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Rational Energy Recovery from the Condensed Steam as a Component of HEN Retrofit

Mariusz Markowski*, Krzysztof Urbaniec, Witold Suchecki

Warsaw University of Technology, Faculty of Civil Engineering, Mechanics and Petrochemistry, Lukasiewicza 17, 09-400 Plock, Poland
Mariusz.Markowski@pw.edu.pl

The paper is concerned with retrofitting a heat exchanger network (HEN) using a Pinch-based method (PT) and simultaneously minimizing energy losses caused by the expansion of steam condensate. The disadvantages of conventional multi-stage condensate expansion are identified, and the application of condensate subcooling is proposed. The case study considers a Methyl-Tert-Butyl Ether (MTBE) process plant where the consumption of hot utility (steam) in the existing HEN is 4,386 kW. Using the PT method to determine the maximum possible heat recovery, it is found that heat recovery from hot process streams can be increased, leading to an increase by 510 kW in the combined heat recovery from hot process streams and condensate. Additionally, electricity production in the CHP plant (coupled with the MTBE plant by steam and condensate streams) can increase by 120 kW. HEN reconfiguration is proposed considering local constraints like the existing heat transfer areas and locations of heat-transfer equipment units. The proposal leads to a new HEN structure and a new arrangement of the equipment units in the steam and condensate system.

1. Introduction

In the process industries, heat exchanger networks (HENs) are essential for energy-saving because they enable recovering heat from hot process streams to others leading to a reduction in energy demand. The practice has shown that HEN re-design and retrofitting can significantly meet energy efficiency targets for industrial plants. Energy efficiency can be improved through better HEN design using mathematical programming (Grossmann and Sargent, 1978), Pinch Technology (Linnhoff and Hindmarsh, 1983), and combined methods (Briones and Kokossis, 1996). In the 1990-ties, HEN retrofitting methodologies based on the mentioned approaches were developed in the US (e.g., Yee and Grossmann, 1991) and in the UK (e.g., Asante and Zhu, 1997). This research area was further explored at the beginning of the 21st century, as summarized in the monograph edited by Klemeš (2013) and review paper by Sreepathi and Rangaiah (2014).

Recent years have seen further progress in HEN retrofitting methodologies focused on the needs of crude oil distillation systems (Ochoa-Estopier et al., 2015) and in industrial applications such as retrofitting an Egyptian refinery (Kamel et al., 2017) and some more retrofit examples (Jiang et al. 2018). New methods and mathematical tools are also available for maximizing productivity and minimizing operating costs in a broader class of industrial heat-integrated systems (Čuček et al., 2019). New ideas were recently presented on optimizing multi-period HENs (Langner et al., 2020) and the optimal selection of heat exchangers and material types (Wang et al., 2021). New examples of HEN retrofit projects in various industry branches include a system for crude oil extraction from bitumen resources (Rho et al., 2020) and an oleochemical plant (Trisha et al., 2021).

A problem frequently overlooked or regarded as a less important one in HEN retrofit studies is the rational energy recovery from the steam that has been delivered from the combined heat and power plant (CHP) to the HEN and condensed. In the present paper, the author’s view of the problem is outlined and illustrated by a case study.

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2. Crude oil heating in a refinery

In a standard solution of heat supply from CHP plant to crude-oil heating (Figure 1a), steam drawn from the turbine bleed passes temperature-controlled valve CV-1 and enters heat exchanger E-1 where the steam is condensed. The condensate (saturated water) flows through steam trap ST-1 and is subjected to throttling, that is, expansion at constant enthalpy. As a consequence of pressure drop, condensate temperature decreases from T1 to T2, and a part of the condensate stream is converted into secondary steam in a saturated state. From the point of view of the first law of thermodynamics, there is no energy loss as the enthalpy flow of generated steam is equal to the reduction in the enthalpy flow of saturated water. However, as condensate expansion is irreversible, the entropy is increased (Figure 1b), and from the point of view of the second law of thermodynamics, exergy loss is unavoidable. This loss affects the thermodynamic system comprising the CHP plant and process heating subsystem supplied with steam from the turbine bleed. Consequently, the turbo-set generates less power, and heat recovery in the HEN is reduced, leading to increased fuel consumption in steam boilers.

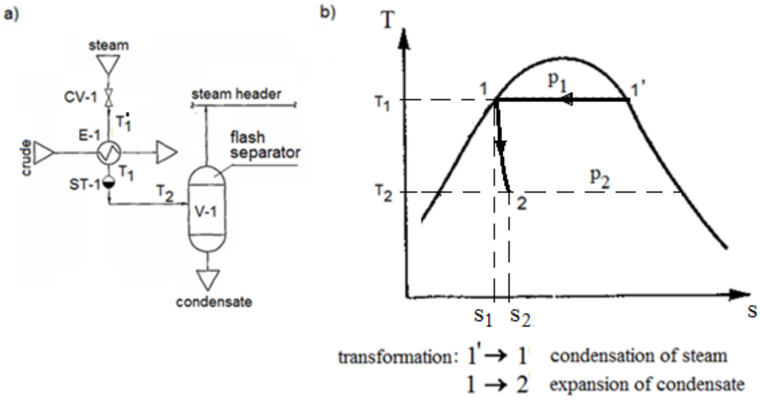

Figure 1: Heat supply from CHP plant to crude-oil heating: a) flow diagram; b) changes in the thermodynamic state of steam and its condensate in the T-s diagram

3. Condensate subcooling in a steam-heated heat exchanger

The exergy loss associated with the expansion of steam condensate can be reduced if the heat exchanger is operated to enable condensate subcooling. In the suitable flow diagram shown in Figure 2a, the control valve is installed in the condensate discharge line. Assuming pressure losses in the heat exchanger are negligible, the condensate at pressure p_1 is cooled down to temperature T_2' as illustrated in Figure 2b. The thermodynamic state 2' is that of subcooled water. If the condensate is then expanded at constant enthalpy to state 2 close to water saturation (pressure p_2, temperature T_2), no secondary steam is generated, and the exergy loss is reduced.

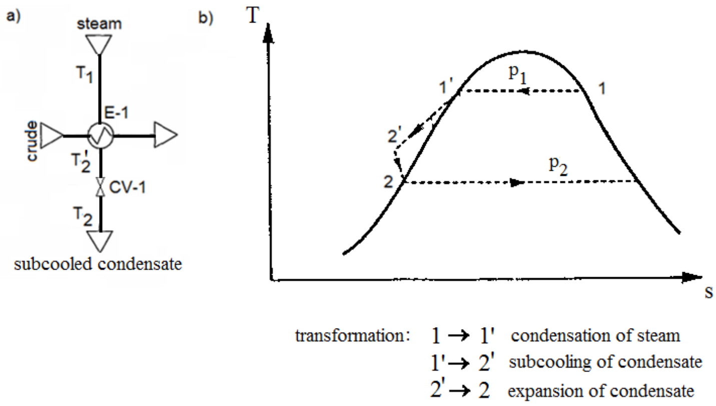

Figure 2: Crude oil heating with subcooling of steam condensate: a) flow diagram, b) changes in the thermodynamic state of steam and its condensate in the T-s diagram

4. HEN structure featuring condensate subcooling in the heaters

According to the principles of Pinch Technology, the reduction of heat-exchange-induced exergy losses can be achieved if the heat exchanger network is supplied with heat at a temperature level above the pinch point. In the case of condensate subcooling applied in the HEN, the final temperature of the condensate cannot be lower than pinch-point temperature T_{PH}, Figure 3a. If the condensate temperature is equal to T_{PH}, then the losses are minimized, and power generation in the CHP plant that supplies the heating steam is maximized.
Figures 3b and 3c illustrate the idea of developing the structure of a HEN in which condensate subcooling is applied in steam-heated heat exchangers denoted H*. Opportunities for installing such exchangers way are created by splitting one or more selected streams into a few substreams.

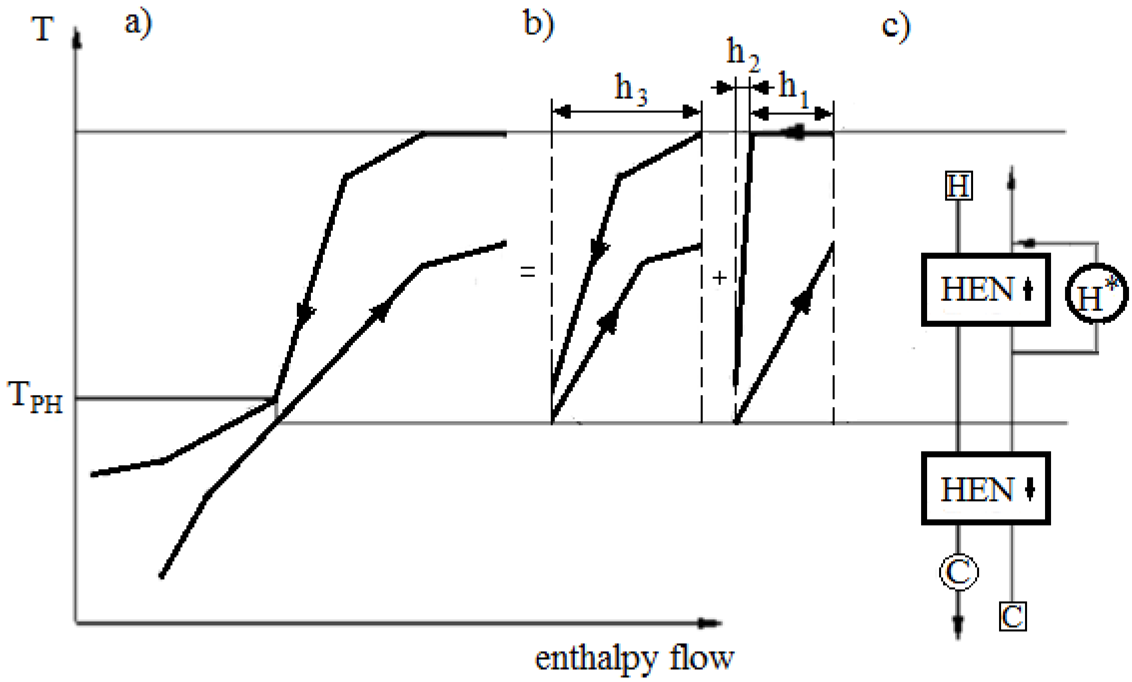

Figure 3: HEN retrofit concept to enable condensate subcooling in selected heaters denoted H: a) Balanced Composite Curves, b) temperature profiles of the heat exchange in heaters H* [heat duty h1 and h2], and network part HEN↑ [heat duty h3], c) simplified block scheme of the HEN including its parts operated above and below Pinch temperature [HEN↑ and HEN↓]; C – coolers*

5. Case study – HEN retrofit in an EMTB plant

The case study is concerned with the existing Methyl-Tert-Butyl Ether (MTBE) process plant, where the hot utility (steam) consumption in the existing HEN is 4,386 kW. The composite curves characterizing the energy content of all the process streams involved in MTBE production can be seen in Figure 4. The heat from the CHP plant is supplied to the MTBE unit using steam on two temperature levels: 158 °C and 200 °C. HEN retrofit includes optimizing the heat recovery scheme and introducing condensate subcooling, as discussed in Section 4 above. Based on information derived from the composite curves, the existing HEN was re-designed using Pinch Technology combined with the approach illustrated in Figure 2 above.
In the original HEN, the condensate obtained from heating steam is flashed in a set of flash vessels, generating vapor (secondary steam) that flows back to the steam mains (Figure 5a). Due to steam-condensate cooling applied in the retrofitted HEN (Figure 5b), one vessel is sufficient, and no generation of secondary steam occurs. Compared to condensate management in the original HEN, neither condensate pump nor vapor cooler is needed, and process control instrumentation is straightforward. The simplification of the condensate subsystem leads to reduced capital and operation costs.

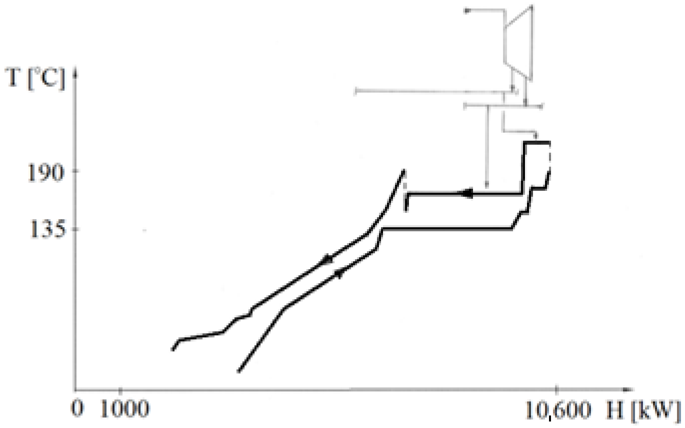

Figure 4: Balanced Composite Curves illustrating heat recovery with the subcooling of steam condensate, and symbolic representation of steam supplies from turbine extraction

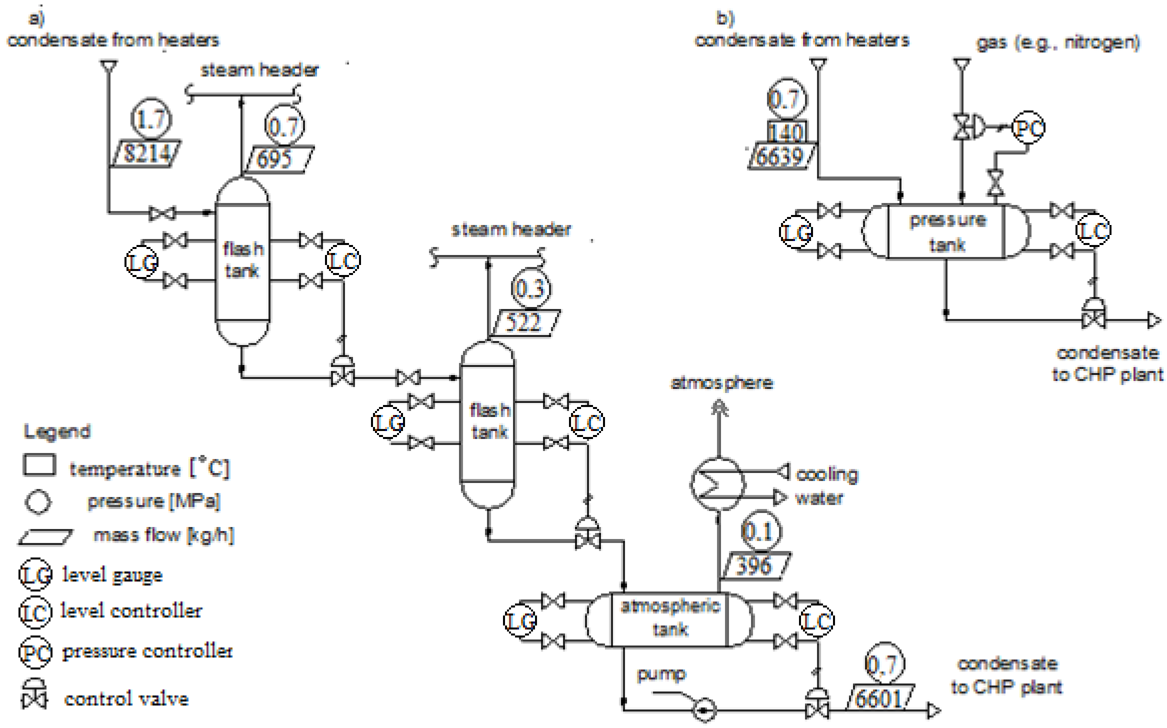

Figure 5: Scheme of condensate management in the MTBE plant: a) condensate flashing in the existing HEN arrangement, b) condensate tank connected to the retrofitted HEN

The retrofitted HEN is represented by the grid diagram shown in Figure 6. The changes made to the original set of process streams are following:
- process stream 11 has been split into three substreams to be heated using two existing heat exchangers (W-5 and H-6) and a new one (W-7),
- process stream 13 has been split into two substreams to be heated using two new heat exchangers (H-8 and H-9).

Two process streams numbered 10, and 12 (not involved in the heat recovery) represent evaporation processes within MTBE production, consuming heat supplied in steam from the CHP plant. Steam is also supplied to the existing heaters H-1, H-2, H-3, H-5, H-6, H-7, and new ones H-8 and H-9, where condensation of steam and subsequent subcooling of condensate occurs. (Note: in the existing HEN, heaters H-1 and H-2 are destined for periodic operation; therefore, their heating duties in the retrofitted HEN are set to zero). Heat recovery occurs by thermal interactions between hot streams (1 ÷ 6) and cold streams (7 ÷ 13) in the existing heat exchangers W-1 ÷ W-5 and new ones W-6 and W-7. The waste heat is discharged through the existing coolers C-1 ÷ C-6.

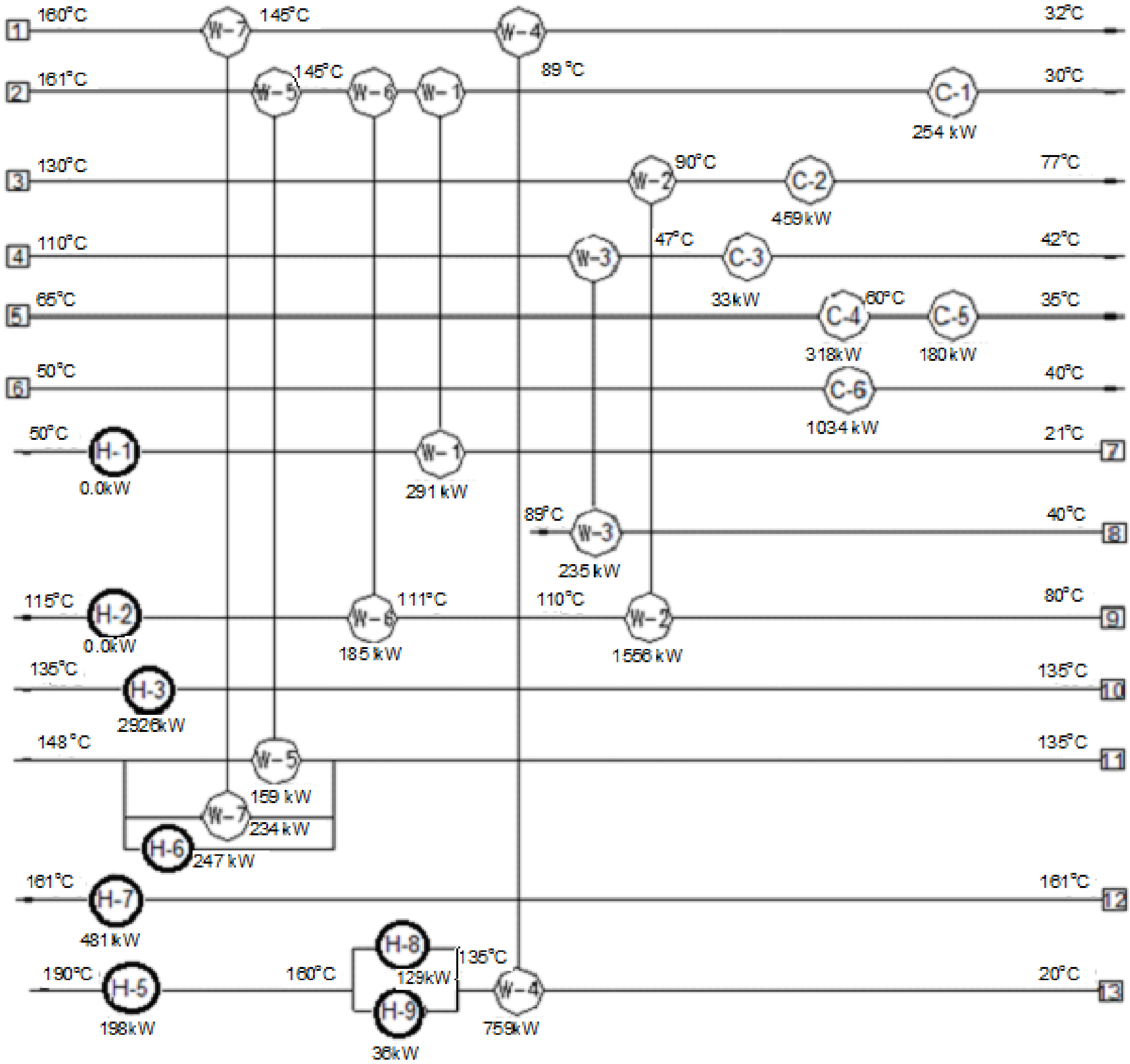

Figure 6: Grid diagram of the retrofitted HEN with the subcooling of steam condensate

Compared to the existing HEN, the heat recovery from hot process streams can be increased by 397 kW leading to an increase of 510 kW in the combined heat recovery from hot process streams and condensate. Additionally, electricity production in the CHP plant (coupled with the MTBE plant by steam and condensate streams) can increase by 120 kW.

Assuming the following emission factors of hazardous pollutants originated from combustion of fuel oil: CO_2: 3.2 kg/kg; NO_x: 0.002395 kg/kg; SO_2: 0.000814 kg/kg; dust: 0.00041 kg/kg; benzopyrene: 0.00001 kg/kg, the emissions of pollutants to the environment decrease by: CO_2: 2.1 Mkg/y; NO_x: 1553 kg/y; SO_2: 528 kg/y; dust: 266 kg/y; benzopyrene: 7 kg/y.

6. Conclusions

The authors proposed a modified approach to HEN retrofit, aiming at more effective energy recovery from steam condensate. The energy recovery is improved by condensate subcooling in selected steam-heated heat exchangers. This approach requires the control systems of the said exchangers to be reconfigured by moving the control valve from the steam side to the condensate side (see Figure 1 vs. Figure 2). At the same time, the condensate management system is simplified compared to standard solutions applied in the industry (see Figure 5a vs. Figure 5b).

The case study results indicate positive effects of the proposed approach to the HEN retrofit in the MTBE plant, where heat consumption in the existing HEN is 4,386 kW. HEN structure has been changed by splitting two selected process streams and installing three new heat exchangers. The increase in heat recovery relative to the existing HEN is 510 kW, and simultaneously, power generation in the CHP plant can increase by 120 kW.
The ecological contribution of HEN retrofit is reduction of hazardous pollutants by: 2.1 kt/y CO_2, 1,553 kg/y NO_x, 528 kg/y SO_2, 266 kg/y dust and 7 kg/y benzopyrene.
The authors are aware that in the presented article only the energy aspects are considered and in the future works on the proposed technology they also recommend to take into consideration the reliability and economic aspects.

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