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Data Reconciliation Focusing on the Utility System of a Total Site

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In this paper, the modelling of data reconciliation in Total Site is revisited. Only the equipment in the utility systems is considered during data reconciliation. The obtained result is then further used as inputs for individual heat exchanger network data reconciliation. In this work, an illustrative case study is used to demonstrate the effectiveness of this approach. The results obtained from this approach are less accurate but within an acceptable range, when compared to the results when the whole site is considered in the reconciliation process.

1. Introduction

Data extraction is a crucial step before any Heat Integration study can commence (Klemeš, 2013). For retrofitting existing plants, data reconciliation is part of data extraction to obtain representative data (Klemeš and Varbanov, 2010). The main Heat Integration analysis method – Pinch Analysis, requires heat capacity flowrates (CP) and temperatures (T) of process streams. While there are already publications on reconciliation of measured Heat Exchanger Network (HEN) data (Nemet et al., 2015), works presenting data reconciliation for Pinch Analysis are scarce. Reconciling with two parameter types simultaneously causes a high degree of non-linearity in the model. It is due to the energy constraint in the model is the function of temperature and heat capacity flowrates. Ijaz et al. (2013) handled this complexity by first reconciling the heat capacity flowrates and the temperatures afterwards. This introduces certain inaccuracy as the model has energy constraint in the function of temperature only. To deal with this non-linearity, Yong et al. (2016) proposed an iterative method reconciling one parameter at a time to reduce the computation effort, sacrificing some of the accuracies. Although the non-linearity in the energy constraints is dealt with by the iterative procedure, the data reconciliation problem is made more complex when the number of heat exchangers increases. This is the case when the scope of the measurement is expanded to the Total Site level. In this paper, the direction of how a data reconciliation in Total Site is revisited. Within a Total Site there are many heat exchangers. Each site plant has its own individual sets of chemical equipment and HENs. They are connected to the same utility system, as shown in Figure 1a. Instead of including all heat exchangers of every plant in the data reconciliation problem, the utility system can be reconciled first. After obtaining the reconciled result for utility system, each HEN from each plant can be reconciled separately using the method introduced in Yong et al. (2016). In this paper, only the parameters of inlets and outlets of utility systems such as heaters, coolers, furnace and cooling tower in Total Site are included in the data reconciliation problem. This significantly reduces the number of variables to be reconciled. Each type of utilities has its own sets of steam headers. All steam headers, coolers and heaters are modelled as black boxes. In Heat Integration, flows in steam header diagram are usually expressed in terms of energy flowrate, such as kW. It should be noted that energy flowrate cannot be measured directly. In data reconciliation process, all flows are measured and expressed in terms of mass flowrate instead.

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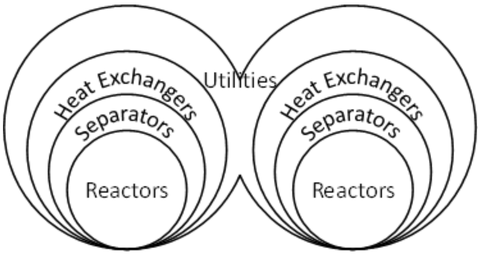
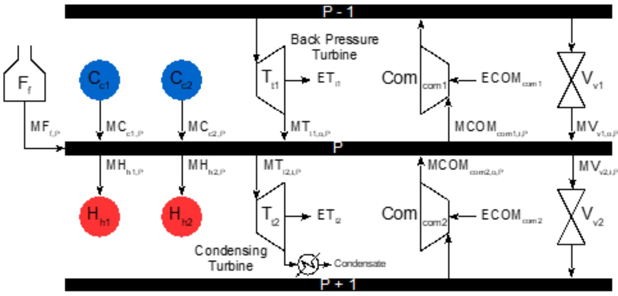
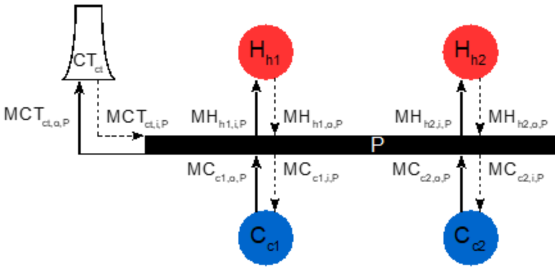


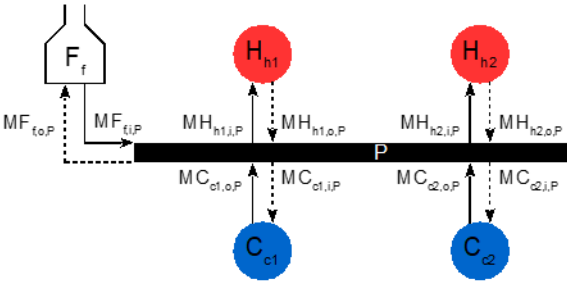
(a) Onion diagram for Total Site sharing utilities



(b) Different headers for an isothermal utility in Total Site



(c) Non-isothermal cooling utility (Cooling Water) in Total Site



(d) Non-isothermal heating utility in Total Site (e.g. flue gas)

Figure 1: Model representation

2. Model and equations used

2.1 Overall representation

Steam streams are grouped according to pressure and assumed to be in the saturated state. Steam headers are used as black boxes for each steam pressure level. Only turbines, compressors and valves are connecting between two steam headers. Figure 1b shows steam used as the utility. The steam pressure is highest at P-1 and decreases in the order of P-1 > P > P+1. Additional steam may be provided by the furnace. Beside steam, there can be also non-isothermal cooling (Figure 1c) and non-isothermal heating (Figure 1d).

2.2 Assumptions

All utilities used in the Total Site do not mix. Each type of utilities used (e.g. steam, hot oil, cooling water) has its own sets of steam headers. All steam headers, coolers and heaters are modelled as black boxes. In Heat Integration analysis, flows in steam header diagram are usually expressed in terms of energy flowrate, such as kW. It should be noted that energy flowrate cannot be measured directly. In data reconciliation process, all flows are measured and expressed in terms of mass flowrate instead. Especially for heaters or coolers using non-isothermal utilities, the supply and return streams are measured in terms of mass flowrates. For equipment with just inlets and outlets, the mass balance around the equipment is just total mass flowrate in equals to total mass flowrate out. For example, for a letdown valve connecting two headers (Figure 1b), the mass balance around the valve is given in Eq(1).

$$RMV_{v,i,P1} = RMV_{v,o,P2} \tag{1}$$

2.3 Cooler and heaters

For isothermal utility such as steam, it is generated in coolers (if the temperature is sufficiently high) and consumed in heaters. The inlets for coolers and outlets for heaters are not considered in the study. This is due to the qualities of the steam is different, although the streams are at the same pressure. As steam header is assumed to have only saturated steam, only latent heats are involved in these coolers and heaters. It is also assumed that there is no pressure drop in both coolers and heaters. Only mass flowrates are considered, as steams with known pressure are fed directly from/to steam header. The furnace is modelled as a cooler.

As for non-isothermal utility, both inlet and outlet are considered if the data is available for a heater or cooler. Else, the only one of the streams is sufficient to be included in the data reconciliation process. A furnace is modeled as a cooler while cooling water is modeled as a heater.

2.4 Steam turbine

Steam turbine takes higher pressure steam to produce electricity and rejects lower pressure steam. Back pressure turbine and condensing turbine are commonly used. In Total Site, back pressure turbine is more common as lower pressure steam can be used for further heating. Back pressure turbine connects between two steam headers. If lower pressure steam is not required, a condensing turbine can be used. Since the outlet of condensing turbine is not included into any steam header, only the condensing turbine inlet is reconciled.
For a back pressure turbine, T_t (Figure 1b), the mass balance around the turbine is shown in Eq(2). As for condensing turbine, Eq(2) is not used as there is no outlet.

$$RMT_{t,i,P1} = RMT_{t,o,P2} \tag{2}$$

As for the energy balance around the turbine, it is simplified to have power generated per unit steam mass flow and its enthalpy drop h_t. The efficiency, η_{Tt} is considered a constant.

$$RMT_{t,i,P1} \times h_t \times \eta_{T_t} = RET_t \tag{3}$$

2.5 Compressor

Although compressor is uncommon in Total Site, it is used sometimes to upgrade lower grade isothermal utilities to higher grade. For a compressor, e.g. COM_{com} in Figure 1b, the mass balance around the compressor is shown in Eq(4).

$$RMCOM_{com,i,P2} = RMCOM_{com,o,P1} \tag{4}$$

As for the energy balance around the compressor, the used power is modelled as proportional to the product of the steam mass flow enthalpy increase h_{com}. The efficiency, ηCOM_{com} is considered a constant.

$$RMCOM_{COM,i,P1} \times h_{com} \times \eta COM_{com} = RECOM_{com} \tag{5}$$

2.6 Overall mass balance

The mass balance around one steam header for isothermal utility is given in Eq(6).

$$\begin{aligned} \sum^{f} RMF_{f,P} + \sum^{c} RMC_{c,P} + \sum^{t} RMT_{t,o,P} + \sum^{com} RMCOM_{com,o,P} + \sum^{v} RMV_{v,o,P} \\ = \sum^{h} RMH_{h,P} + \sum^{t} RMT_{t,i,P} + \sum^{com} RMCOM_{com,i,P} + \sum^{v} RMV_{v,i,P} \end{aligned} \tag{6}$$

The mass balance around one steam header for non-isothermal utility is given in Eq(7) and Eq(8). For cooling utilities,

$$\sum^{ct} RMCT_{ct,i,P} + \sum^{h} RMH_{h,i,P} = \sum^{c} RMC_{c,o,P} \tag{7}$$

For heating utilities,

$$\sum^{f} RMF_{f,i,P} + \sum^{c} RMC_{c,o,P} = \sum^{h} RMH_{h,i,P} \tag{8}$$

2.7 Objective functions

For all Isothermal Utilities, UI_P,

$$
\begin{aligned}
OBJ_I = & \sum^{P}\sum^{h}\sum^{n}\left(MH_{h,P,n} - RMH_{h,P}\right)^2 + \sum^{P}\sum^{c}\sum^{n}\left(MC_{c,P,n} - RMC_{c,P}\right)^2 \\
& + \sum^{P}\sum^{f}\sum^{n}\left(MF_{f,P,n} - RMF_{f,P}\right)^2 + \sum^{P}\sum^{t}\sum^{n}\left(MT_{t,o,P,n} - RMT_{t,o,P}\right)^2 \\
& + \sum^{P}\sum^{t}\sum^{n}\left(MT_{t,i,P,n} - RMT_{t,i,P}\right)^2 + \sum^{t}\sum^{n}\left(ET_{t,n} - RET_{t}\right)^2 \\
& + \sum^{P}\sum^{com}\sum^{n}\left(MCOM_{com,i,P,n} - RMCOM_{com,i,P}\right)^2 \\
& + \sum^{P}\sum^{com}\sum^{n}\left(MCOM_{com,o,P,n} - RMCOM_{com,o,P}\right)^2 \\
& + \sum^{com}\sum^{n}\left(ECOM_{com,n} - RECOM_{com}\right)^2 + \sum^{P}\sum^{v}\sum^{n}\left(MV_{v,i,P,n} - RMV_{v,i,P}\right)^2 \\
& + \sum^{P}\sum^{v}\sum^{n}\left(MV_{v,o,P,n} - RMV_{v,o,P}\right)^2
\end{aligned} \tag{9}
$$

For all non-isothermal Utilities, UN_P

$$
\begin{aligned}
OBJ_N = & \sum^{P}\sum^{c}\sum^{n}\left(MC_{c,P,o,n} - RMC_{c,P,o}\right)^2 + \sum^{P}\sum^{h}\sum^{n}\left(MH_{h,P,i,n} - RMH_{h,P,i}\right)^2 \\
& + \sum^{P}\sum^{c}\sum^{n}\left(MC_{c,P,i,n} - RMC_{c,P,i}\right)^2 + \sum^{P}\sum^{h}\sum^{n}\left(MH_{h,P,o,n} - RMH_{h,P,o}\right)^2 \\
& + \sum^{P}\sum^{f}\sum^{n}\left(MF_{f,P,o,n} - RMF_{f,P,o}\right)^2 + \sum^{P}\sum^{ct}\sum^{n}\left(MCT_{ct,P,i,n} - RMCT_{ct,P,i}\right)^2 \\
& + \sum^{P}\sum^{f}\sum^{n}\left(MF_{f,P,i,n} - RMF_{f,P,i}\right)^2 + \sum^{P}\sum^{ct}\sum^{n}\left(MCT_{ct,P,o,n} - RMCT_{ct,P,o}\right)^2
\end{aligned} \tag{10}
$$

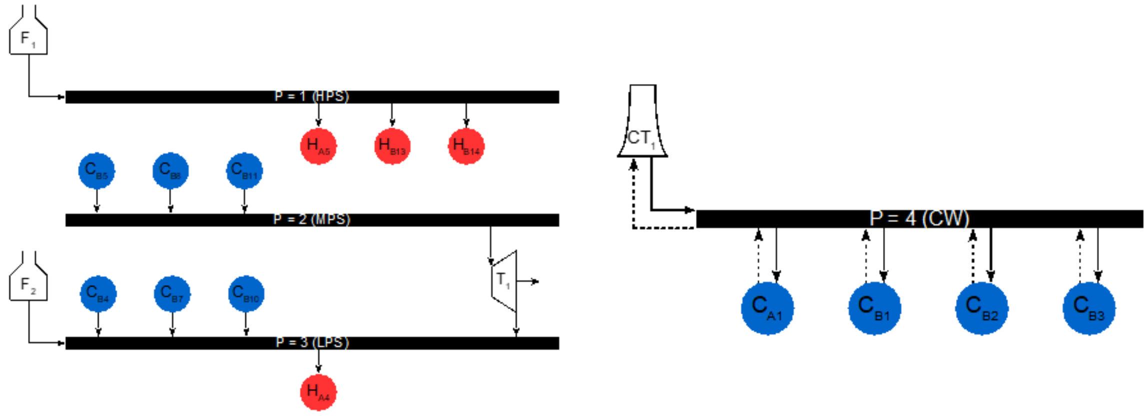
Overall the objective is to

$$
\begin{aligned}
& Min\ (OBJ_I + OBJ_N) \\
& = \sum^{P}\sum^{h}\sum^{n}\left(MH_{h,P,n} - RMH_{h,P}\right)^2 + \sum^{P}\sum^{c}\sum^{n}\left(MC_{c,P,n} - RMC_{c,P}\right)^2 \\
& + \sum^{P}\sum^{f}\sum^{n}\left(MF_{f,P,n} - RMF_{f,P}\right)^2 + \sum^{P}\sum^{t}\sum^{n}\left(MT_{t,o,P,n} - RMT_{t,o,P}\right)^2 \\
& + \sum^{P}\sum^{t}\sum^{n}\left(MT_{t,i,P,n} - RMT_{t,i,P}\right)^2 + \sum^{t}\sum^{n}\left(ET_{t,n} - RET_{t}\right)^2 \\
& + \sum^{P}\sum^{com}\sum^{n}\left(MCOM_{com,i,P,n} - RMCOM_{com,i,P}\right)^2 \\
& + \sum^{P}\sum^{com}\sum^{n}\left(MCOM_{com,o,P,n} - RMCOM_{com,o,P}\right)^2 \\
& + \sum^{com}\sum^{n}\left(ECOM_{com,n} - RECOM_{com}\right)^2
\end{aligned} \tag{11}
$$

$$
\begin{aligned}
&+\sum^{P}\sum^{v}\sum^{n}\left(MV_{v,i,P,n}-RMV_{v,i,P}\right)^{2}+\sum^{P}\sum^{v}\sum^{n}\left(MV_{v,o,P,n}-RMV_{v,o,P}\right)^{2}\\
&+\sum^{P}\sum^{c}\sum^{n}\left(MC_{c,P,o,n}-RMC_{c,P,o}\right)^{2}+\sum^{P}\sum^{h}\sum^{n}\left(MH_{h,P,i,n}-RMH_{h,P,i}\right)^{2}\\
&+\sum^{P}\sum^{c}\sum^{n}\left(MC_{c,P,i,n}-RMC_{c,P,i}\right)^{2}+\sum^{P}\sum^{h}\sum^{n}\left(MH_{h,P,o,n}-RMH_{h,P,o}\right)^{2}\\
&+\sum^{P}\sum^{f}\sum^{n}\left(MF_{f,P,o,n}-RMF_{f,P,o}\right)^{2}+\sum^{P}\sum^{ct}\sum^{n}\left(MCT_{ct,P,i,n}-RMCT_{ct,P,i}\right)^{2}\\
&+\sum^{P}\sum^{f}\sum^{n}\left(MF_{f,P,i,n}-RMF_{f,P,i}\right)^{2}+\sum^{P}\sum^{ct}\sum^{n}\left(MCT_{ct,P,o,n}-RMCT_{ct,P,o}\right)^{2}
\end{aligned}
\qquad (12)
$$

3. Illustrative case study

The following case study is adapted from Liew et al. (2012) – Figure 2. The steam pressures are at 55 bar (P1 = HPS), 10 bar (P2 = MPS) and 3 bar (P3 = LPS). For HPS, there are only heaters, and a furnace (F1) producing HPS. There is an excess of MPS, which is fed to the turbine (T1) producing electricity. Furnace (F2) generates steam in addition to the exhaust fromT1 and generation from coolers. Cooling water (P4) is also used. The turbine, the efficiency is assumed to be 75 %.
It is assumed that all streams are recorded, including the outlets of coolers and inlet to the cooling tower. All stream parameters are measured repeatedly over a period of time. Outliers are identified and discarded. Ten sets of measurements are selected for data reconciliation. Table 1 shows mean measured values.



(a) Steam levels (b) Cooling header

Figure 2: Different steam headers as the isothermal and non-isothermal utility for the illustrative case study

4. Results and discussion

All the parameters satisfy the constraints. When compared with the mean values, the differences are no more than 2 % (Table 1). Low-value parameters tend to have higher differences, particularly those below 100 kg/h. To solve this issue, in a future work, weight could be given to low-value parameters such that they carry the same importance as the high-value parameter. This will have more evenly distributed difference. When this method is compared with an iterative method, in this illustrative case the differences are mostly < 1 %, and at most 2.5 %. As with simultaneous method, in this illustrative case study, the differences are all below 2 %. It can be concluded that this method of just considering the utility systems is performing well as close as an iterative method and simultaneous method. Some parameters have better results when Iterative Method is used. The computational effort when using this method is significantly lower than the other two methods. The parameters are reduced from 168 to 25. In terms of computational speed, in this case study, although it just merely cut the time from 2 s to 1 s, it would have significant differences when a larger Total Site study is used.

Table 1: Results obtained and comparisons with other methods

Parameters	Unit	Mean value	Reconciled Value (This Study)	Percentage difference (%)		
				This Study	Iterative Method	Simultaneous Method
$MH_{A5,1}$	kg/h	1,233.5	1,233.9	0.03	-0.37	-1.17
$MH_{B13,1}$	kg/h	89.7	90.0	0.33	-1.25	-1.54
$MH_{B14,1}$	kg/h	134.4	134.8	0.30	-1.26	-0.06
$MF_{1,1}$	kg/h	1,459.0	1,458.7	-0.02		
$MC_{B5,2}$	kg/h	17.8	18.1			
$MC_{B8,2}$	kg/h	26.7	27.0	1.69	-0.15	-1.98
$MC_{B11,2}$	kg/h	338.8	339.1	1.12	-1.00	-2.20
$MT_{1,i,2}$	kg/h	385.2	384.2	0.09	-0.37	-0.30
$MC_{B4,3}$	kg/h	77.3	78.1	-0.26		
$MC_{B7,3}$	kg/h	116.1	117.0			
$MC_{B10,3}$	kg/h	1,467.3	1,468.2	1.04	0.54	-1.26
$MT_{1,o,3}$	kg/h	384.3	384.2	0.78	-0.24	-0.94
$MF_{2,3}$	kg/h	783.4	784.2	0.06	0.60	0.50
$MH_{A4,3}$	kg/h	2,832.6	2,831.8	-0.03		
ET_1	kJ/h	47,127.3	47,127.3	0.10		
$MCT_{1,i,4}$	kg/h	31,284.3	31,309.4	0.08		
$MCT_{1,o,4}$	kg/h	31,349.6	31,309.4	-0.13		
$MC_{A1,i,4}$	kg/h	17,127.9	17,136.5	0.05	-0.80	0.12
$MC_{A1,o,4}$	kg/h	17,130.0	17,136.5	0.04	-0.80	0.12
$MC_{B1,i,4}$	kg/h	4,860.0	4,872.9	0.27	0.56	-0.28
$MC_{B1,o,4}$	kg/h	4,870.7	4,872.9	0.05	0.56	-0.28
$MC_{B2,i,4}$	kg/h	2,798.6	2,804.0	0.19	0.05	-0.48
$MC_{B2,o,4}$	kg/h	2,794.3	2,804.0	0.35	0.05	-0.48
$MC_{B3,i,4}$	kg/h	6,501.4	6,496.1	-0.08	2.52	1.83
$MC_{B3,o,4}$	kg/h	6,475.7	6,496.1	0.32	2.52	1.83

5. Conclusions

This paper presents a new approach to solve data reconciliation problem on Total Site. A model to solve data reconciliation of a utility system is presented, illustrated by a case study. In the illustrative case study, the difference compared to respective mean values has no more than 2 %. Compared to the iterative method and simultaneous method at no more than 2.5 %, it is found to perform better by not including all heat exchangers in the data reconciliation problem. Overall, it is shown to need less computational effort at the expense of lower accuracy, when compared to other methods. It is suitable to be used in Heat Integration study particularly retrofitting heat exchange network, which does not need a high level of accurate data.

Acknowledgements

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