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Optimal Stream Discharge Temperatures for a Dryer Operation Using a Thermo-Economic Assessment

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A typical drying process that has liquid and gas discharge streams has been analysed and the impact of selecting various combinations of soft temperatures on heat recovery, utility targets, area targets, capital cost and total cost is reported. The method is based on the plus-minus principle and traditional pinch analysis methods for utility, area and capital cost targeting with the modification of using a ΔT contribution. Results show that there is significant benefit from optimising discharge temperatures for total cost. To achieve minimum energy consumption and total cost, heat recovery from the dryer exhaust air is necessary. Heat recovery from liquid heat sources is shown to be preferable over gas streams due to a higher film coefficient resulting in less heat exchanger area and capital cost. There is also value in making process modifications, such as combining streams or removing small streams to be solely heated by utility, to reduce the number of network heat exchangers. For the best case, the discharge temperatures of the leaving streams are 18.0 °C for water condensate (liquid stream) and 52.4 °C for the exhaust air (gas stream).

1. Introduction

Heat recovery and utility targets generated using pinch analysis express from a thermodynamic point of view the minimum energy consumption required for a process (Linnhoff and Flower, 1978; Smith, 2005; Klemeš et al., 2010). These targets are a property of the defined system boundary, which includes stream temperatures, flow rates and states, and when an attribute of the system, such as the target temperature of a stream, changes so do the energy targets. However for many processes some of the stream data is “soft”, meaning that select stream properties or process requirements can vary without impacting the overall product quality and safety. Designers can use this flexibility to their advantage by applying the plus-minus principle, which allows stream data to vary within a defined range until a minimised energy target is obtained (Zhang and Zhu, 2000; Klemeš et al., 2010).

A classic example of a soft temperature is the discharge temperature of streams leaving a process. Where the leaving streams are hot it may be desirable to recover the heat, but to include this heat recovery in pinch analysis a target temperature, or discharge temperature, of the stream must be chosen prior to targeting. Heat recovery from liquid streams is also valuable to drive the discharge temperature to below the temperature limits (T_{limit}) set by environmental regulators. Furthermore there is often a significant range of acceptable discharge temperatures below any T_{limit}. Since the leaving stream discharge temperatures affects the pinch targets, there is value in understanding this effect so stream temperatures that minimise energy use and total cost can be identified and used.

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Drying processes, in particular, often have large amounts of low-grade waste heat contained in exhaust gases and, therefore, the selection of the final discharge temperature after heat recovery can significantly influence the pinch targets. To select the most advantageous discharge temperatures, the plus-minus principle previously developed (Klemeš et al., 2010) has been applied in a spreadsheet tool and the soft temperatures of the evaporator water condensate (WC) and the exhaust dryer air (EA) have been varied until utility targets are minimised. The best waste stream temperatures have been obtained by a thermo-economic assessment similar to the traditional selection of ΔT_{min}. A ΔT_{min} temperature contribution, ΔT_{cont}, (Kemp, 2007) based on the state of the stream has also been applied within the spreadsheet tool to allow for more explicit calculation of the basic energy and heat exchanger area targets.

2. Methodology

The analysis method is based on traditional pinch analysis techniques for utility, heat exchanger area and capital cost targeting with the modification of using a ΔT_{cont} instead of a global ΔT_{min}. Specified soft temperatures are systematically varied in an effort to reduce energy consumption. To target heat exchanger area, utilities are added to create a balanced composite and then broken into enthalpy intervals (*i*). Each interval is considered individually and the heat exchanger area is calculated using the log-mean temperature difference approach and a heat flow (CP) weighted-average of the film coefficients. The sum of the area for all intervals, ΣA_i, gives an estimate for the total heat exchanger network (HEN) area including utility exchangers. The area targeting approach is taken from Smith (2005) and assumes vertical heat transfer takes place. Although It is recognised that cross heat transfer can reduce the area target especially when streams have significantly different film coefficients. Film heat transfer coefficients for all process and utility streams were taken from Smith (2005). Once the area target is obtained and the minimum number of heat exchangers in the network is calculated, Eq.1 is applied to calculate the annualised capital cost, C_c.

$$C_c(\$/y) = N\left(10000 + 1500\left(\frac{\Sigma A_i}{N}\right)^{0.57}\right) \tag{1}$$

Where N is the number of heat exchangers in the network, which is assumed to be the minimum number of units to achieve the target, A_i is the heat exchanger area for interval *i*. Heat exchanger cost coefficients have been adapted from Bouman *et al.* (2005), using with a Lang factor of 3.5, for a generic shell and tube heat exchanger and the coefficients are annualised using a discount rate of 15 % and an expected life time of 10 y. The process operates for 5000 h/y. The combined annual utility cost, C_u, is calculated using the utility pricing in Table 1 and the operating hours.

3. Dryer process and utility stream data

The dryer process and corresponding system boundary is shown in Figure 1. Utility and stream data for the process are presented in Tables 1 and 2. The process includes an evaporator train and spray drying operations and produces around 23 t/h of dried powder. The hot water use, mainly for cleaning, is also included in the analysis. The undefined, or soft, discharge or outlet temperatures in Table 2 are $T_{WC,out}$ and $T_{EA,out}$. The three WC streams are assumed to have the same target temperature. From environmental regulations $T_{WC,out}$ must be below T_{limit} of 28 °C, otherwise cold utility is applied to achieve a temperature below 28 °C.

Table 1: Utility data

Utility	Hot/ Cold	T_s °C	T_t °C	ΔT_{cont} °C	Cost \$/kWh	h^1 kWm^{-2}°C^{-1}
Steam	H	220.0	219.0	1.0	0.045	5.000
Cooling water	C	20.0	30.0	2.5	0.005	1.250
Chilled water	C	1.0	5.0	2.5	0.040	1.250

[1] *Film coefficients taken from Smith (2005).*

Table 2: Stream data

Stream	Hot/ Cold	State	T_s °C	T_t °C	CP $kW°C^{-1}$	ΔH kW	ΔT_{cont} °C	h[1] $kWm^{-2}°C^{-1}$
Liquid input	C	L	8.0	74.5	278		2.5	1.250
Evap. water condensate (1)	H	L	67.5	$T_{WC,out}$	146		2.5	1.250
Evap. water condensate (2)	H	L	61.0	$T_{WC.out}$	86		2.5	1.250
Evap. water vapour (3)	H	V	54.0	53.9		2411	1.0	2.500
Evap. water condensate (3)	H	L	53.9	$T_{WC,out}$	13		2.5	1.250
Liquid concentrate	C	L	54.0	65.0	38		2.5	1.250
Dryer inlet air	C	G	32.0	200.0	121		10.0	0.025
Fluidised bed inlet air (1)	C	G	32.0	49.0	10		10.0	0.025
Fluidised bed inlet air (2)	C	G	32.0	45.0	15		10.0	0.025
Exhaust air, sensible heat	H	G	75.0	$T_{EA,out}$	168		10.0	0.025
Exhaust air, latent heat	H	G	39.5	$T_{EA,out}$	1265		10.0	0.040
Hot water	C	L	15.0	55.0	32		2.5	1.250

[1] Film coefficients taken from Smith (2005).

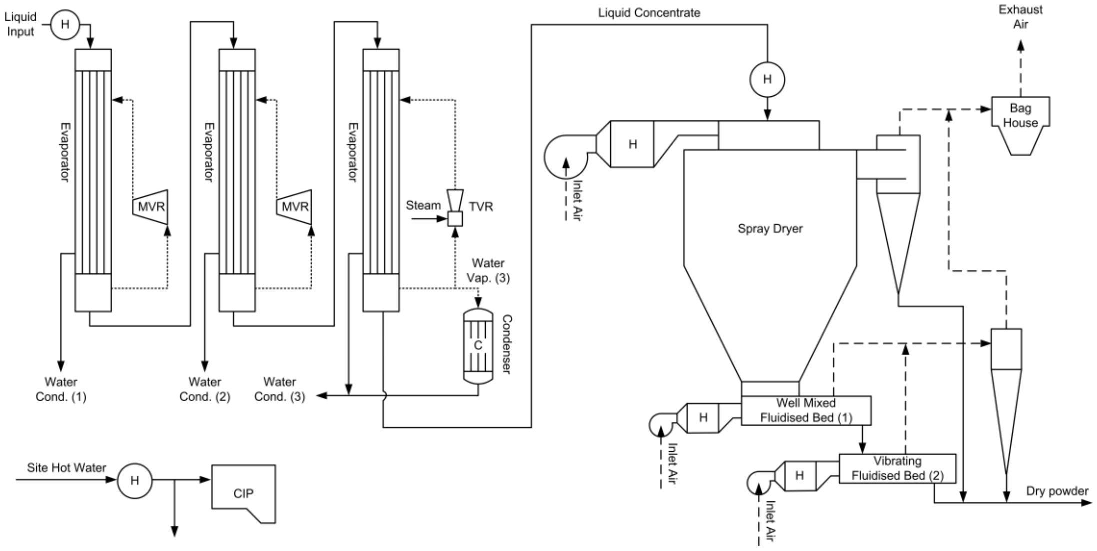

Figure 1: Drying process schematic.

4. Results and discussion

4.1 Utility targeting

In the drying process two temperatures, $T_{EA,out}$ and $T_{WC,out}$, are soft and have been systematically varied and the hot and cold utility targets and cost were calculated. Figure 2a maps the effects of changing $T_{WC,out}$ and $T_{EA,out}$ on total annual utility cost, C_u, and has been presented as percentage of $C_{u,min}$. The results show the minimum utility consumption is \$5.0 million per year (mil/y) and may be obtained using several combinations of $T_{WC,out}$ and $T_{EA,out}$. When $T_{WC,out}$ is chosen to be greater than T_{limit}, cold utility must be used to cool the liquid stream to 28.0 °C.

Figure 2a shows the substantial value of heat recovery from the dryer exhaust air. Selecting $T_{EA,out}$ as 75 °C indicates that no heat from the exhaust air stream will be recovered. As a result C_u increases by at least \$0.8 mil/y or 17 %, which increase is minimized when $T_{WC,out}$ is 13.0 °C. The driver behind $T_{WC,out}$ being best discharged at 13.0 °C ($T_{EA,out}$ = 75 °C) is the pinch temperature of 10.5 °C. The 2.5 °C difference between the water condensate and the pinch temperature is the ΔT_{cont}. Figure 2b takes a cross-sectional cut of Figure 2a at $T_{WC,out}$ = 13.0 °C and plots how $T_{EA,out}$ affects the hot utility use (Q_{hot}), cold utility use (Q_{cold}), heat recovery (Q_{rec}), and utility cost (C_u). For $T_{WC,out}$ = 13.0 °C, $C_{u,min}$ occurs when $T_{EA,out}$ is 52.3 °C (Figure 2b- line B). If a different $T_{EA,out}$ was chosen, it can be seen that the utility cost will rise. In the case of $T_{EA,out}$ greater than 52.3 °C, the rise in costs results from rejecting heat in the exhaust air stream that has the potential to be recovery; whereas if $T_{EA,out}$ is lower than 52.3 °C, the cold utility load increases.

The global minimum utility cost can be achieved using different combinations of $T_{WC,out}$ and $T_{EA,out}$. Common to all these temperature combinations are a constant hot and cold utility requirement and identical total heat recovery. Effectively along the $C_{u,min}$ line in Figure 2a one heat source is exchanged for another heat source without affecting overall heat recovery or utility cost. This minimum line is constrained by T_{limit} (28 °C) on one side and the pinch temperature on the other side. Both constraints apply to the water condensate stream. T_{limit} is set in council and government issued consents and may vary from site to site depending on where the liquid stream is discharged to.

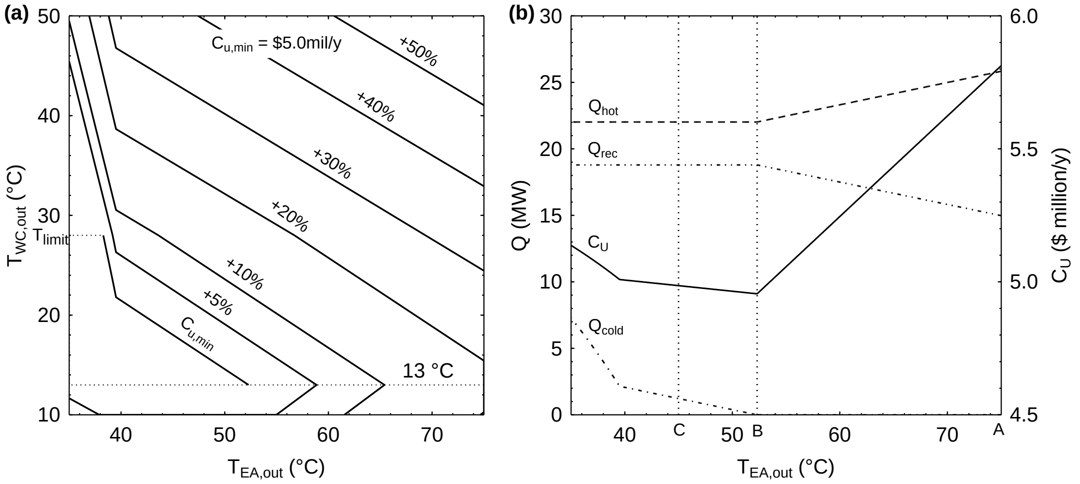

Figure 2. (a) Contour plot of utility cost for a range of $T_{WC,out}$ and $T_{EA,out}$, (b) Q and C_u for a range of $T_{EA,out}$ using a constant $T_{WC,out}$ of 13.0 °C.

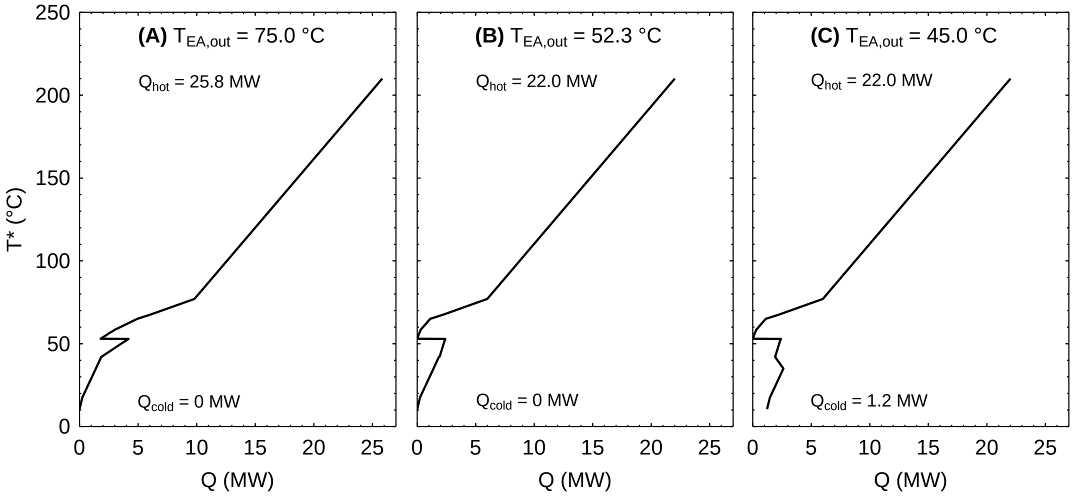

Figure 3: Grand composite curve for various $T_{WC,out}$ and $T_{WC,out}$ = 13.0 °C. Pinch temperatures are 10.5 (A,B) and 53.0 °C (B, C).

The Grand Composite Curve (GCC) is an functional tool for quickly identifying when a minimum utility cost point is reached. To demonstrate this concept, three GCC's are shown side by side in Figure 3 that correspond to the three $T_{EA,out}$, A = 75.0 °C, B = 54.3 °C and C = 45.0 °C, which are identified in Figure 2b. Figure 3a shows the GCC when no heat is recovered from the exhaust air. Due to the shifted exhaust air temperature being higher than the pinch temperature of 10.5 °C, recovered heat from the exhaust air helps reduce the heat deficit until $T_{EA,out}$ = 54.3 °C. For these conditions, a second pinch point occurs at 53 °C (Figure 3B). Now because a pinch temperature is greater than the shifted exhaust air temperature, the additional heat recovery adds to the cooling load requirement. Driving down to $T_{EA,out}$ = 45.0 °C, pushes the lower part of the GCC to the right, showing the increase in cold utility use. As demonstrated in Figure 3, a distinguishing feature of the global minimum utility cost line on Figure 2a is a two pinch temperatures, which is consistent with the idea that energy consumption is minimised at these discharge temperatures.

4.2 Area and capital cost targeting

Focusing on minimising C_u does not guarantee the total cost (C_T), which includes the Heat Exchanger Network (HEN) capital cost (C_c), is also a minimum. To better select $T_{WC,out}$ and $T_{EA,out}$, an estimation of HEN area is needed (Figure 5a) and C_c is calculated using Eq. 1. C_u, C_c and C_T can be referenced to the case when $T_{EA,out}$ is 75 °C and $T_{WC,out}$ = 13.0 °C and the change in cost is plotted in Figure 5b. Figure 5 has two regions; the region to the right of B has a constant $T_{WC,out}$ (13.0 °C), whereas the region to the left of B follows the $C_{u,min}$ line in Figure 2a and $T_{WC,out}$ varies. Figure 5b (right of B) shows increases in HEN area returns diminishing benefit in terms of heat recovery. On the left of B, the plot suggests that in terms of area it is less expensive to recovery heat from the liquid condensate stream than the gaseous exhaust stream due to a difference in film coefficients.

The discharge temperatures that result in the minimum total cost fall outside the combinations of minimum utility cost (Figure 5b). The minimum total cost occurs when $T_{EA,out}$ is 56.6 °C and $T_{WC,out}$ = 13.0 °C. The potential savings from exhaust air heat recovery after taking into account capital cost is, therefore, \$220,000 per year. The total cost curve in Figure 5b illustrate the typical tension between savings from heat recovery and capital cost.

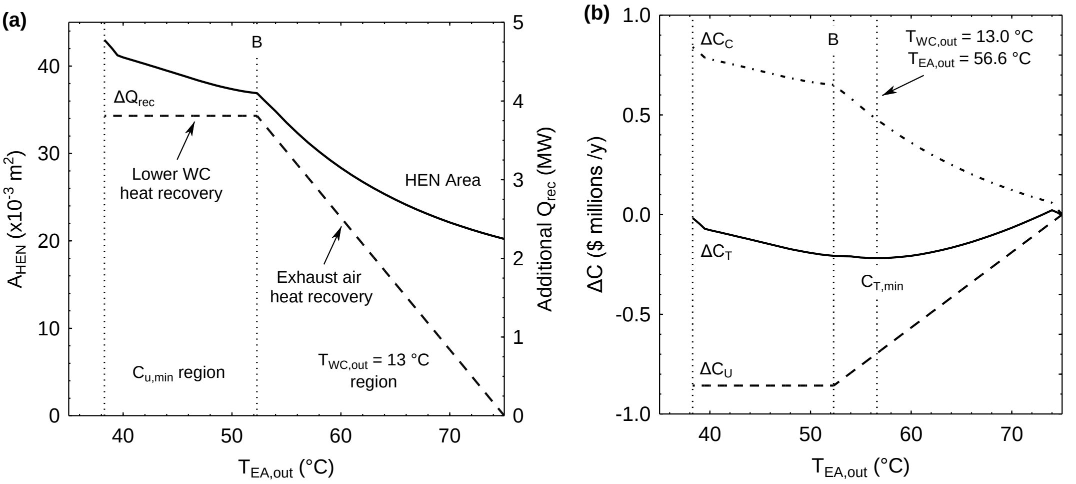

Figure 4: Total heat exchanger network area (a) and change in costs (b) for a range of $T_{EA,out}$ and $T_{WC,crit}$. Costs are referenced to $T_{EA,out}$ = 75 °C, i.e. no heat recovery from the exhaust air stream.

4.3 Process modifications

Three modifications to the process were investigated to understand their effect on the total cost and the optimised discharge temperatures of WC and EA (Figure 6); (I) the fluidised bed air streams and the liquid concentrate are heated by steam due to location and are unavailable as heat recovery sinks,

(II) the WC streams are mixed to form a single stream with a temperature of 64.5 °C, and (III) the combination of I and II. Implementing modifications I and II together, i.e. III, reduced the total cost estimate by $140,000/y, even though utility costs increased by $120,000/y. The major reason for the lower capital cost is the minimum number of heat exchangers has reduced by 4 units. In both cases of combining the WC streams (II and III), the best discharge temperature of the stream is 18.0 °C. All modifications achieved the goal of reducing the number of required heat exchangers. This paper has focused on using a thermo-economic assessment to choose the best discharge temperature of two leaving streams. The method can be extended to include the multi-variable optimisation of ΔT_{cont} to find the global total cost minimum.

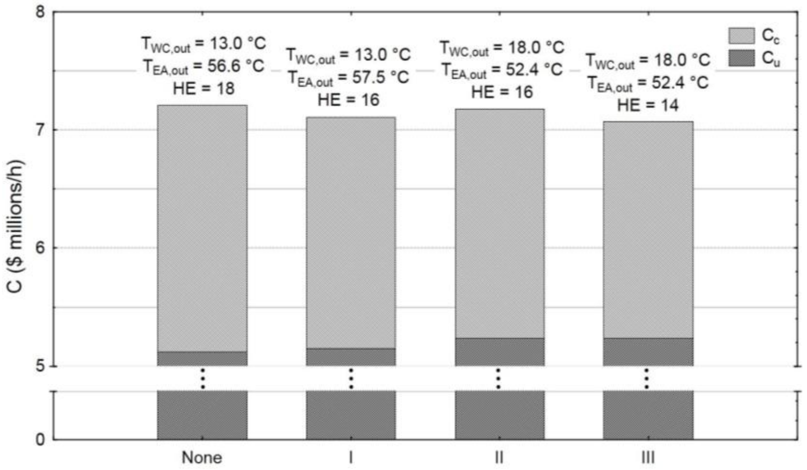

Figure 5: The minimum total cost, heat exchanger number and discharge stream temperatures for various process modifications. Modifications: (I) two fluidised bed air streams and the liquid concentrate are heated by utility, (II) WC streams are combined, and (III) hot water demand is doubled.

5. Conclusion

For the drying process, there is significant benefit in optimising the soft discharge temperatures of the water condensate and exhaust air streams, for cost. Heat recovery from the dryer exhaust gas is necessary to achieve minimum energy consumption and minimum total cost. The choice of heat recovery from liquid heat sources is preferable over gas streams due to the film coefficient being higher, which results in lower area targets and capital cost. To achieve the optimal total cost target, two process modifications are recommended; use utility to heat the fluidised bed air streams and the liquid concentrate and combining the water condensate streams into a single liquid stream. For this best case, the discharge temperatures are 18.0 °C for water condensate and 52.4 °C for the exhaust air.

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