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Utility Exchanger Network Design for Non-Isothermal Utility Considering Process Control

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This paper investigates a preliminary control strategy based on bypass control loop of Utility Exchangers Network (UEN) for non-isothermal utilities in a Total Site Heat Integration (TSHI) system. Few details on the design and control of non-isothermal utility systems, e.g. hot water loops, that includes Total Site heat recovery are presented in the literature. Heat Exchanger Networks (HEN) can be considered as a combined Heat Recovery Network (HRN) and UEN for each individual processes within the Total Site. Control strategy presented in the current paper are based on the control of utility side in a process – utility heat exchanger match to control process stream target temperature and analyse Total Site (TS) utility system in a Process Integration point of view. Bypass control has been used in the research. A Hot Water loop as representative of a large industrial plant utility system is studied as a case study. The process stream segment target temperature to be achieved and process stream segment supply temperature and flow rate may vary up to ±15 %. The HW utility temperature in the loop is controlled by using indirect heat transfer from higher and lower level utility and by using HW loop bypass. A 24 h period has been considered for the study. Results show that the HW utility loop has a 2.4 MW heat deficit in time-average condition. By controlling the HW utility loop using the proposed heuristics, utility heating requirement may vary between 0.7 to 3.5 MW, which is supplied by the Low Pressure steam main.

1. Introduction

Heat Exchanger Networks (HEN) are widely used in process industries to increase Heat Recovery (HR) and reduce utility consumption by energy exchange, in term of heat energy, between cold and hot streams. HEN consisting Heat Recovery Network (HRN) and Utility Exchanger Network (UEN) is responsible for transferring majority of generated process heat within the plant (Tarighaleslami et al., 2017b). The inter-process heat transfer using UEN linked to a central utility system to provide required heat and power for processes within a plant is commonly referred to as Total Site Heat integration (TSHI), (Klemeš, 2013).

Implementation of TSHI for non-isothermal utility loops in practice is challenging to achieve heat recovery levels near Total Site targets, especially for non-continuous processes. Tarighaleslami et al. (2017a) developed a new Unified TSHI targeting method with emphasis on practical targets for non-isothermal utility loops. Utility temperature selection can also be optimised to achieve greater benefits (Tarighaleslami et al., 2017c). To support the new targeting method, Tarighaleslami et al. (2017b) compared UEN designs from the new and conventional TSHI methods. Although the new method showed an improved design and practical application, there has been the challenge of how to control non-isothermal utility loops where the target temperatures of both the process and utility flow should be achieved. The design of TSHI for non-isothermal utility loops considering bi-objective control has been identified as an area that requires additional research. The development of effective TS designs including process control are essential to promotion and realisation of TS heat recovery benefits in the industry.

Several papers have dealt with heat exchanger and HEN control strategies. The optimal operation and control of HEN depend on two factors, i) control structure selection, and ii) online optimisation algorithm determination. Glemmestad et al. (1996) showed that utility stream flow rate control, bypass control, and the split ratio control are the most common HEN control system structure. Economy evaluation and control performance are two common problems with bypass control. One of the common control strategies that satisfy demand on energy savings is

Model Predictive Control (MPC) which is based on the solution of an optimisation problem (Mikleš and Fikar, 2007). Aggelongiannaki et al. (2007) presented an online MPC configuration which is based on neural network connections. Vasičkaninová et al. (2011) used Neural Network Predictive Control (NNPC) to control a parallel flow shell and tube heat exchanger. They showed that by applying NNPC, significant energy savings could be achieved compared to the conventional PID control. Bakošová and Oravec (2014) proposed a robust Model Predictive Control (RMPC) for HEN. The RMPC presents an effective control algorithm for optimisation of the control performance considering process inlet and outlet constraints, and process uncertainties. Luo et al. (2013) presented an approach to perform HEN online optimisation, margin design, and control using bypass concept. The same research group, recently, extended the work to coordination of bypass control and economic optimisation for HEN with stream splits (Sun et al., 2017). They showed that applying the new method can increase double control purpose and optimal economic while it may scarify small amounts of control performance.

Fluctuation in temperature and/or flow rate of process stream(s) is a typical operating issue in the process industries. In a HEN for an individual process, when flow rate and/or supply temperature of process stream change, HEN performance can still satisfy the process requirements using cold and hot utility, while the extra heat load on the utility system may have an impact on the other processes. When the target temperature of process stream (or process stream segment) is a constraint to keep the product specification in range or heat recovery targets balanced, utility plays a significant role. This means TS heat recovery and utility targets will be affected by such changes and non-isothermal utility control may be in advanced.

Implementing process control strategies on the utility side of the process–utility heat exchanger match in UEN can provide better insight of heat recovery and utility targets in TSHI systems. Although the HEN control is well developed from the control point of view, minimal details in HEN and UEN control is presented in the literature based on TSHI concept for non-isothermal utility loops. As one of the few, Walmsley et al. (2014) performed area targeting and storage temperature selection for process–utility matches in a Heat Recovery loop. However, more research is needed to address the UEN control and how it affects the TS targets.

This paper aims to present a design based on a bypass control strategy for UEN with non-isothermal utility. The scope of the research considers changes in HR and utility targets in a TSHI system when process streams' (or segments') target temperature are a constraint. The control strategy for non-isothermal utility system assumes process stream (segment) target temperatures could be hard or soft temperatures. TSHI targets are calculated using UTSI Excel™ software tool (Tarighaleslami et al., 2017a). An Excel™ spreadsheet has been developed to calculate intermediate temperatures, utility flow rates, bypass flow rates, and heat demand/surplus in designed UEN.

2. Control strategy of non-isothermal utility loops

Process target temperatures in different processes can be divided into two types; i) soft temperature, and ii) hard temperature. Soft target temperatures can be within in a range above/below a certain temperature; however, it is not allowed to pass beyond below/above that temperature while hard temperatures must be strictly achieved. Stream variability in both temperature and flow rate affect both heat recovery targets and the performance of the HRN. Typically target temperatures (i.e. controlled temperatures) are achieved by varying the flow rate of utility streams going to the utility heat exchangers. However where non-isothermal utility loops are used control presents more of a challenge because i) the overall balance between the hot and cold sides need to be maintained, and ii) the heat transfer is actually in-direct process-to-process and therefore changes in the process stream conditions affect each other.

In a closed non-isothermal utility system (e.g. water loop or oil loop), fluctuations in temperature and/or flow rate of the process stream (or process stream segment) will affect the outlet temperature of the utility side of the utility-process exchanger, altering the temperature of the utility loop.

If there is only one heat exchanger on the utility branch, process target temperature can be controlled by controlling the flow rate of the utility. When there are more than one utility-process matches on a non-isothermal utility branch (heat exchangers in series), the outlet temperature of the first utility-process match is the inlet temperature of the next utility-process match. In the current paper, this temperature is called Middle Temperature (T_{Mid}). Changes in the Middle Temperature will affect the performance of the second exchanger. To operability and feasibility of the loop, T_{Mid} may need to be controlled to a hard temperature or within a range (i.e. soft temperature). One method to achieve this is to use a simple bypass control method (Young et al., 2006). Figure 1 presents a simple bypass design for the utility-process match on the utility side of a non-isothermal utility system to control the hard process temperature.

To design a control strategy for such systems, Degree of Freedom (DOF) should be considered as:

Number of DOF = Number of Candidates for manipulated Variables – Number of Controlled Variables – Number of Loops

Where for DOF < 0 there are not sufficient manipulated variables and it is not possible to keep all the target temperatures under control; for DOF = 0 the operation of the heat exchanger network is feasible, that is, process control can be achieved, and for DOF > 0 the operation of the heat exchanger network is feasible and some more sophisticated control structures can be implemented.

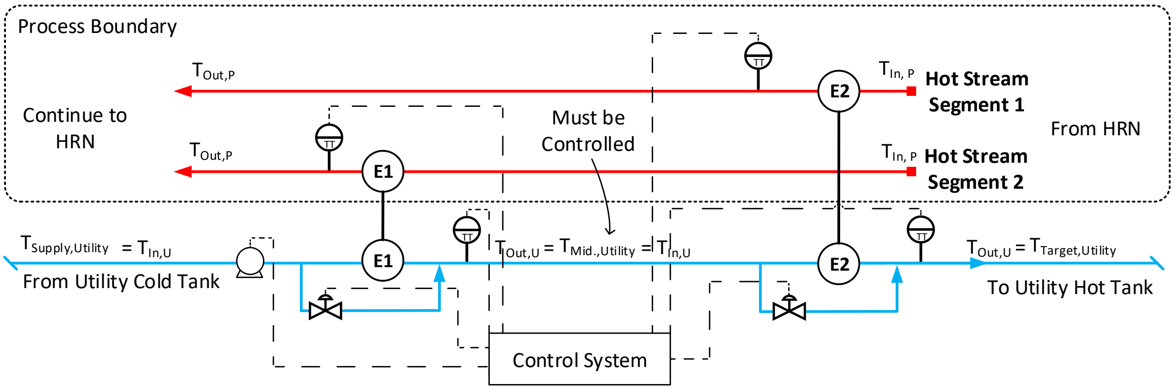

Figure 1: Schematic of a simple bypass design to control process stream target temperature by controlling non-isothermal utility target temperature in a utility loop.

Figure 2 presents a summary of different strategies to control process stream outlet temperature using non-isothermal utility loop considering hard process stream (segment) outlet temperatures where T_{Mid} of the utility must be achieved. Similar analysis can be applied for soft process (segment) temperature where the temperature could be violated in a range. It should be noted that all control elements are connected to the control system and the specific control strategy details will be addressed in future work.

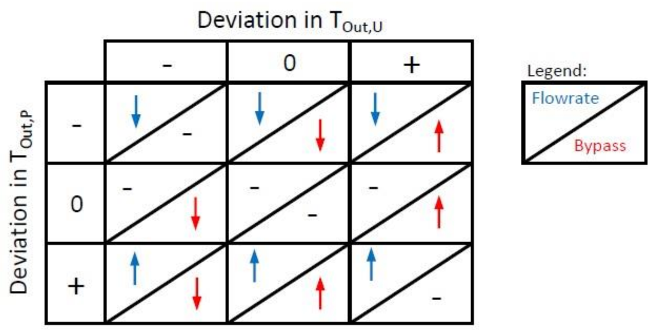

Figure 2: Control strategy matrix to control outlet temperature ($T_{Out,P}$) of process stream by controlling outlet temperature ($T_{out,U}$) in each side of the utility-process heat exchanger match.

3. Illustrative case study

To illustrate the merits of the proposed control strategy, Hot Water (HW) loop as a part of TSHI utility system in a large industrial plant is separated and presented individually as a case study. Seven different process stream segments presented in Table 1 are available in TS integration from 4 distinct processes are connected to both hot and cold side of the utility system (here HW loop).

Table 1: Stream data for existing processes and stream segments in the Total Site.

Process	Stream	Stream Type	T_s (°C)	T_t (°C)	CP (kW/°C)
Process A	Stream 1	Cold	3.0	15.0	59.83
	Stream 2	Cold	4.3	30.1	75.93
	Stream 3	Cold	40.0	47.0	74.71
Process B	Stream 4	Cold	1.9	20.0	186.08
Process C	Stream 5	Cold	8.3	47.0	91.50
Process D	Stream 6	Hot	84.1	69.2	404.97
	Stream 7	Hot	94.6	87.2	229.86

The temperature and flow rate of the loop is controlled by using two separate HW tanks at both hot and cold side of the loop as presented in Figure 3. Cold HW tank is controlled at 25 °C and hot HW tank is controlled at 57 °C. TS has been studied in its best practice and optimal utility temperatures have been selected. All heat exchangers have been considered as double pipe heat exchanger and Effectiveness – NTU method has been applied for heat exchanger calculations (Çengel, 2007).

4. Results and discussion

The presented method can be used for all available TSHI methods. In this case study, UEN has been strictly designed based on UTST method UEN synthesis and design procedure, Figure 3. In the design based on UTST method, the heat exchangers that represent utility-process match can be in series on a utility match if they are only from the same process (Tarighaleslami et al., 2017a).

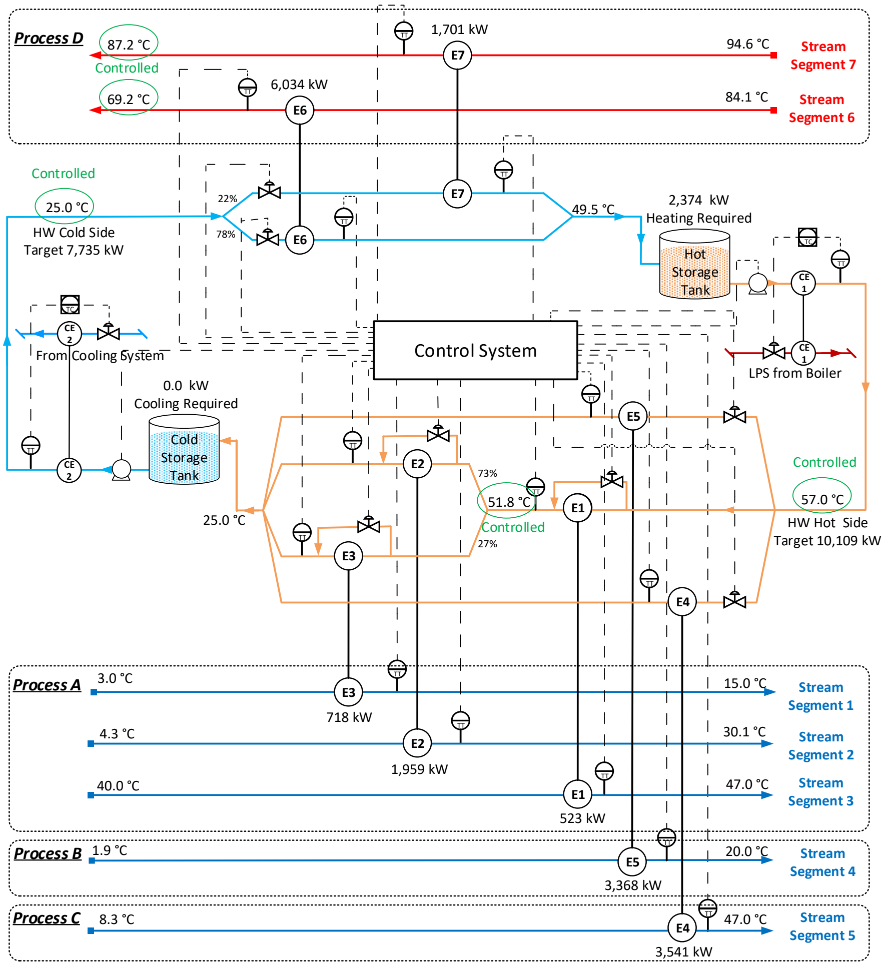

Figure 3: HW utility loop design for the case study, including both hot and cold side of the HW loop, control systems, HW tanks, and external heating/cooling system.

As it can be seen from Figure 3 on the cold side of the HW loop there are two utility-process matches in parallel that both are from Process D, i.e. exchangers E6 and E7. On the hot side of the loop, there are three utility branches in parallel that each branch is matched with a process, i.e. processes A, B, and C while in the middle branch exchanger E1 is in series with each exchangers E2 and E3 where E2 and E3 are in parallel. Each exchanger has a control loop that is connected to the Control Box. Only one Middle Temperatures is recognised in this design, which is after E1 that is calculated to be 51.8 °C. DOF of this point is zero as there is three manipulated variables and three control variables around the point. The mixture of utility in the hot side of the HW loop is sent to HW cold tank, and the cold side of the HW loop is sent to the hot thank to control the mass and energy balance of the loop. In this paper, the fluctuation of the process stream segments' supply temperature and flow rate of each process stream segments have been considered up to 15 %. Results have been recorded for 24 equal time intervals a day (i.e. every hour) which in each time interval supply temperature and flow rate of process streams vary randomly in the range of ±15 %.

As it is demonstrated in Figure 3, HW cold side target is 7.73 MW and HW hot side target is 10.11 MW. It means the heat sink is greater than heat source, i.e. there is 2.4 MW heat deficit in the loop, which must be provided from other utilities in the TS. This required heat energy can be supplied by the higher level utility, e.g. Low Pressure Steam (LPS), and be transferred to the HW loop a heat exchanger match between the utility loop after HW hot tank and a steam stream. Similarly, on the cold side of the HW loop, the cold storage tank is designed to be linked to a cold utility system. Since there is always a potential flow at the different time of the operating period that heat source may exceed heat sinks.
Figure 4 shows the fluctuation of HW loop heat requirement in 24 deferent time intervals which are not quantitatively constant. Therefore, the higher temperature utility source, targets may vary between 0.7 MW to 3.5 MW compared to 2.4 MW time-average targets. On the other hand, if the TS system was generating large quantity of low grade heat, e.g. Kraft Pulp Mill plant, the source duty will be greater than sink duty which surplus heat in the cold utility tank could be rejected to a lower grade cold utility, e.g. cooling tower system, or be upgraded to higher level energy using thermodynamic techniques, e.g. heat pumps.

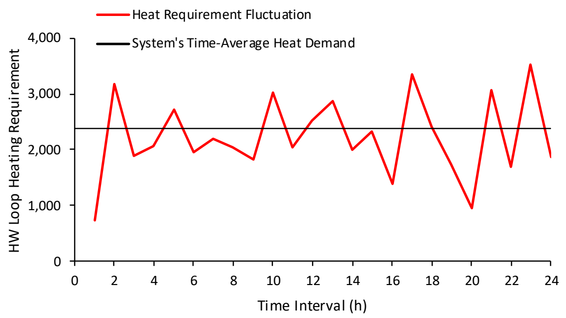

Figure 4: Heat requirement of the HW loop in Total Site

Deviation from target temperature of HW utility at the end of each side of the loop is shown in Figure 5.

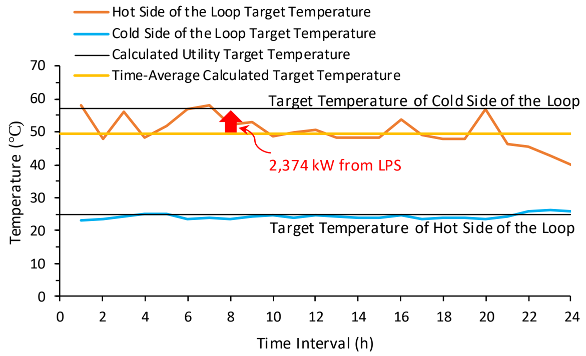

Figure 5: HW utility target temperature deviation from the calculated target temperature.

As it is shown in Figure 5, HW loop hot and cold utility target temperatures are predicted to be 57 °C and 25 °C. For 24 different time intervals, there is no significant deviation from the predicted 25 °C on the hot side of the HW loop, while on the cold side of the loop utility does not achieve the 57 °C predicted target temperature. For time-average condition, the target temperature of the cold side of HW loop has been calculated to achieve 49.5 °C, Figure 3, which means there is 2.4 MW heat deficit in the HW utility loop that is supplied by LPS to the utility after the hot storage tank. This heat will lift the temperature of the hot side of the HW loop to achieve its target temperature at 57°C. Figure 5 shows in the dynamic situation, there is a fluctuation of the target temperature of the cold side of the loop around 49.5 °C that is due to heat deficit of the utility system.

5. Conclusions

A control strategy proposed to control process stream target temperature by controlling non-isothermal utility temperature in a Utility Exchanger Network. Based on the proposed control strategy the key temperature that should be considered is the utility temperature between two exchangers in series configuration. The control strategy applied to a Hot Water loop of a large industrial case study as a part of the Total Site utility system. Results show that up to 15 % fluctuation of temperature and flow rate of process stream segments may need up to two times higher heating demand of the loop which must be transferred to the utility loop from higher utility level in the Total Site utility system. It is essential to consider such fluctuations in the utility targeting of a Total Site Heat Integration system in case of heat recovery and cost estimation. The controllability and reliability of the Utility Heat Exchanger Network of Total Site Heat Integration systems will be presented in future studies.

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