network is shown as a point on the stages-load diagram. In this example, the existing network lies on the curve, which indicates that the total number of stages used is the minimum possible for the existing MSA flow rates. This means that, in this example, the retrofit curve coincides with the target curve. Fraser and Hallale (2000) show how to contract a retrofit path when the existing network lies above the curve.

The next step is to construct the savings-investment curve from the stages-load plot. As we move to the left of the plant's current operation on this diagram, the MSA load is reduced and additional stages are added. Converting the MSA flow rate targets and number of stages targets to costs for each point on the retrofit path, using the costing information given above, leads to the savings-investment curve shown in Figure 4. This figure shows the ideal MSA cost savings that can be expected for a given capital investment, as well as lines corresponding to various payback periods.

The point where the six-month payback line cuts the savings-investment curve gives the retrofit targets for this example. This point corresponds to an ε value of 0.001. The savings target is $500,720/yr, and the capital investment target is $250,360.

The ability to target savings, investment, and payback means that the savings-investment diagram captures the capital and operating cost issues which are relevant in a retrofit.

Retrofit Design

We have now established that the approach of Tjoe and Linnhoff (1986) for HEN retrofit targeting may be successfully applied to MEN retrofit targeting. The next step in proving our postulate is to demonstrate that these targets may be achieved in an actual retrofit design. The retrofit design method set out below is directly analogous to the approach of Tjoe and Linnhoff.

(1) The first step in design is to draw the existing network, showing the pinch point for the appropriate ε value, which in this case is 0.001 (Figure 5). This diagram highlights exchangers that transfer mass across the pinch and which are responsible for the excessive use of S_2.

(2) The second step is to eliminate the cross-pinch exchangers and to change the flow rate of S_2 to its target value (Figure 6). The reason for doing this is that in order to meet the MSA savings target, no mass may be transferred across the pinch.

(3) The third step is to complete the network using the design rules developed by El-Halwagi and Manousiouthakis (1989) to ensure that the MSA targets are achieved, and those developed by Hallale and Fraser (1998a) to ensure that the

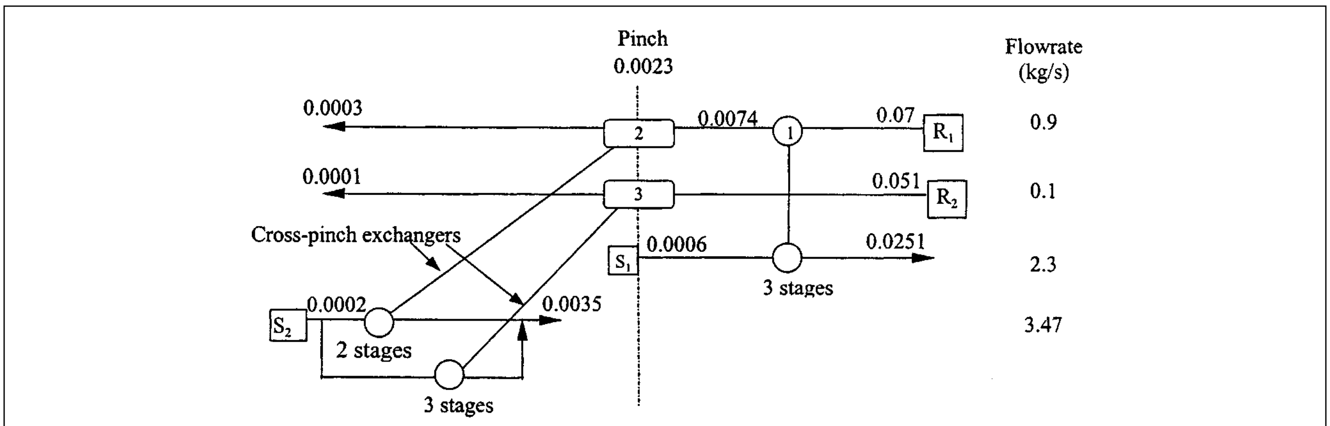

Figure 5. Existing design shown with a pinch corresponding to ε = 0.001.

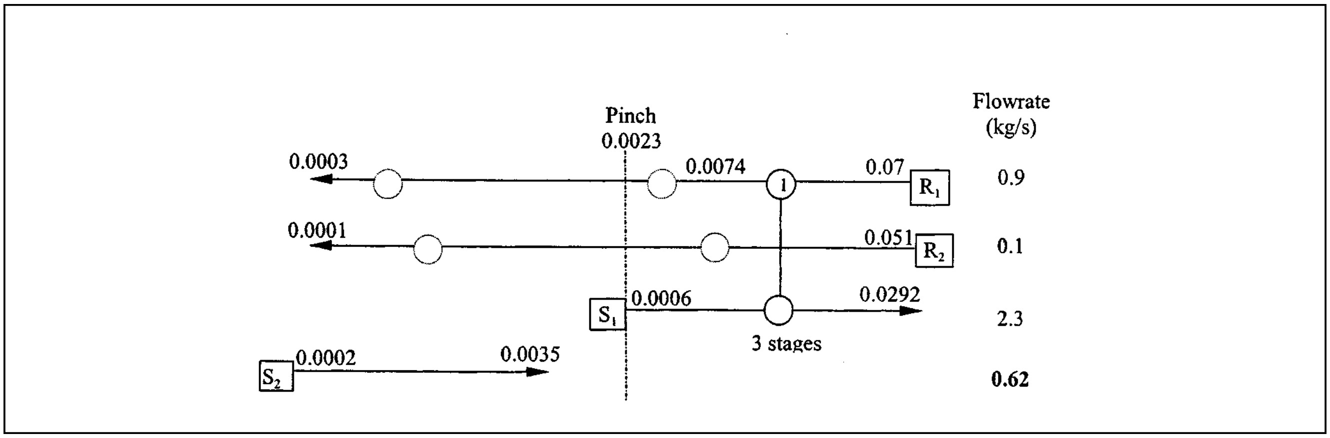

Figure 6. Elimination of cross-pinch exchangers and setting of S_2 to its target flow rate.

capital cost targets are closely approached. Note that this step is essentially the same as a grassroots design, but at the correct value of ε for the retrofit economics. Designing for the minimum capital cost involves superimposing prospective matches on the *y*-*x* composite curve plot in order to evaluate their utilization of driving forces. Good matches will fit the composite operating line well, while poor ones will deviate from it. Hallale (1998) applied this method to a wide range of mass exchange network problems and showed that it allows the capital cost targets to be approached to within 5% or less for grassroots problems. This is similar to what was found for HENs. It is, therefore, anticipated that the same approach to the capital cost target can be expected for retrofit designs.

Figure 7 shows proposed matches which all fit the composite operating line closely. The corresponding network design is shown in Figure 8. Note that when moving from Figure 6 to Figure 8, re-use of previously-removed exchangers has not yet been considered.

(4) The final step is to see where the existing exchangers can be re-used in the design developed above, because the retrofit targets were based on the assumption that existing exchangers would be re-used and not discarded. This means comparing the number of stages required in each exchanger with the number of stages available in each one that was previously removed. By comparing Figure 8 with Figure 1, it is clear that exchangers 1, 2, and 3 from Figure 1 can be re-used, with the addition of 1 extra stage to exchanger 2 and 4 extra stages to exchanger 3. This leads directly to the final design shown in Figure 9. This design employs all the existing exchangers and requires one new one. Besides the new exchanger, the only structural modification is the added stream split on S_1. The capital investment is \$250,360−exactly on target.

It was noticed that the flow rate of S_1 could actually be reduced slightly without increasing the number of stages required. This is because the number of stages is rounded up to an integer value. The flow rate can therefore be reduced with no penalty until the number of stages in an exchanger reaches the next integer value. This occurs at a flow rate of 2.22 kg/s for S_1. This means that the operating cost saving is \$509,630/yr, which is slightly more than was targeted. The resulting payback is 5.9 months compared with six months targeted.

Note that in this design there was no conflict between reduction of MSA by avoiding cross-pinch mass transfer and achieving the targeted investment. In fact, avoiding cross-pinch mass transfer is a necessary condition for making the best use of driving forces.

We recognize that costing all the additional stages as if they were new installations will overestimate the capital costs and is therefore somewhat conservative. Fraser and Gillespie (1992) presented a costing method for stretching heat ex-

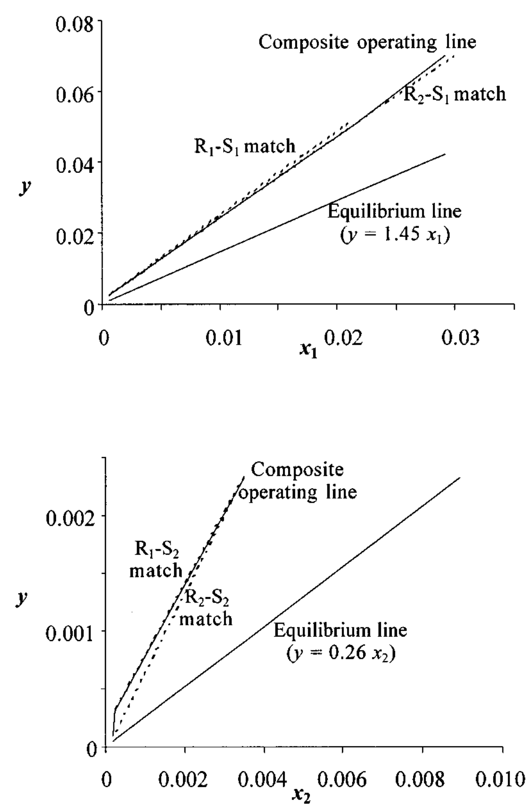

Figure 7. *y*-*x* composite curve plot is used to ensure that the minimum capital cost target is achieved.

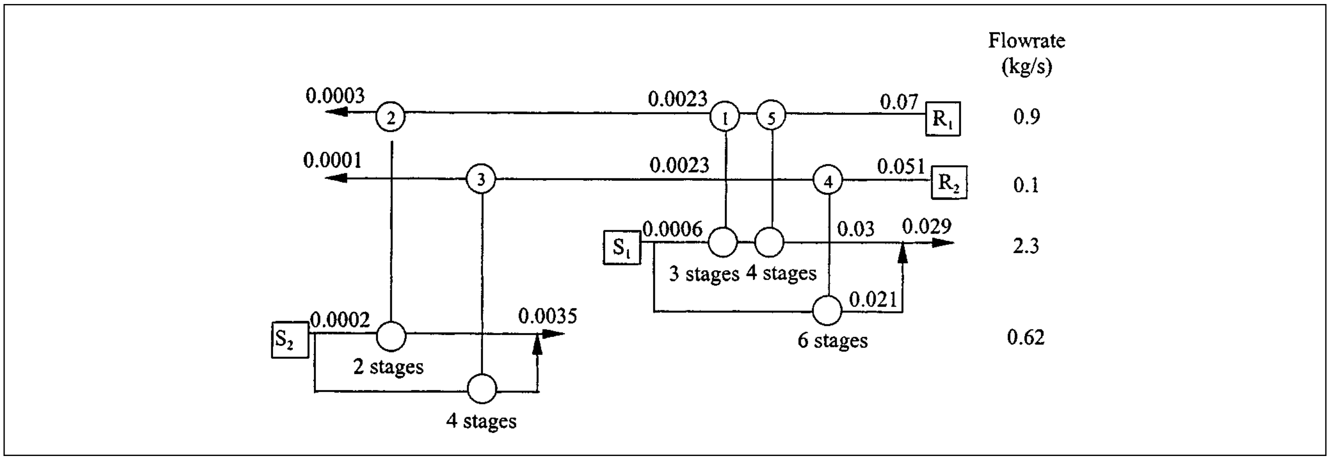

Figure 8. Network design for the coke-oven gas example.

changers, based on suggestions made by industrialists. They assumed that, given an installation factor of around 4.0 for converting a purchased equipment cost to an installed cost for a new plant or a new piece of equipment, one could reasonably take the installation factor for extending an existing piece of equipment to be around 2.0, given that the equipment is already installed, and only piping changes need to be accounted for. If this is taken into account for the proposed design, then the capital investment for the process is only \$193,460 and the resulting payback period is 4.6 months.

This section has demonstrated that the approach to HEN retrofit design used by Tjoe and Linnhoff (1986) may be successfully adapted to MEN retrofit design, using grassroots design techniques for MENs.

Conclusions

This article has examined the postulate that the Pinch Technology approach used for retrofitting HENs could be successfully applied to MENs. The approach involves setting targets for MSA load and mass exchanger size, using grassroots targeting techniques. These targets are plotted as a size-load diagram and compared to the existing plant situation. A retrofit path is then chosen, which allows one to determine the savings achieved for extra size. Costing these yields the savings-investment diagram. The savings to be achieved and the minimum investment required are determined from this diagram. Techniques for grassroots MEN design are then used in a retrofit framework to develop a retrofit design to meet the savings and investment targets. Elimination of cross-pinch transfer and appropriate use of driving force are the key design principles used.

For the example studied, this approach was successfully used to generate the size-load diagram as well as the savings-investment diagram, and to design a retrofit network which met the targets at the specified design criterion of a six-month payback period.

For simplicity, this study made use of a capital cost correlation which was based only on the number of stages. Other factors, such as the number of columns, the column diameters, and the use of nonequilibrium stages, should also be considered in a more rigorous approach.

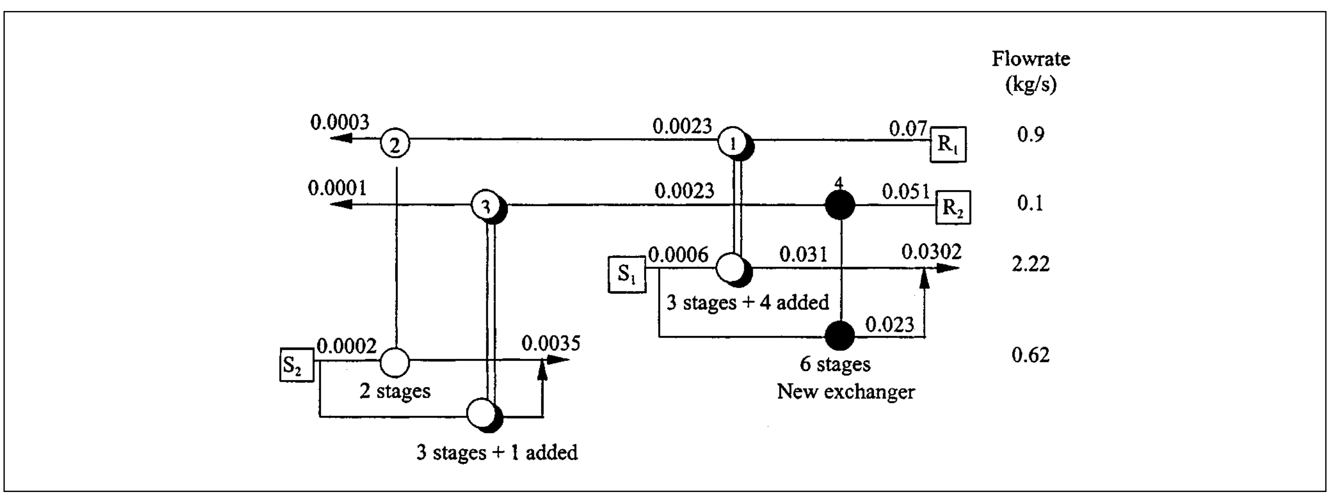

Figure 9. Final retrofit design redeploys all the existing exchangers and requires one new exchanger.

This study has demonstrated that the HENs approach to retrofit may be successfully applied to retrofit design of a simple MEN. Further work will need to be done to demonstrate its wider applicability for more complex problems.

Acknowledgment

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Notation

G = rich stream flow rate, kg/s
L = lean stream flow rate, kg/s
N = number of equilibrium stages, dimensionless
x = lean stream composition, mass fraction
y = rich stream composition, mass fraction
ε = minimum composition difference, units of lean stream composition

Subscripts

i = rich stream number
j = lean stream number

Superscripts

c = constrained value
s = supply composition
t = target composition

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