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INDUSTRIAL HEAT UTILISATION THROUGH WATER MANAGEMENT

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ABSTRACT

The focus of this paper is on the dependence between water and energy in industry and the way these resources can be managed in an integrated and more sustainable manner. The fundamental methodology supporting the concept of simultaneous management of water and energy is the process systems approach guided by deep understanding of the simultaneous mass and heat transfer, considering phase and pressure changes. Special attention in this case is paid to the utilisation of the latent heat of water evaporation and condensation (allowing for water and heat recycling). The paper takes a new view to water solutions management especially when processes experience difficulties for direct heat recovery. The paper also highlights the link between water management, heat recovery, process efficiency improvement and capacity de-bottlenecking, which bring additional positive impact of proposed methodologies. The advantages of efficiency improvement, water saving and improved environmental impact of proposed solutions are analysed and demonstrated on an industrial case.

INTRODUCTION

The underlying concept of this paper is to take a guided approach to efficient water and energy use and conservation. The approach is based on fundamental techniques of integrated water and energy management utilising the strong thermodynamic link between water and energy interactions in industrial processes. The foundation of this concept is based on the following: Ahmetovi in [1] stressed that water and energy are the most extensively used commodities in process industries. In high-income countries with developed infrastructure and industries the trend is to use around 50-60% of national water supply for industrial purposes [2]. Statistical evidence indicates however, that in Europe as much as 60% of industrial water is lost by evaporation, while in Africa this percentage reaches 80% [3]. Wastage of such a vast amount of water by evaporation highlights the importance of the link between water and energy management. It also indicates the potential economic saving that such a synergy possesses. This point of view towards simultaneous management of water and energy resources extends the work of Savulescu et al., [4], and Zhelev, [5].

NOMENCLATURE

F	[kg/s]	hot stream mass flow rate
S	[kg/s]	cold stream mass flow rate
G	[kg/s]	vapour flow rate
c_p	[J/(kg.K)]	specific heat capacity
t	[K]	Temperature
h	[J/kg]	specific enthalpy
h_{fg}	[J/kg]	latent heat of evaporation
U	[W/(m2K)]	heat transfer coefficient
A	[m^2]	heat exchanger area
L	[kg/s]	output hot stream mass flow rate
P	[Pa]	Pressure
Q	[W]	Heat
T	[K]	hot stream temperature
t_c	[K]	condensation temperature
t_g	[K]	vapour temperature
Special characters		
ϕ	[K]	temperature change due to non-condensable gases
ψ	[K]	temperature change due to superheating
Subscripts		
S		related to cold stream
F		related to hot stream
w		Vapour
NC		Non-condensable gases

OBJECTIVES

The objectives of this paper are to achieve beneficial energy and water management by exploring inherent dependence between heat and mass transfer, thus manipulating and guiding these simultaneous processes towards resources conservation. Many aspects of energy-water nexus have been accounted for by the scientific community, therefore our concrete tasks can be summarised as follows: 1. Analysis of pressure manipulation and pressure change in water systems with a focus on water and energy integration (flash heat recovery from scaling or flossy solutions). This will allow assessing (targeting) recycling potential and formulating design/redesign guidelines for controlling scaling and optimal process efficiency improvement through recovery of water and heat from water solutions with severe scaling properties; 2. Study of the impact of non-condensable gases and their management towards better heat recovery.

These problems are normally found extensively in metallurgical industry, in water desalination, multi-effects evaporators, bio-fuel (bio-ethanol) and many other industrial sectors.

METHODOLOGY

Freshwater, wastewater, industrial cooling water, wash-water, desalination water, water/moisture content in gases, flue gases, latent heat of condensation/evaporation are only few of water-related issues related to simultaneous heat and mass transfer involving the link between water and energy conservation, as discussed in this paper.

1.1. Fundamentals

This work utilises two fundamental scientific methodologies:

1.1.1. Combined Heat and Mass Transfer

The fundamentals of heat and mass transfer underlining the interactions in industrial processes between water and energy include phase changes consideration (evaporation, condensation), driving forces management (temperature differences and concentration), pressure – temperature interactions, thermodynamic limitations and constraints, etc. The utilisation of these interactions can serve as a guide in management of water and energy resources.

1.1.2. System Approach to Water Saving

The second underlying approach of this paper is the application of the system approach to industrial resources management (area of knowledge known as process systems engineering), including conceptual process integration approach and mathematical approach utilising the power of mathematical modelling, simulation, system analysis and optimisation. This approach allows water using processes to be analysed in conjunction with the rest of the processing system and resources to be managed in more sustainable, cost efficient, safe and environmentally friendly manner. Systematic approaches for industrial water management have been introduced following the pioneering work of El-Halwagi [6] and further developed by Smith and co-workers, [7-9]. These design concepts have been successfully applied to improve the efficiency of water systems and reduce aqueous emissions to the environment. Following these conceptual design methods, automated design methods based on mathematical optimisation techniques have been developed [10] to deal with the design of water systems taking into account design complexity, different contamination and engineering constraints.

1.2. Integrated Systems Considering Water and Energy

Recent scientific effort has been made in the process engineering communities to extend the research focus from stand-alone water systems to integrated water systems in which water and energy are significantly interacting. Savulescu et al., [4] proposed a graphical method to simultaneously minimise energy and water consumptions in water systems by sequential targeting and design procedure. This graphical method has been further extended with the aid of mathematical optimisation techniques, which allows for systematic evaluation of design interactions and allows performance of rigorous economic trade-offs between water and energy cost, against capital investment such as piping cost [11]. Zhelev, [12] generalised the groups of processes where gain in water and energy can be simultaneously achieved, whereas authors of [13] and [14] focused on structural optimisation of utility systems (cooling systems and boiler systems) that achieve gain in fresh water and energy conservation with supplementary waste water minimisation.

The analysis of the state of the art demonstrates a tendency towards improved complexity when attempting to solve integration problems and waiving initial simplifying assumption allowing for industrial scale processes and different resources interactions to be considered.

1.3. The European Dimension

Authors' starting point for guided water and energy management is the bulk chemical production (large systems, where the complexity of the problem requires extensive computing), where the methodologies for resources management have taken an early "flying start". Currently the structure of the European industry indicates that 99% of European enterprises are already of small to medium size and mainly focused on high value low tonnage products. Therefore, Europe needs to focus its energy and water efficiency initiatives at the integration of small size plants and achieve efficient operation, low resource usage, high profit and sustainable environmental consciousness.

1.4. Phase change, Water Generation, Control of Water Loss and Recycling

The approaches to energy linked water saving have the potential to impact on many industrial operations. An important aspect of water management is the control of water loss by evaporation and the possibility of water generation by vapor condensation (known as changes of the aggregative phase). We are suggesting particular attention to the utilisation of the latent heat of phase change (allowing for water saving through preventing evaporation loss, thus saving substantial quantities of water and in parallel allowing heat recycling). The loop of possible activities in this suggested direction include recovery of water from exhaust gases (drying, calcinations, combustion, etc.), sludge dewatering in wastewater treatment, management of cooling water systems in power-generation or in manufacturing and number of activities, which close back to the old and well-proven resources conservation approach, which happens to be the cheapest and quickest way to gain substantial impact in water saving per unit of product.

1.5. Aiming for Water, Hitting Energy

In many cases the level of heat recovery has direct implication on plant's efficiency and may cause obstacles to plant profitability (in case of slim profitability margins), plant's throughput and plant capacity improvement. In energy intensive processes such as evaporation systems, distillation systems and digester systems pressure distribution between stages becomes an issue. The trade-off between capital and energy cost forces some reasonable evaluation of the number of stages and the optimal distribution of driving forces to heat transfer. In cases of severely scaling water solutions water vapour is used as heat transfer medium. Latent heat of evaporation is off-set by latent heat of condensation, leaving the entropy loss as the only waste of the process. This way heat is transferred between two streams without a wall or direct contact between fluids, thus deviating from the two main ways of heat exchange (recuperative and regenerative). In fact the only control of the process is through the size of the condenser (the area of heat exchange) (see Figure 1).

1.6. Single flashing stage

What happens in a single flashing stage (system) can be observed in Figure 1.

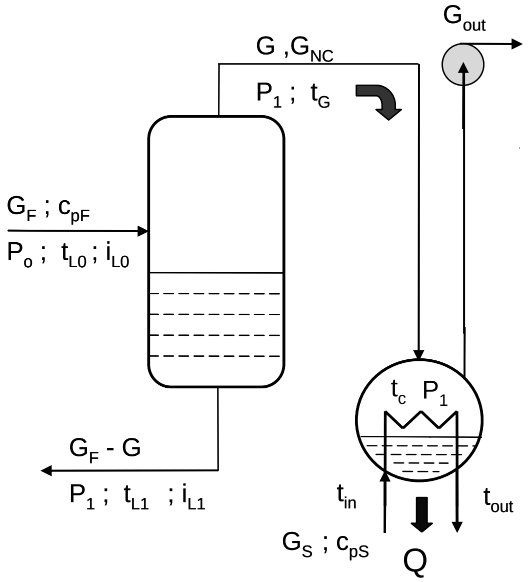

Figure 1 Single flash tank condensation unit

Here the hot stream is fed to the flash tank, where as result of pressure release the water vapor is released and supplied as heating agent to the condenser. The cold stream is heated there as result of the condensation. The question is why we need G_{out} – any gases out if the idea is to condense generated in the flash tank water vapor fully?

Mass flow of gases G includes water vapor G_w and non-condensable gases G_{NC}. The usual amount of NC gases is 1%. Purging some vapor G_{Wout} in order to eliminate NC gases (a usual practice) leads to loss of energy recovery because of lost and uncondensed water vapor.

$$G = G_w + G_{NC}$$
$$G_{NC} \sim 0.01G_w \qquad G_{Wout}= \frac{RG_{NC}T_{Gout}}{P - p_W} \qquad (1)$$
$$G_{out}=G_{Wout}+ G_{NC}$$

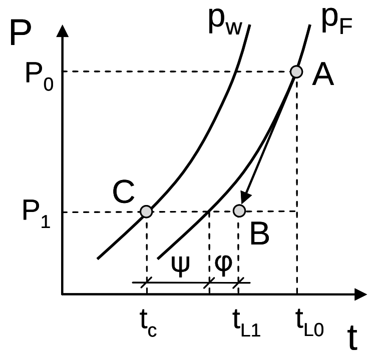

Figure 2 Presentation of flashing process

As set in the Objectives, analysis of pressure manipulations will allow assessing energy recycling potential and the control of energy efficiency improvement. Therefore Figure 2 focuses on the process from Figure 1 and its progress linking temperature and pressure. Instead of arriving at point C, the process of flashing starting at point A ends at point B as shown in pressure over temperature plot. This process is automatically controlled. The pressure drop, the evaporated water and finally the heat recovered depends only of the area of the heat exchanger (condenser). Therefore the proposed model links this area to the recovered heat *Q*. NC gases are also accounted for.

1.7. The Model

$$Q = K_S \frac{\exp(UA/K_S)-1}{\exp(UA/K_S)}(t_c - t_{in}) \qquad (2)$$

$$Q = \frac{K_S \dfrac{C-1}{C}}{1+\dfrac{K_S}{K_F}\dfrac{C-1}{C}}\left(t_F - t_{in} - \psi - \varphi\right) \qquad (3)$$

Considering the multistage flashing for safe heat recovery of scaling streams we succeeded to represent the heat flow considering the pressure of flashing stages recurrently:

$$T_{i+1} = (1-K_{1,i})T_1 + K_{1,i}t_{i+1} + K_{1,i}\delta_{1,i} \qquad (4)$$
$$t_i = (1-k_{1,i})t_{i+1} + k_{1,i}T_1 - k_{1,i}\Delta_{1,i}$$

the coefficients $K_{1,i}, k_{1,i}, \Delta_{1,i}, \delta_{1,i}$ are defined by reccurent formulae

$$k_{1,i} = \frac{k_{1,i-1} + k_i - k_i k_{1,i-1} - k_i K_{1,i-1}}{1-k_i K_{1,i-1}} = 1 - \frac{(1-k_i)(1-k_{1,i-1})}{1-k_i K_{1,i-1}},$$

$$K_{1,i} = \frac{K_{1,i-1} + K_i - K_i K_{1,i-1} - k_i K_{1,i-1}}{1-k_i K_{1,i-1}} = 1 - \frac{(1-K_i)(1-K_{1,i-1})}{1-k_i K_{1,i-1}},$$

$$k_{1,i} \bullet \Delta_{1,i} = k_{1,i-1}\Delta_{1,i-1} - (1-k_{1,i-1})\frac{k_i K_{1,i-1}\delta_{1,i-1} - k_i \pi_i}{1-k_i K_{1,i-1}}, \qquad (5)$$

$$K_{1,i} \bullet \delta_{1,i} = K_i \pi + (1-K_i)\frac{K_{1,i-1}\delta_{1,i-1} - k_i K_{1,i-1}\pi_i}{1-k_i K_{1,i-1}},$$

where $K_F = Fc_{pF}$ and $C = \exp(UA/K_S)$; $K_S = S.c_{pS}$ and $\pi_i = \Psi_i + \varphi_i$

More details about the model can be found in [15].

ANALYSIS

This approach can deal with treatment of process water solutions, which tend to scale or block equipment during operation, thus decreasing process performance (heat transfer), bottlenecking throughputs and increasing maintenance cost. In these cases, water is evaporated from the hot solution (through a pressure drop) and then water vapour is used to give back gained heat to the cold fluid through condensation. Usually this is done not in a single (as shown in Figure 1), but in several stages. A three stage flash evaporation process conducted under vacuum is shown in Figure 3. The distribution of driving forces in this system is shown in Figure 6. Figure 5 gives an idea of the strong influence of non-condensable gases (NC) on heat exchange. The model of an arbitrary system of flash heat recovery is given through equations 1-5. It is based on the understanding of the process. This model can be used as an important part of a management tool for guided design of corresponding multistage water/energy recovery systems for bio-ethanol production or residual heat recovery in alumina production (Bayer process). Important to underline is that the heat transferred in each stage of the multistage flash heat recovery system is expressed only as a function of the inlet temperature and design parameters (heat transfer area). This can allow us to balance the heat recovery in each of the separate flash-modules and match it to the process equilibrium.

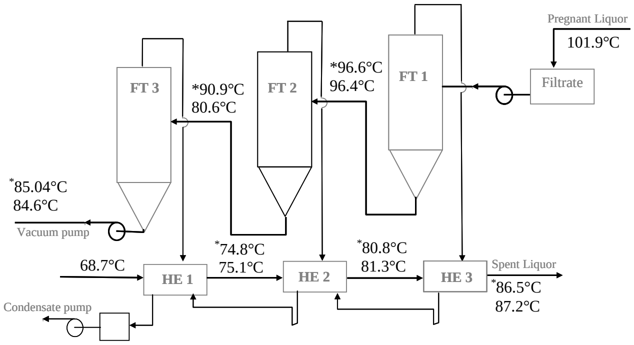

Figure 3 A cascade of flash tank – condenser units
(* denotes model simulation results)

As mentioned such a complex design is used for heat recovery in highly scaling environments. Using flashed water vapour as a heat recovery agent does not ignore the potential scaling in the tubes of the heat exchangers (condensers). The deposits (fouling) inside tubes have to be watched carefully because of their substantial impact on heat transfer rate. Figure 4 gives an idea of the degree of this impact.

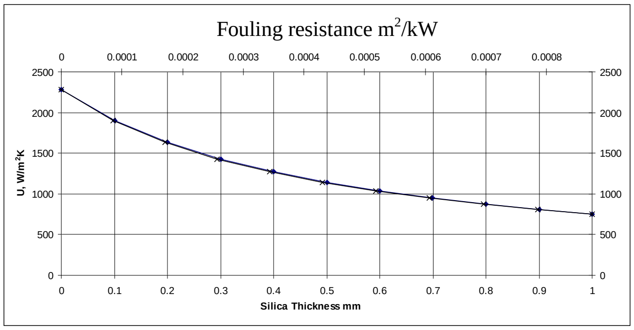

Figure 4 The impact of fouling

The next important factor influencing the recovered heat in each of the flash-units is the existence of non-condensable gases (NC). Their origin can be sealing deficiencies or unaccounted chemical reactions. It is normal to expect around one percent of these gases (mostly air) in industrial systems. In many cases this percentage is much higher. NC gases share partial pressure with the water vapour and occupy the upper part of the condensation surface making it inaccessible for vapour condensation. Therefore their existence should be also considered. The elimination of these gases is not straightforward. In flash systems working under pressure this normally is done through purging some of the vapour from the upper far end of the heat exchanger. Releasing some of the vapour helps to eliminate the severe impact of these gases. The task of elimination of NC in systems working under vacuum is more difficult. We have a good idea how to deal with them effectively in such cases.

Figure 5 Influence of non-condensable gases

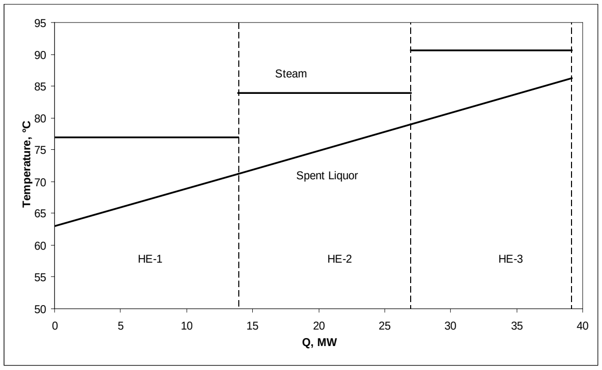

Figure 6 Composite curve

The graphical presentation from Figure 6 above demonstrates the goal of heat recovery in a series of flash units. The optimisation is visibly related to the optimal distribution of driving forces to heat transfer. The distribution of the load between flash-units ordered in a sequence is analogous to so-called appropriate placement as discussed in [16] in the case of multi-stage evaporators. We are showing our simple graphical approach to this problem, which is based on the classical heat and mass transfer presentation including equilibrium curve and operating lines and combines it with the typical for the Pinch

Analysis Composite Curves and Grand Composite Curve presentation [17] (Figure 7). In this case the top dotted line represents the border line of hot screams, when the bottom line shows the single cold stream of the spent liquor. The stages are drawn restricted between this line and the equilibrium curve. In the case of water solution the curvature of this curve is comparatively small. The Grand composite [17] shows "pockets", representing the amount of heat transferred in each of the flash-units. The recommended way to reach a balance between stages is to control/equalise the surface area of these "pockets".

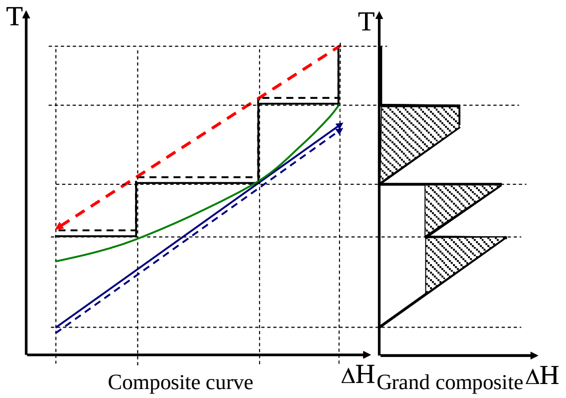

Figure 7 Graphical guidelines for heat distribution

SIMULATION

The results of a trial simulation based on the model presented in this paper are shown below. Table 1 gives the input data, whilst Table 2 compares the simulation results with the real readings for three-effects flash heat recovery system. The results are showing very reasonable deviation of computer simulation from real measurements.

Table 1. Input data

Number of effects	3	
T_{in}	101.9	°C
t_{in}	68.7	°C
F_{in}	1458	m^3/h
F_{out}	1397	m^3/h
S	1336	m^3/h
ρ_S	1252	kg/m^3
ρ_F	1263	kg/m^3
V_S	1336	m^3/h
V_F	[1458 1438 1397]	m^3/h
U	[2109 2138 2162]	W/m^2K
A	750	m^2
Cp_S	3575	kJ/kgK
Cp_F	3499	kJ/kgK
φ	0.4	°C
Ψ	6.1	°C

Table 2. Simulation results

Flash Tanks	**°C**	**FT 1**	**FT 2**	**FT 3**
Hot stream T original	101.90	96.40	90.60	84.60
Hot stream T simulation	101.90	96.60	90.98	85.04
Deviation	0	-0.21%	-0.42%	-0.52%
Heat Exchangers	**°C**	**HE 1**	**HE 2**	**HE 3**
Cold stream t original	68.70	75.10	81.30	87.20
Cold stream t simulation	68.70	74.83	80.81	86.52
Deviation	0	0.36%	0.61%	0.79%

Impact

The vapour from flash tanks is superheated because of two factors:

- Boiling point raise of solution $\Psi = 6.1$ K;
- Influence of non-condensable gases (1% wt.) $\varphi = 0.4$ K

The superheating energy required by one flash tank is

$$Q_s = G.c_{ps}\,(\psi + \varphi) = 70 \text{ kW}$$

Impact on the heat exchanger:

Overall heat transfer coefficient: $U = 70$ W/(m^2.s)

Extra heat exchanger area required to compensate superheating: $F_s = 85$ m^2

It is a substantial extra surface area amounting for 10.7 % from the total area required for three flash-units or 62.0 % from the surface area of one unit (section).

ELIMINATION

Elimination of vapour-superheating is possible with small water sprays installed in the steam-ducts. Practically water can be supplied from the condensate wasted from the above system. The required flow of hot condensate spraying by nozzles in this case is 115 kg/h.

GUIDED CONTROL

Figure 8 below demonstrates some extra beneficial process operation changes guided by the approach presented above.

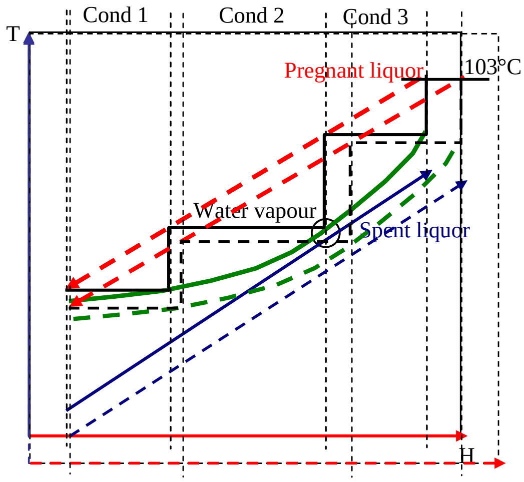

Figure 8 Guided beneficial process changes

It demonstrates the effect of supplying spent liquor (cold slurry) at lower temperature to the flash heat recovery system. This will lead to better pregnant liquor cooling (important result because cooling is more difficult than heating) and thus opening the need for extra heating, where waste heat (which is in excess) can be used. This increases the overall efficiency of the heat recovery system.

CONCLUSION

The presented investigation demonstrates that there are areas of heat integration that need further investigation. One of these is the inclusion of pressure in the analysis, when heat integration is concerned. The first message of inclusion of pressure into the conceptual approach to heat integration, such as Pinch analysis are coming from one of the authors with substantial contribution in this area. His name is Truls Gundersen. The developments in this area are forced by the industry dealing with massive gas liquefaction in off-shore terminals, where cooling requires large amount of energy and liquefaction requires precise consideration of pressure [18-20]. Therefore we better watch this space expecting more to come in the area of rational use of energy and heat integration. Our intent here is to demonstrate the application of pressure amalgamated approach to heat integration for highly scaling water solutions. The approach unlocks the possibility of throughput debottlenecking. Proposed adjustments for presented case study compensate the boiling point raise and the non-condensable gases. This leads to 27% improvement of heat utilization, which reflects to cost savings for energy (fuel/steam) in the range of MMEUR4. Mentioned savings do not consider debottlenecking and the option for throughput improvement. The paper demonstrates operating and design guidelines coming from the graphical conceptual process integration approach (Figures 7 & 8). In parallel it reports the development of an adequate model, which can be used for further process and system's improvements. The model includes consideration of the boiling point rise and proposes practical compensation for lost heat recovery efficiency. It accounts for the negative influence of non-condensable gases and guided by these findings authors engineered appropriate practical solution, which has separate intellectual property value. Finally, the loop of activities proposed in this paper closes back to the old and well proven resources conservation approach, which is known to be the cheapest and quickest way to gain substantial impact in saving of water and energy.

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