

Safety Issues Consideration for Direct and Indirect Heat Transfer on Total Sites

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Total Site Heat Integration (TSHI) is a widely used methodology. When implementing the TSHI method safety issues are important to account for and need to be paid attention throughout the process design. Most safety evaluation tools focus mainly on the safety of the reactor and separator process modules. Energy targeting and safety issues should be considered jointly. The suggested considerations focus on the safety issues of pipelines, heat exchangers and the streams that exchange heat at TS level. These issues affect the heat recovery networks and utility targets on a site and influence energy consumption. The direct and indirect HI scenarios are analysed using the assessment tool. The safety analysis identifies the critical equipment and streams requiring increased attention for and can reveal the potential risks of heat loss. The safety assessment result confirms that the indirect HI scenario bears less risk and less unexpected heat loss compared with direct HI scenario.

1. Introduction

Total Site Heat Integration (TSHI) has been established as an extension of Pinch Technology, well implemented in industry (Klemeš et al., 2013). Introduced by Dhole and Linnhoff (1993), the methodology has been gradually extended and developed. Hu and Ahmad (1994) developed a graphically based procedure using the utility system. Klemeš et al. (1997) added targeting of power co-generation. Perry et al. (2008) enhanced TSHI by integrating waste and renewable energy to reduce the carbon footprint. Matsuda et al. (2009) applied TSHI to a large industrial area in Japan, identifying large energy saving potential. Klemeš and Varbanov (2010) summarized a 20 steps guideline to achieve a credible solution on TSHI, and presented data extraction rules. Chew et al. (2013) investigated the main issues that can influence the implementation of TSHI on the industrial sites. Several key issues have been identified as being of vital importance for the industries: design, operation, reliability, regulatory policy and economics. Chew et al. (2015) also proposed to extend the TSHI methodology by considering the pressure drop factor during the minimum energy requirement targeting stage. Process safety is defined by AIChE as a blend of engineering and management skills focused on preventing catastrophic accidents, particularly explosions, fires, and toxic releases, associated with the use of chemicals and petroleum products (CCPS-AIChE, 2015). Safety issues are important when considering TS as they are more complex than individual processes (Chew et al., 2013). In TSHI there is risk of explosion, flammability and toxic releases. Under some operation conditions frozen streams can pose also possible risk in TSHI, since a frozen stream can reduce the flow or block a pipe completely. The risks have to be identified to be mitigated or prevented. They have been several available techniques within the safety fields of a process or industry processes: (1) The safety assessment for process R&D design, which can eliminate the risk during design increasing a module or plant inherently safety. Included Prototype Index for Inherent Safety - PIIS (Gupta and Edwards, 2003), inherent safer design – ISD (Shariff et al., 2013), and extended ISD approaches (Shariff et al., 2013) and (2) Risk identification where hazards in a plant are systematically identified, to eliminate the risks by design and operating procedure. Included PHA - Preliminary Hazard Analysis (PHA) (Ericson, 2005), HAZOP - Hazard and Operability analysis (Bahr, 2014).

To substitute materials, change process technologies, moderate the operation conditions are some of the common options to improve the safety level of the processes. Current risk identification and safety assessment techniques are commonly focused on the reactor and separator modules of a process, which usually are not substantially influenced by TSHI design. Such traditional considerations also do not provide the detailed descriptions of the safety criteria on Heat Exchange Network.

The following key points should be considered in safety issue assessment for the TSHI:

- i) Utility. Reduction of utility use is the main goal for TSHI. Utility demand is a major constraint on safety issue assessment. The heat load, temperature, and pressure of the utility are also related to safety concerns in TSHI design.
- ii) Equipment items and infrastructure. Heat exchangers and pipes are critical site hardware necessary to monitor and maintain for preventing catastrophic events. The number of heat exchangers and their pipe connections also affect the TSHI safety issues.
- iii) Distance. The distance of transporting a stream in a pipe network needs to be considered (Wang et al., 2013). All risks normally arising in heat and mass transfers are amplified with the distance as a result of the increased chance of failure. This is tightly related to the issue of dangerous materials (next).
- iv) Dangerous materials. If flammable, explosive and toxic materials are processed – including heat exchange or transportation, their integration tends to increase the risk of unwanted or catastrophic events, such as explosion or contamination.
- v) Heat exchange mode. Dealing with HI among plants at long distance from each other or with dangerous streams, indirect HI using utilities: steam or water, substitutes direct HI and can reduce the risk of failure. Based on the presented points, a safety issues assessment tool for TS is proposed, focusing on the streams in of process HENs and the utility system, the pipes and heat exchangers integrating the heating and cooling. The objective is to provide a preliminary safety evaluation and to improve unambiguous risk identification and safety assessment of TS.

2. Proposed safety assessment method for TSHI

Each TS is usually served by a central utility system, which links the processes – an example is shown in Figure 1. An individual process receives heat and power from the utility system. The essential elements of the TSHI infrastructure are in the safety focus: pipes, heat exchangers, pumps, compressors.

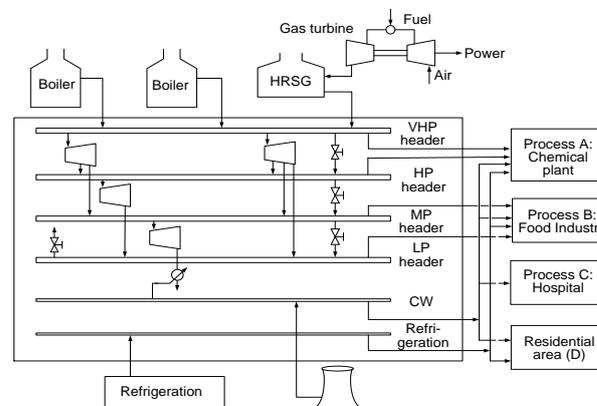


Figure 1: The configure of TS (after Perry et al., 2008)

2.1 The assessment scope and simplifying assumptions

There are several assumptions employed in this safety assessment:

- 1) Pipes connect unit operations – reactors, separators, heaters, coolers, recovery heat exchangers. The connections are within and among processes.
- 2) The valves, flanges and separators, connected to a pipe are treated as the same as pieces of pipe and they are not considered in the current study.
- 3) Water quality, humidity, equipment breakdown time, human factors have not been considered yet.

The structure for the safety evaluation is shown in Figure 2. Pipes implement the connections on a TS, forming the integrated network. Pipe network safety is the primary concern for TS safety. The exchangers for the inter-process heat recovery, utility generation systems (boiler house, HRSG, cooling system, refrigeration) and the auxiliary equipment (pumps and compressors) are connected by the pipe network.

The safety issues arising in them can be propagated via the network and affect the TS. In this study the utility generation systems are set aside for simplicity, but should be evaluated in the future.

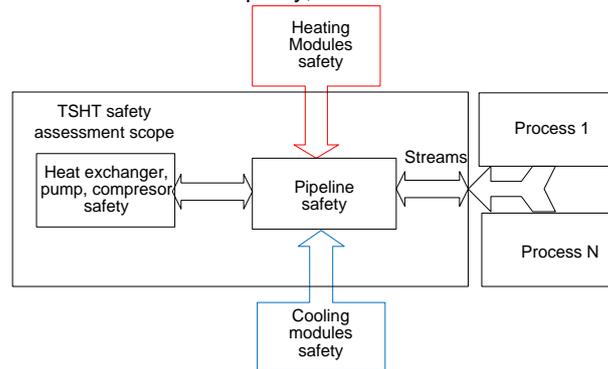


Figure 2: Safety evaluation structure for TSHI

2.2 Method

The proposed procedure for safety issue assessment for TSHI consists of five steps, designed to help engineers in decision making on site-level safety. The severity identification and assessment are TS-specific and should be extended/amended accordingly. Beside heating and cooling losses some other issues can occur – pressure loss, temperature increase etc, which are again specific to the particular sites.

Step 1: Data Extraction

The process streams and their properties, required utility streams and equipment information are identified. The data include temperatures and heat capacity flowrates (or flowrates and specific heat capacities). Network and equipment data include topology and connectivity, pipe lengths, heat exchanger number, required pump or compressor number in TSHI. Temperature range (T_i) of each steam level and pipe length (L_i), heat exchanger count (N_h), counts of compressors and pumps (N_p) are extracted. The latter is even more important for TS where the pipe lengths can be considerable.

Step 2: Severity identification

This step identifies the specific worst potential consequence of a failure on a TS. Based on process streams chemical nature, the TS required utility information, the specific severity of each stream – process or utility, and the infrastructure are identified, including flammability, explosiveness, toxicity, or frost potential. Failures related to process and utility streams in turn cause failures at TS level. The levels of preliminary severity of process streams S_p and of required utility streams S_u on a TS are identified. Every severity parameter is assigned a value in the range 0 to 10. Rank of 0 means no risk, while higher values mean higher risk and 10 denotes an ultimate (unacceptable) risk level. Generally, cooling water (CW) poses no risk reflected but parameter values of 0. Steam is normally neither toxic nor flammable, but steam explosions because of vessel rupture can take place and be dangerous, reflected by the specified values.

Step 3: Risk level assessment

Quantitative risk assessment for TS is performed using cause-effect analysis. Each additional unit of pipe distance, each heat exchanger, pump and compressor bring a certain probability of failure risk. Longer sequences of such elements increase the probability of overall system failure. Equipment failure probability is calculated following Eq(1-3), where P_p , P_h , P_{pc} are the failure probability for pipelines, heat exchangers, pumps and compressors, P_{pu} , P_{hu} , P_{pcu} are the unit length pipe rupture rate, heat exchanger failure probability, and pump/compressor failure probability.

$$P_p = P_{pu} \times L_i \quad (1)$$

$$P_h = P_{hu} \times N_h \quad (2)$$

$$P_{pc} = P_{pcu} \times N_p \quad (3)$$

High operating temperatures also increase the probability of equipment failure. The probability of temperature condition P_T is set following this. The risk level is a combination of probability (P) and severity (S) – Eq(4). Based on preliminary severity list and the failure probability list, the risk levels of a stream (R_i) and of a TS (R_{TS}) are calculated using Eq(5-6), where i is the stream in TS, n is the total streams number.

$$\text{Risk Level} = \text{Probability}(P) \times \text{Severity}(S) \quad (4)$$

$$R_i = S_{p,i} \times (P_{p,i} + P_{h,i} + P_{pc,i}) + S_{p,i} \times P_T \quad (5)$$

$$R_{TS} = \sum R_i \quad (i=1 \text{ to } n) \quad (6)$$

Step 4: Unexpected heat loss level assessment

Unexpected heating source or cooling source loss also can cause accidents. The failures of the discussed system elements (pipes, heat exchangers, pumps) may cause unexpected heat loss in critical TS processes. The heat loss level is evaluated in this step, which is calculated on the equipment failure rate, as shown in Eq(7). The heat loss level of a heat exchange path (HL_j) and the total heat loss level (HL_{TS}) on a TS are calculated following Eq(8-9), where H_j is heat exchange load in heat exchanger “j”, m is the total heat exchanger number.

$$\text{Heat loss level} = \text{Probability (P)} \times \text{Heat load (H)} \quad (7)$$

$$HL_j = (P_{p,j} + P_{h,j} + P_{pc,j}) \times H_j \quad (8)$$

$$HL_{TS} = \sum HL_j \quad (j=1 \text{ to } m) \quad (9)$$

Step 5: Priority decision based on safety assessment results

The comparisons of the various potential scenarios are conducted after identifying the levels of accident risk and unexpected heat loss. The priority decision is obtained based on these two aspects.

3. Case study

To demonstrate of the proposed safety assessment tool, a simple TS example is used. The TS comprises an ammonia and a rubber plants. The distance between them is 2 km.

Step 1: Data extraction

Table 1 shows the extracted process stream data for heating and cooling demands. The detailed data extraction procedure are in Klemeš (2010). To demonstrate the proposed safety assessment tool, both direct and indirect integration have been analysed - Figure 4. The indirect HI uses utility steams to transfer heat between plants. The water used as cooling utility is outside the current safety assessment scope.

Table 1: Process stream data

Stream	Supply temperature (°C)	Target temperature (°C)	CP(kW/°C)	Duty (kW)
Ammonia plant				
Hot 1	239	111	17	2,176
Hot 2	295	56	13	3,107
Rubber plant				
Cold 1	28	195	11	1,837
Cold 2	56	172	13	1,508
Cold 3	83	195	13	1,456

Step 2: Severity identification

No stream has temperatures under 0 °C, which excludes frost risk. The remaining risks to analyse are those associated with flammability, explosiveness, and toxicity from chemical leakage. The preliminary risk parameters (severity) of the process and utility streams are listed in Table 2. Stream 1 has a rank of 7, which may indicate high content of a dangerous component such as H₂.

Table 2: Preliminary severity list

Severity parameters	Hot 1	Hot 2	Cold 1	Cold 2	Cold 3	CW	LP	MP
Flammability	7	2	4	5	4	0	0	0
Explosiveness	7	3	5	4	5	0	2	3
Toxicity	3	2	3	2	2	0	0	0

Step 3: Risk level assessment

Table 3 shows the failure probability, including infrastructure and temperature range failure probability. Based on the preliminary severity parameters and failure probabilities, the overall risk level of the direct and indirect HI scenarios can be assessed. Tables 4 and 5 show the safety assessment results based on the model in Eq(5-6). FR, ER, TR are the flammability explosiveness and toxicity risks. Each risk level is calculated at different equipment operation step and temperature range. The total risk level is the sum over the evaluated paths. In the direct scenario, Stream 1 has the highest risk, and the transferring pipe has the highest risk compared with other pipeline. In the indirect scenario, Streams 4 and 5 have the highest risk rate, which should consider to grant of heat exchange operation.

Step 4: Unexpected heat loss level assessment

Based on Eq(8-9), unexpected heating or cooling source loss results for both scenarios are shown in Tables 6 and 7. Higher value of unexpected heat loss, would make necessary increased attention to improve backup utility reliability. The analysis gives the details on which utility type backup is critical for improving the safety.

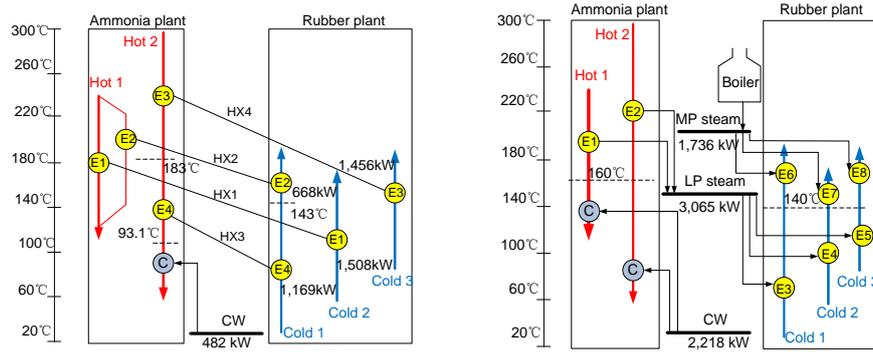


Figure 4: Direct and Indirect TSHI design scenarios

Table 3: Failure probability specifications

Item	Operation step			Temperature range (°C)			
	Unit pipe	HE	Pump/Compressor	0 - 50	50 - 100	100 - 200	200 - 300
Probability setting	0.05	0.1	0.05	0	0.05	0.1	0.2

Table 4: Risk level assessment of Direct Scenario

Item	Hot 1			Hot 2			Cold 1			Cold 2			Cold 3		
	FR	ER	TR	FR	ER	TR	FR	ER	TR	FR	ER	TR	FR	ER	TR
Heat exchange	1.4	1.4	0.6	0.2	0.3	0.2	0.4	0.5	0.3	1	0.8	0.6	0.8	1	0.4
Pipeline	0.7	0.7	0.3	0.2	0.3	0.2	0.4	0.5	0.3	0.5	0.4	0.2	0.4	0.5	0.2
Pump	0.7	0.7	0.3	0.2	0.3	0.2	0.4	0.5	0.3	0.5	0.4	0.2	0.4	0.5	0.2
0 - 50 °C	0		0	0	0	0	0	0	0	0	0	0	0	0	0
50 - 100 °C	0.35	0.35	0.15	0	0	0	0	0	0	0	0	0	0.2	0.25	0.1
100 - 200 °C	0.7	0.7	0.3	0.2	0.3	0.2	0.4	0.5	0.3	0.5	0.4	0.3	0.4	0.5	0.2
200 - 300 °C	0	0	0	0	0	0	0	0	0	0	0	0	0.8	1	0.4
Total risk level	3.85	3.85	1.65	0.8	1.2	0.8	1.6	2	1.2	2.5	2	1.3	3	3.75	1.5

Table 5: Risk level assessment of Indirect Scenario

Item	Hot 1			Hot 2			Cold 1			Cold 2			Cold 3			LP	MP
	FR	ER	TR	FR	ER	TR	FR	ER	TR	FR	ER	TR	FR	ER	TR		
Heat exchange	1.4	1.4	0.6	0.4	0.6	0.4	0.8	1	0.03	1	0.8	0.6	0.8	1	0.4	1	0.9
Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.45
Compressor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.23
0 - 50 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50 - 100 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100 - 200 °C	0.7	0.7	0.3	0.2	0.3	0.2	0.4	0.5	0.3	0.5	0.4	0.3	0.4	0.5	0.7	0.2	0.3
200 - 300 °C	0	0	0	0.4	0.6	0.4	0	0	0	1	0.8	0.6	0.8	1	0	0	0
Total risk level	2.1	2.1	0.9	1	1.5	1	1.2	1.5	0.9	2.5	2	1.5	2	2.5	2.1	1.5	1.88

Step 5: Priority decision

Table 8 shows safety assessment results of these two scenarios, including risk level and unexpected heat loss level. The results show that the indirect HI scenario has both less risk and unexpected heat loss compared with the direct integration scenario.

Table 6: Unexpected heat loss based safety issues consideration of Indirect Scenario

Item	HX1	HX2	HX3	HX4
Heat exchange count	1	1	1	1
Pipeline length (km)	4	4	4	4
Compressor count	1	1	1	1
Heat loss probability	0.35	0.35	0.35	0.35
Heat recovery load(kW)	1,508	668	1,169	1,456
Unexpected heat loss level (kW)	527.8	233.8	409.2	509.6

Table 7: Unexpected heat loss based safety issues consideration of Direct Scenario

Item	E1	E2	E3	E4	E5	E6	E7	E8	LP	MP
Heat exchange count	1	1	1	1	1	1	1	1	0	0
Pipeline length (km)	0	0	0	0	0	0	0	0	2	0
Compressor count	0	0	0	0	0	0	0	0	1	1
Heat loss probability	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.05	0.15
Heat recovery load (kW)	1,343	1,755	1,232	1,092	741	605	416	715	3,098	1,736
Unexpected heat loss level (kW)	134.3	175.5	123.2	109.2	74.1	60.5	41.6	71.5	154.9	260.4

Table 8: Overall levels of risk (columns 2, 3, 4) and unexpected heat loss (columns 5, 6)

Scenario	Flammability	Explosiveness	Toxicity	Heating source (kW)	Cooling source (kW)
Direct	11.75	12.80	6.45	1,680.35	1,680.35
Indirect	8.80	12.98	5.30	725.1	594.9

4. Conclusions

The proposed safety assessment tool considers the risks on the streams in HEN and operation condition of the equipment including HEN and pipeline in TS. This assessment can identify the risk parameters and help to identify the preliminary design route in the HI. The quantification identifies the critical risk equipment and the streams. The direct and indirect HI scenarios are analysed. The critical streams can be identified at the risk level assessment step. The direct HI has higher levels of flammability and toxicity risks and unexpected heat loss, while the indirect HI has lower levels making it safer and more practical for TS. In the future the method should be extended considering the utility units as boilers and furnaces. The safety parameters are going to be considered with possible TSHI modifications (Chew et al., 2015) to provide a more comprehensive safety assessment for TS.

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