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A Modified Energy Transfer Diagram for Heat Exchanger Network Retrofit Bridge Analysis

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The aim of this paper is to modify the Energy Transfer Diagram (ETD) to be able to graphically determine retrofit options and the amount of heat transferred. The ETD is a graphical methodology to represent a process and/or Heat Exchanger Network (HEN). For HENs, the ETD contains valuable information about where in the network exist heat surpluses and deficits, after considering a global (or contribution) minimum approach temperature. The important advancement in this work is the identification of which segments of the ETD represent heat surplus/deficit within a heat exchanger and then to show this on the ETD. Further clarity is drawn from the labelling of what segments relate to which process stream. Behind the ETD is the well-known surplus/deficit cascade for each heater, cooler, and exchanger, which is also analysed and presented to reinforce the graphical approach. A simple four-stream problem with an existing HEN that falls 1,950 kW short of Pinch targets is used to demonstrate the methodological step forward. In the example, the initial network has a total of 5 heat exchangers and after two bridge modifications the Maximum Energy Recovery network is achieved, which requires 8 heat exchangers.

1. Introduction

Economic retrofitting of Heat Exchanger Networks (HEN) is an important industrial problem. Methods to retrofit HEN can be classified into three general categories: i) graphical methods such as Pinch Analysis (PA), ii) mathematical programming methods, and iii) hybrid methods using a combination of graphical and programming methods. PA has been effectively applied to chemical plant design to reduce energy consumption while also containing excellent graphical communication tools. Determining Composite Curves (CC) and Grand Composite Curves (GCC) for a plant leads to insights and energy targets that aid the economic design of a HEN and the Total Site utility systems. A limitation of the graphical tools used in PA is that they lack information regarding the current HEN for retrofit cases. Some studies have attempted to develop new PA tools to graphically determine and communicate HEN retrofit potential. Recent examples include Advanced Composite Curves (Nordman and Berntsson, 2009), Temperature Driving Force Curves (Kamel et al., 2017), and the Energy Transfer Diagram (Bonhivers et al., 2014a).

Bonhivers et al. (2014a) introduced the concept of bridge analysis and developed the Energy Transfer Diagram (ETD). The ETD assisted to identify heat transfer bridges within an existing HEN and for explaining how energy is transferred through a network from hot utility to cold utility and ultimately the environment (Bonhivers et al., 2014b). Additional graphical tools were developed including a heat exchanger load diagram (Bonhivers et al., 2015a) and a hybrid balanced CC and ETD diagram (Bonhivers et al., 2016). Bridge analysis has been applied to a Kraft pulp mill (Bonhivers et al., 2015b) and milk processing plant (Rohani et al., 2016).

The aim of this paper is to extend the ETD approach to include the HEN heat surplus/deficit table and a modified ETD that shows the heat surplus and deficit streams of the HEN for easier determination of bridge options. Specifically, the modified ETD better illustrates the maximum heat surplus or heat deficit that can be transferred within a temperature region, the availability of the process streams for the transfer, the Heat Recovery (HR) path options, the temperature driving force of each exchanger and the exchanger and HEN areas required to get the HR savings.

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2. Retrofit Pinch Analysis and the modified Energy Transfer Diagram

The modified method for retrofitting a HEN is illustrated using a simple four stream problem taken from Klemeš et al. (2014). The original HEN is presented in Figure 1. There are currently two heat recovery exchangers with a combined duty of 3,200 kW, a heater of 2,700 kW, and two coolers with a combined load of 2,950 kW.

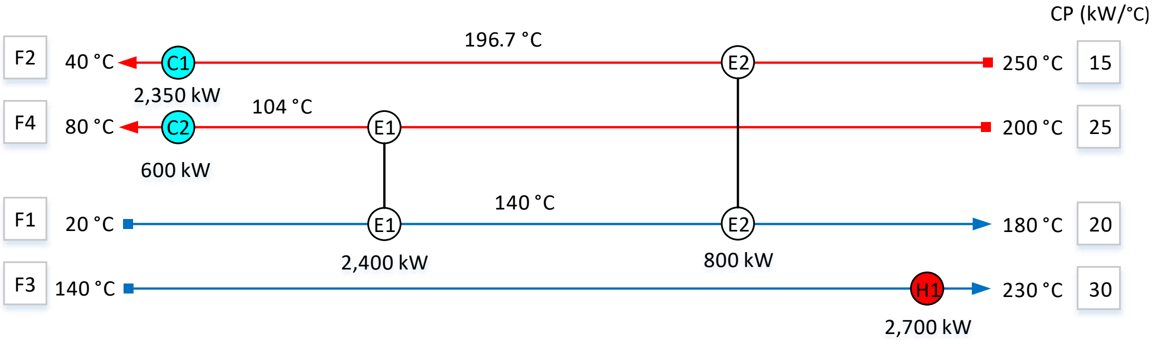

Figure 1: Existing Heat Exchanger Network for a four streams problem.

Application of conventional PA to the four streams problem generates the Shifted Composite Curve (SCC) and Grand Composite Curve (GCC) in Figure 2 based on a global ΔT_{min} of 10 °C. The Minimum Energy Targets (MET) are 750 kW for heating and 1,000 kW for cooling with a Pinch Temperature of 145 °C. Both the SCC and the GCC identify these values from the thermodynamics of the problem and are independent of the existing HEN. The GCC also illustrates the temperature regions of heat deficit (blue lines and positive slope), generally located above the Pinch, and heat surplus (red lines and negative slope), generally located below the Pinch. Heat recovery pockets form when there are heat deficits below the Pinch and/or heat surpluses above the Pinch.

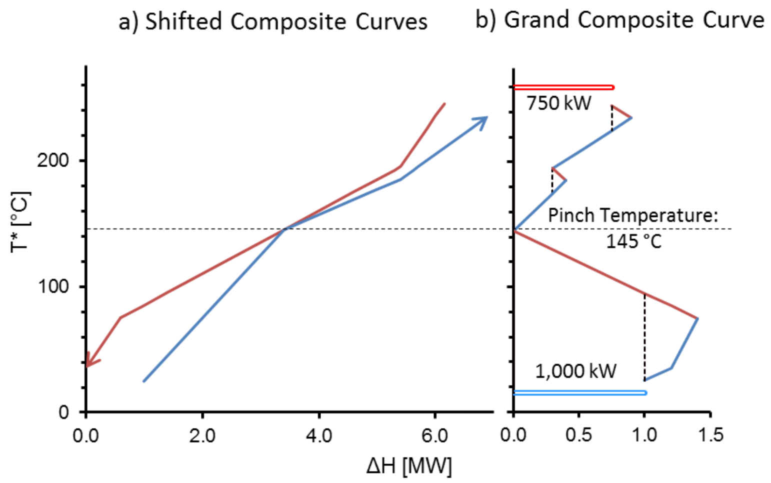

Figure 2: Shifted Composite Curves and Grand Composite Curves for the four streams network in Figure 1.

The GCC is useful for targeting and understanding a process and its thermodynamic Pinch points but lacks the fidelity of how heat is exchanged within the HEN. The Energy Transfer Diagram (ETD) provides the next layer of detail for how heat is transferred within the HEN. In this paper, the ETD is improved by showing the heat surplus (red) and deficit (blue) stream segments on the ETD for each recovery exchanger, heater, and cooler, which can be used to quantify the heat available to transfer across a so-called bridge.

The modified ETD construction method is illustrated in Figure 3. The SCC for each exchanger in the network (H1, E1, E2, C1 and C2) form the starting point for constructing the modified ETD. Each exchanger SCC translates to produce a corresponding exchanger GCC and set of temperature intervals. The modified ETD is constructed by stacking (adding to the right-hand side) the GCC's for each exchanger at each temperature interval for the network. In this paper, the preferential stacking order is heaters, coolers, and then recover exchangers. For this problem, this stacking order enables easier identification of the bridges that start at a cooler and end at a heater (or vice versa).

Individual (balanced) heat exchangers are typically represented in GCC form by a closed heat recovery pocket (e.g. E1 in Figure 3b and E2 in Figure 3e). The exchanger pocket shows the temperature and quantity of heat in surplus and deficit with respect to the minimum approach temperature. Where a heat exchanger is operating at the minimum approach temperature at both terminals of the exchanger, the pocket disappears, meaning there is no available heat surplus or deficit and no possible improvements can be made. The temperature starting points on the y-axis are the (shifted) inlet temperatures of the two streams to the heat exchanger.
The area of a pocket (or exchanger GCC) is proportional to the exchanger's duty and temperature driving force. Where the GCC area is large (e.g. H1, C1 and E1 in Figure 3d), the temperature driving force and/or the duty in the exchanger is likely to be large and the exchanger area is likely to be small. Conversely, where exchanger GCC areas are small (e.g. C2 and E2), the temperature driving force and/or the duty is likely to be small and exchanger area is likely to be large.
The modified ETD has a right-hand profile that mirrors the process GCC (Figure 2b) but is shifted to the right by 1,950 kW, which corresponds to the maximum energy savings for a HEN retrofit. The Pinch Temperature remains the same and (likely) Cross Pinch violations of exchanger's C1 and E1 are visible in the ETD. The stacking order of the exchangers does not affect the right-hand side profile of the ETD but does affect the internal layout of the exchanger lines within the ETD. For different stacking orders, the temperature intervals (y-position) of the heat surplus and deficit for each heat exchanger is unchanged, whereas the position on the enthalpy scale (x-axis) does change.

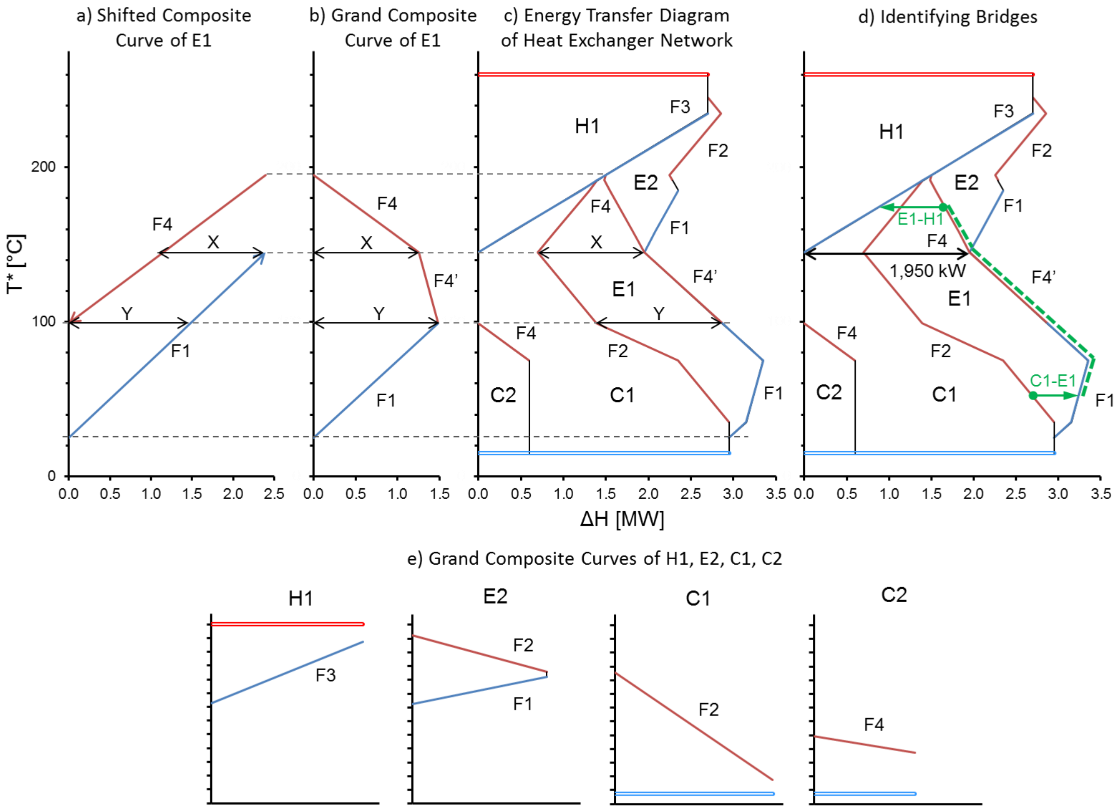

Figure 3: Development of the modified ETD for the HEN presented in Figure 1.

3. Using the modified Energy Transfer Diagram to identify maximum bridge heat flow

The extra stream information shown on the modified ETD (Figure 3d) enables bridge retrofit opportunities to be identified and quantified directly on the ETD diagram. For example, a heat transfer bridge can be represented by a horizontal line from the heat surplus stream F2 (red line) of the cooler C1, to the heat deficit stream F1 (blue line) of exchanger E1 (step 1), followed by a dashed line, starting from the region of heat deficit, to the heat surplus stream F4 of exchanger E1 and a second horizontal line from F4 to heat deficit stream F3 of the heater (step 2). The maximum amount of heat transferred can be determined by the horizontal lines on the ETD as shown more clearly in Figure 4a. The transfer consists of two steps across four enthalpy levels with the minimum enthalpy level acting as the bottleneck. 2,350 kW of heat is available to transfer below the pinch from stream F2 to F1. Stream F1 however only has 1,480 kW of deficit heat available at or below the same temperature interval, so only 1,480 kW of the 2,350 kW can transfer. However, at the pinch temperature, heat surplus stream F4 has only 1,250 kW available to transfer to heat deficit stream F3, which can receive up 1,500 kW across the same temperature intervals. The bridge between E1-H1 with a maximum heat transfer of 1,250 kW is, therefore, the bottleneck and the maximum heat that can be transferred for entire bridge option 1.

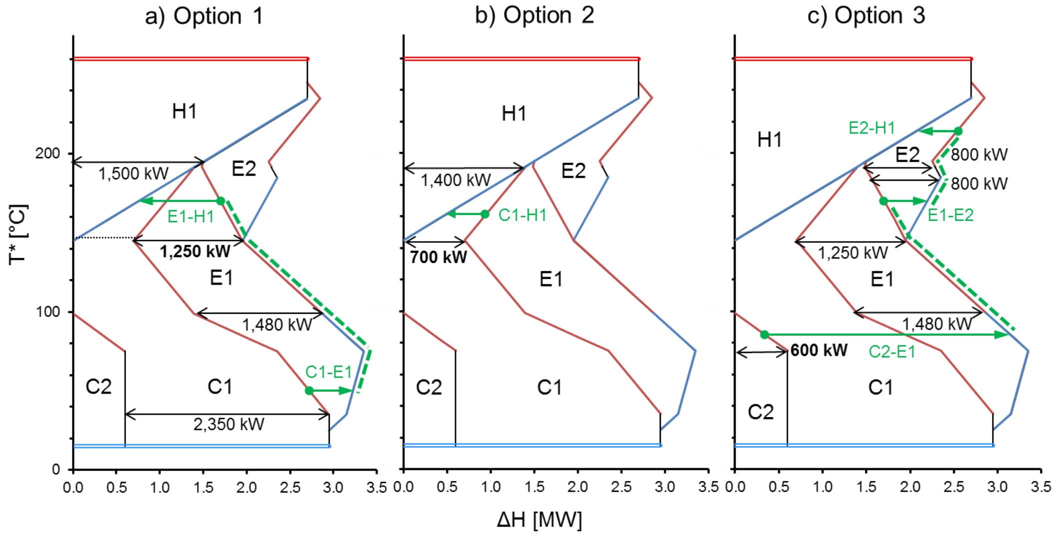

Figure 4: ETDs for three different bridge retrofit options.

Other bridge options can similarly be determined from the modified ETD. This is illustrated in Figure 4b for the simple case of transferring 700 kW heat directly from the cooler C1 heat surplus stream F2 to the heater H1 deficit stream F3 above the pinch. A third option (Figure 4c) is, where 600 kW of heat is transferred from cooler C2 via heat surplus stream F4 to heat deficit stream F1 in exchanger E1 below the pinch. E1 is then reduced by 600 kW to enable 600 kW of heat to be transfer above the pinch from F4 to F1. Three more bridges are also possible from the starting network in Figure 1.

4. Using heat surplus/deficit problem tables to identify maximum bridge heat flow

Another valuable tool for helping to identify bridges is the HEN Heat Surplus/Deficit Table (HSDT). The table is derived by calculating the heat surplus or heat deficit in the shifted temperature intervals of each exchanger in the HEN. The method is illustrated in Table 2 for the four stream HEN in Figure 1. Starting with C1, stream F2 with a CP of 15 kW/°C has a heat surplus of 2,350 kW spread across 5 temperature intervals. Similarly, C2 has a heat surplus of 600 kW in 1 temperature interval and H1 has a heat deficit of -2,700 kW spread across 4 temperature intervals. Recovery exchangers E1 and E2 have a balance of both heat deficit (negative values) and heat surplus (positive values) across a range of temperature intervals.

Table 2: Heat surplus/deficit problem tables for each heat exchanger, demonstrating bridge option 1.

Shifted Temperature	ΔT*	C1			C2			E1				E2				H1		
Interval (°C)	(°C)	F2	CP	ΔH	F4	CP	ΔH	F4	F1	CP	ΔH	F2	F1	CP	ΔH	F3	CP	ΔH
245 - 235	10		0	0		0	0			0	0			15	150		0	0
235 - 195	40		0	0		0	0			0	0			15	600		-30	-1,200
195 - 191.7	3		0	0		0	0			25	83			15	50		-30	-100
191.7 - 185	7		15	100		0	0			25	167			0	0		-30	-200
185 - 145	40		15	600		0	0			25	1,000			-20	-800		-30	-1,200
145 - 99	46		15	690		0	0			5	230			0	0		0	0
99 - 75	24		15	360		25	600			-20	-480			0	0		0	0
75 - 35	40		15	600		0	0			-20	-800			0	0		0	0
35-25	10			0			0			-20	-200				0			0
$\sum\Delta H_{Surplus}$				2,350							**1,250**							
$\sum\Delta H_{Deficit}$											-1,480							-1,500

Opportunities for a heat transfer bridge can be identified using the HSDT. For example, C1 has 2,350 kW of heat available via stream F2 to exchange with E1 via stream F1 which has a heat deficit of 1,480 kW. The heat transfer between these two streams via a new exchanger E3 will subsequently reduce the duty of E1 by the

maximum amount that can be transferred (still to be determined), which then enables 1,250 kW of heat from stream F4 of exchanger E1 to be available to transfer to stream F3 of exchanger H1, which has a deficit of 1,500 kW in the right temperature range. These steps form a bridge which requires two new exchangers. The lowest heat surplus/deficit value, 1,250 kW for this case, in the bridge dictates the maximum utility reduction.
On the new HEN (Figure 5), the 1,250 kW of heat are transferred across the bridge through the inclusion of two new heat exchangers E3 and E4 and the reduction of E1 duty by a similar amount. The cooling and heating loads also reduce by 1,250 kW to 1,700 kW and 1,450 kW respectively. Further utility reductions are possible with another round of bridge analysis using the retrofit option 1 HEN (Figure 5) and corresponding new modified ETD (Figure 6a) from bridge option 1.

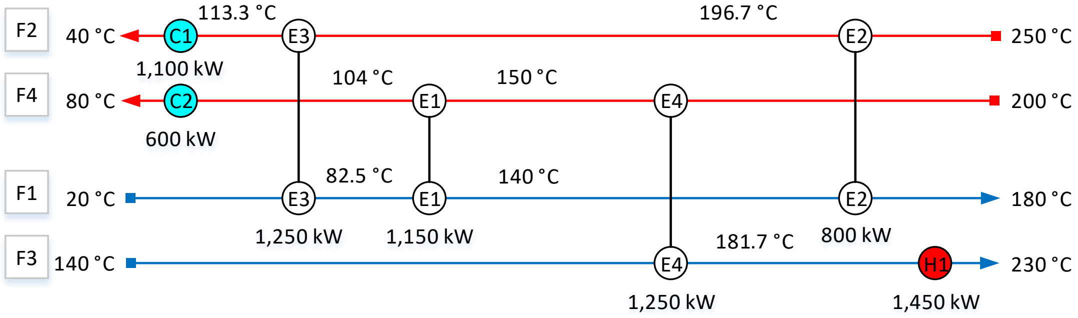

Figure 5: New HEN after applying bridge option 1.

5. Maximum Energy Recovery network and modified Energy Transfer Diagram

Using the modified ETD after one modification (option 1), a final bridge that leads to the Maximum Energy Recovery (MER) is illustrated in Figure 6a.

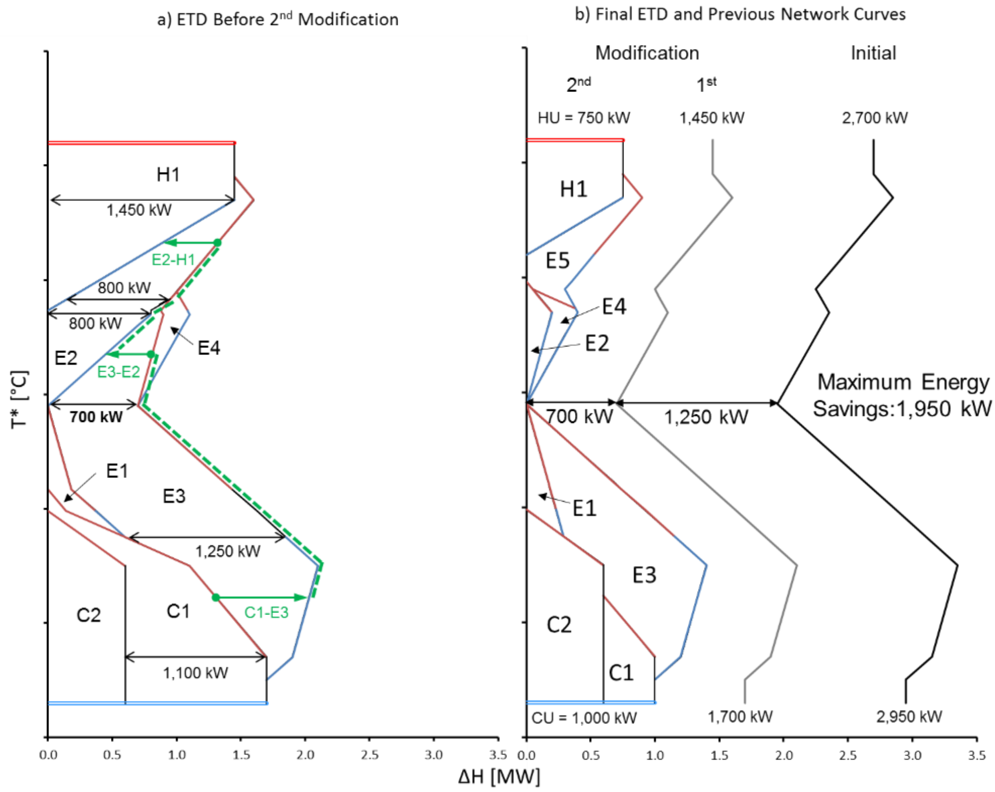

Figure 6: (a) Bridging option 1 for a further 700 kW savings. (b) Resulting ETD and comparison with previous network curves.

The bridge involves 3 steps through a bottleneck transfer of 700 kW between streams F2 to F1. One more exchanger (E5) is required above the pinch between streams F2 and F3, plus a transfer of heat from E3 below the pinch to above the pinch. The MER is presented in Figure 7 and the final ETD is presented in Figure 6b. Further reduction in exchanger number is possible in the MER by combining C1 and C2 into one through the transfer of 600 kW around a utility path but this would sacrifice network controllability. The final ETD has no exchanger Pinch violation and the right-hand side profile of the ETD is identical to the original GCC derived from PA (Figure 2).

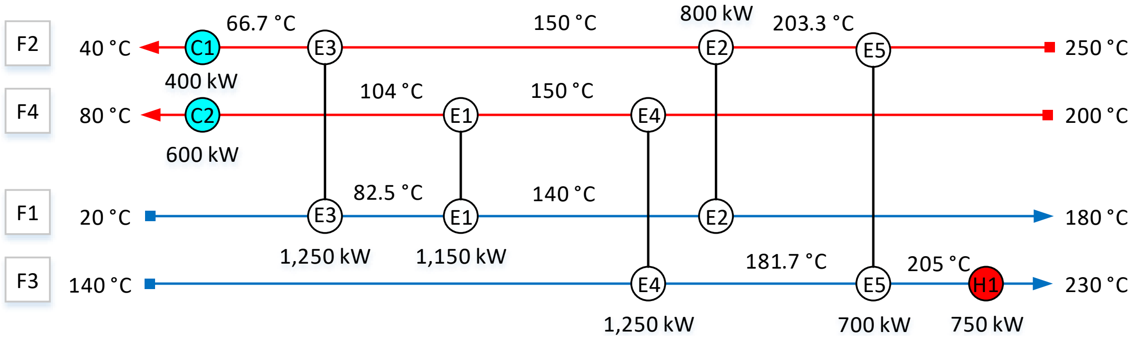

Figure 7: Maximum Energy Recovery network.

6. Conclusions

The modified Energy Transfer Diagrams (ETD), which shows surplus and deficit streams directly on the ETD has been demonstrated to be a useful tool for quickly identifying and quantifying HEN retrofit opportunities. With assistance from the Heat Surplus/Deficit Table, retrofit opportunities can be further confirmed and, for large retrofit problems, quantified. Links between conventional PA tools and the ETD by presenting exchanger CCs and GCCs to show the construction of the ETD are established, which provides fundamental insight to what the ETD represents and how it is developed.

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