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Minimizing Compression Work in a Multi-Pressure Level Steam Network

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Increasing energy requirements and carbon emissions drive towards energy efficiency. In a process industry, one of the efficient ways of becoming cost-competitive is to employ the most efficient techniques and methodologies to utilize the available energy. One such area of energy targeting is compression work in steam networks. Steam is present in various pressure levels. In general, there are various levels of steams that are used in process industries. This paper deals with the development of an algebraic methodology that takes into consideration of pressures of the available steam streams, their temperature and flow rates into consideration. The objective of the proposed method is to calculate the minimum compression work required to satisfy steam demands using steam sources and these steam sources and demands are at various pressure levels. The methodology initially breaks multiple pressure systems into various sub-problems and solving each set of two pressure level sub-problem at a time. The overall cross-flows between all the pressure levels eventually determine the compression work required. The developed methodology is graphical and optimum solutions can be guaranteed. The cross-flow is calculated via a graphical methodology of the shortest path between the two curves. The methodology is illustrated via an example where reduction potential in compression energy is estimated to be more than 80 %.

1. Introduction

Energy requirements are increasing every day, and there is an imminent need for the adoption of novel methods of energy conservation and optimization. Process industry plants being one of the core areas for the application of energy targeting; require optimization techniques to cut the costs. In this regard, shaft work targeting has gained immense importance in the recent past, with industries realizing a major role in cost depreciation and sustainable use of resources (Nair et al., 2017).
Steam system is an essential part of an industrial chemical plant that provides heat and power to the manufacturing process. A steam system generally produces multiple steam grades such as super-high-pressure steam, high-pressure steam, medium-pressure steam, and low-pressure steam (Zhao et al., 2019a)
The design and optimization of site utility systems are one of the most challenging topics in process industries, as the complexity of equipment networks and choice of operating conditions present significant challenges to optimize utility systems in practice.(Khoshgoftar Manesh et al., 2013) Recently a data-driven robust optimization method is proposed to handle uncertainty in the optimization of the steam system in an ethylene plant by (Zhao et al., 2019b).
One potential area where the shaft work minimization could find its application is Combined Heat and Power (CHP) plants and Combined Cooling, Heat and Power Plants (CCHP), which recover energy from the hot steam streams used in turbines present at elevated pressures. Various analysis has been done and methodologies been proposed in the past concerning the performance improvements of the CHPs and CCHPs. Heat and power networks in process design (Townsend and Linnhoff, 1983) have contributed significantly to reducing costs and optimizing the power distribution for Energy distribution, especially in the small power supply networks (Jimenez-Navarro et al., 2020). Early studies by Linnhoff and Dhole (1992) on the shaft work targets for the low-temperature process design have categorically highlighted the impact of this work in the refrigeration industry.

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CHPs and CCHPs are subsets to a large problem set of plants that are grouped under the category of total sites, which incorporate several processes, and the procedures of the Pinch technology are extended from the single processes to Total Sites (Klemeš et al., 2013). Recently (Wang et al., 2021) presented a Pinch Analysis based method for heat and power integration to target the amount of heat that should be recovered from the hybrid energy system. Simultaneous optimization of the utility requirement and the shaft work is one key area that has been dealt with in this paper and which has been left largely untouched, despite having a wide range of potential applications. Pinch technology has been a successful methodology in the past for utility targeting. It can be noted that for minimizing compression work where steam availability is limited a systematic method is needed. This paper deals with the minimization of the compression work that is required in SN having more than one pressure level. The methodology minimizes the intermediate fluid flow, and hence eventually minimizes compression work requirement. The impact of minimizing intermediate fluid is on cost reduction along with the reduction in compression power requirement (Chamorro-Romero and Radgen, 2020). The paper is organized into sections that give problem formulation, targeting algorithm, and an illustrative example.

2. Problem definition

This paper deals with the development of a methodology for targeting shaft work for the multi-pressure level systems in intermediate fluid stream networks. The problem definition is as follows:

- There is a set S of sources where each source *si* {1,2,..., S} have a fixed flow F_{si} and are available at pressure P_i.
- There are another set of D demands where each demand *dj* {1,2,..., D} requires a fixed flow F_{dj} and at a specified pressure P_{dj}.
- An external hot utility and cold utility are available, which has to be supplied to meet the required demands.
- The primary target is to minimize the amount of compression work needed in the conversion of a fluid stream from low pressure to high pressure while having a minimum supply of the external utilities, both hot and cold

It is also assumed that the work done during the transfer of stream from one pressure level to another is done as shaft work, and no amount of heat is used to do this compression work. The entire conversion of fluid streams from one pressure level to another is assumed to be done isothermally. Figure 1 shows the schematic of the problem statement where there are four pressure levels and there is one source and one demand at each pressure level.

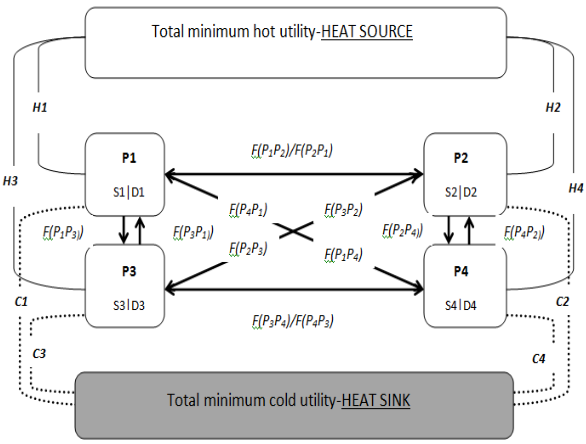

Figure 1: Schematic of the problem definition

3. Mathematical Development and targeting algorithm

This section gives the mathematical development, which is followed by the targeting algorithm. As there is a direct mixing of the streams, an important assumption is that the streams are non-reactive, and no amount of heat is released or consumed during the process of their mixing.

The entire conversion of fluid streams from one pressure level to another is assumed to be done isothermally. The methodology adopted in the paper utilizes the assumption stated above, so without the loss of generality, the available streams, also referred to as the source streams S{*i*=1,2,..., S} are considered to be present at given pressures P_{si}{*i*=1,2,..., S}and the demands D{*j*=1,2,..., D} are required at specific pressure P_{dj}.

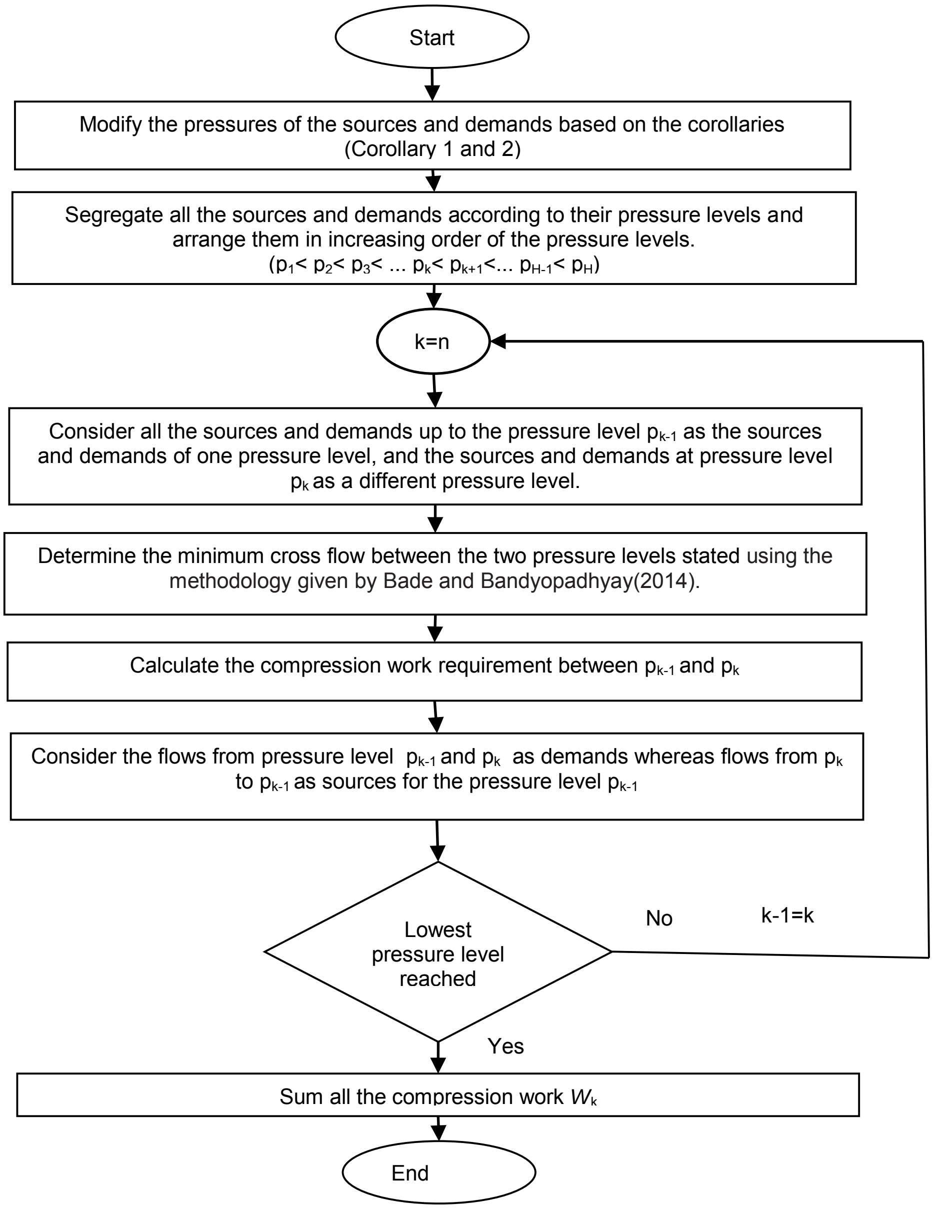

Figure 2: Targeting algorithm for minimizing compression work in a multi-pressure level heat supply network

The minimum amount of utility required in any SN is obtained algebraically using Problem Table Algorithm (PTA) (Linnhoff and Hindmarsh, 1983) or Modified PTA (Bandyopadhyay and Sahu, 2010). The compression work needed for a flow is directed by the initial and final states along with the compression process. For the isothermal process, the work done can be expressed as Eq(1):

$$W_{isothermal} = F_0 * \left(\left(P_0 \ln(P_{out}/P_0)\right) - \left(P_0 \ln(P_{in}/P_0)\right)\right) \quad (1)$$

Where, $F_0$is the standard volumetric flow rate that is compressed and P_0 is the pressure under standard conditions. The compressor inlet and outlet pressure are P_{in} and P_{out}. Note that the quantities $P_0 \ln(P_{out}/P_0)$ and $P_0 \ln(P_{in}/P_0)$ can be denoted as $\mu_{in}$and μ_{out} Respectively and may be called the pressure index for isothermal compression. The compression work for a compressor in the network can be expressed as Eq(2):

$$W_{ij} = F_0(\mu_{out} - \mu_{in})^+ \quad (2)$$

The minimum volumetric flow that needs to be transferred can be calculated via determining minimum cross-flow between the two networks (considering sources and demands at each pressure as individual networks) using the methodology given by Sahu and Bandyopadhyay (Sahu and Bandyopadhyay, 2012). Note that compression work is required to raise the source pressure to demand pressure and this work is minimized via calculation of minimum crossflow and further, calculation of minimum crossflow via determining the shortest path is a widely adopted method (Chaturvedi, 2019). Following two corollaries (Bandyopadhyay et al., 2014) should be utilized to reduce the mathematical computation.

Corollary 1: Sources with higher pressure than the highest demand pressure can be shifted to the highest demand pressure without affecting the total compression work in any feasible network.

Corollary 2: Sources below the lowest demand pressure can be raised to the lowest demand pressure in every feasible network affecting the total compression work by a constant amount.

Figure 2 shows the step by step flowchart of the proposed algorithm for minimizing compression work in a multi-pressure level heat supply network. Initially, sources and demands are segregated as per pressure levels. Let p_1 be the lowest pressure and p_H be the highest. Let p_2, p_3, ..., p_{H-1} be the intermediate pressure levels. $p_1 < p_2 < p_3 \ldots \ldots < p_{H-1} < p_H$ sources and demands can be segregated according to their pressure levels. Let us consider all sources and demands up to p_{H-1} to be a single SN (SNp_{H-1}). The remaining sources and demands at pressure level p_H are considered as other SN (SN-p_H).

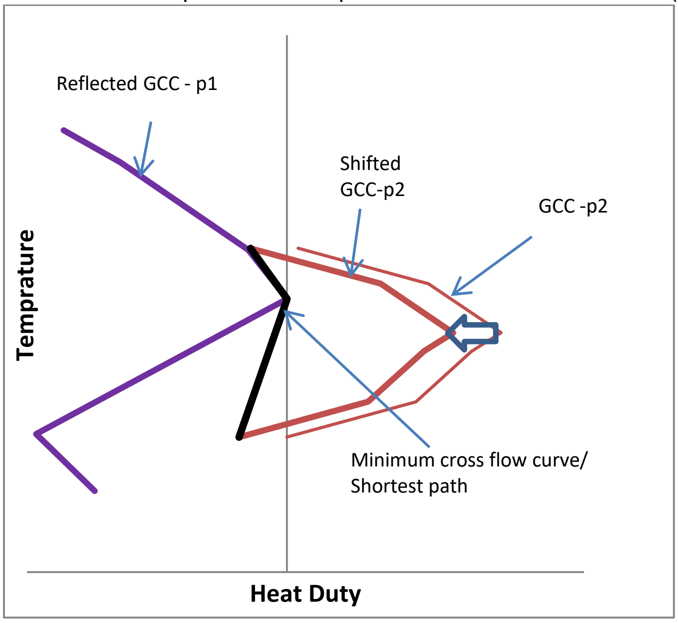

Figure 3: Determination of minimum cross-flow between two GCCs

Next, considering the sources and demand at the highest pressure level, Grand Composite Curve (GCC) is generated using PTA or MPTA. Considering all other sources and demands, another GCC is generated, and minimum cross-flow between these two GCCs is determined using the methodology developed by (Bade and Bandyopadhyay, 2014). Figure 3 shows the graphical method to determine minimum crossflow. The minimum compression work between these two SNs can be calculated using Eq(2). Let the minimum compression work between these two SNs be denoted as $WP_{\mathrm{H-2/H-1}}$. Let us consider all sources and demands up to p_{H-1} to be a single SN (SNp_{H-1}). Remaining sources and demands at pressure level p_H are considered as other SN (SN-p_H). The minimum inter-plant cross-flow between these two SNs can be calculated using the methodology proposed by Sahu and Bandyopadhyay (2012) and hence, the minimum compression work between these two SNs can also be calculated using Eq(2). Let the minimum compression work between these two SNs be denoted as $WP_{\mathrm{H-2/H-1}}$. Flows from p_H to p_{H-1} may be considered as sources at p_{H-1} and flows from p_{H-1} to p_H may be considered as demands at p_{H-1}. Let us consider all sources and demands up to p_{H-2} to be a single SN (SNp_{H-2}). Now sources and demands at pressure level p_{H-1} along with the additional sources and demands, due to inter-plant flow transfer between p_H to p_{H-1}, are considered as other SN (SNm-p_{H-1}). As per Eq(2), the minimum inter-plant flows between these two HANs and the minimum compression work between these two pressure levels ($WP_{\mathrm{H-2/H-1}}$) can be determined along with additional sources and demands at p_{H-2}. This process can be continued till the last two pressure levels are reached. Total compression work required can be expressed as Eq(3).

$$W = WP_{1/2} + WP_{2/3} + \cdots \quad WP_{H-2/H-1} + WP_{H-1/H} \tag{3}$$

Where *W* is total work and *WP* denotes work for subproblem.

4. Illustrative example

The proposed methodology is illustrated using an example consisting of sources and demands at two different pressure levels. The results include hot and cold utilities supplied in the overall HSN. The data set for the process streams for the illustration is shown in Table 1. The specific heat of fluid is assumed to be 1kJ/Sm^3. The work index for pressure 9,620 kPa and 8,850 kPa are calculated to be 461.35 kJ/Sm^3 and 452.9 kJ/Sm^3 for the isothermal process.

Table 1: Dataset for an illustrative example

Stream	Temp. (K)	Flow (Sm³/s)	Pressure (kPa)	Stream	Temp. (K)	Flow (Sm³/s)	Pressure (kPa)
Sources				Demands			
S11	511	15.248	9,620	D11	488	9.144	9,620
S12	444	2	9,620	D12	456	12.66	9,620
S13	388	15.104	9,620	D13	411	10.548	9,620
S21	567	1.15	8,850	D21	588	7.296	8,850
S22	510	3.073	8,850	D22	390	11.86	8,850
S23	478	10.548	8,850				
S24	353	13	8,850				

4.1 Segregation of sources and demands

The sources and demands are segregated according to their pressure levels, which gives two pressure levels in this case. It can be observed that there are three sources (S11, S12, and S13) and three demands (D11, D12, and D13) at the pressure level of 9,620 kPa. Similarly, there are two sources (S21 and S22) and two demands (S21 and S22) at the other pressure level. Using the PTA, the hot utility requirement is calculated for both pressure levels, which come out to be 30.38 kW for the higher pressure level (9,620 kPa) with the Pinch Point at 388 K, and similarly, 601.8 kW hot utility with Pinch at 478 K for the lower pressure level (8,850 kPa).

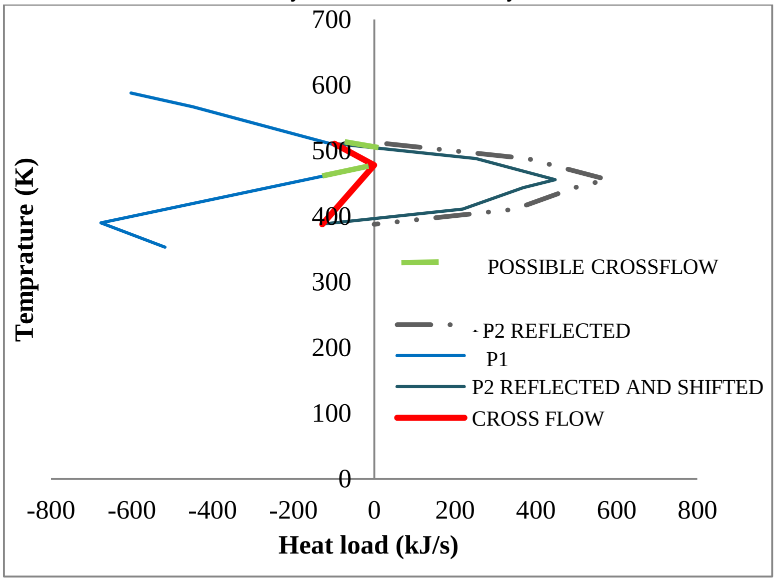

Figure 2: Determination of cross-flow for an illustrative example

4.2 Plotting GCCs and determination of shortest path

Plotting GCC for both of the pressure levels and using PTA. To integrate the two pressure levels, one GCC is reflected about the temperature axis, and the other is shifted to obtain a Site Pinch (Figure 4). The shortest path is plotted between the two GCC (Bade and Bandyopadhyay, 2014) to determine total inter-pressure level cross-flows. The values obtained for the cross-flows are calculated from the slope of the piecewise linear curve, which comes out to be 2.97 Sm^3/s and 1.43 Sm^3/s.

4.3 Compression work calculation

Compression work is required for transfer from low to high pressure, i.e. for 1.43 Sm^3. The compression power calculated from Eq(2) to be 12.08 kW. One other way to transfer fluid between the two SNs is shown as green color lines in Figure 4. The compression power is calculated to be 64.8 kW. This demonstrates around 80 % reduction potential.

5. Conclusions

Steam system is an essential part of an industrial chemical plant. In this paper, a methodology is developed to minimize compression work in steam networks which accounts for pressures of the available steam streams, flow limitations of available streams and their temperature. The methodology initially breaks multiple pressure systems into various sub-problems and solving each set of two pressure level sub-problem at a time. The overall cross flows between all the pressure levels eventually determine the compression work required. The cross-flow is calculated via a graphical methodology of the shortest path between the GCC and reflected GCC of two networks in each sub-problem. The methodology is demonstrated via an example where a reduction potential of around 80 % is estimated. Current work assumes compression work to be carried out in isothermal conditions. Future works are directed towards incorporating other thermal conditions such as adiabatic for compression work.

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