

A Superstructure Approach for the Design of Heating Utility System

Diban Pitchaimuthu*, Jui-Yuan Lee, Mahmoud El-Halwagi, Dominic C. Y. Foo

Centre of Excellence for Green Technologies/Department of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia.
 done_87@yahoo.com

Heavy crude oil produced from reservoir normally requires heating in order to facilitate proper oil water separation at the separator. Providing heat helps to reduce the viscosity of the crude thus reducing the residence time required at the separator and its size. In conventional heating utility system, the heating medium is supplied to its users in parallel design where all the users receive the heating medium at the supply temperature. This design however may lead to overdesign of the heating utility system. In this paper, a novel superstructure approach is proposed to determine the optimum network design of the heating medium system with minimum total annualised cost. The novelty of this approach is that it allows determination of the global optimum solution for the system while taking into consideration of all possible network configuration. The approach caters for capital and operating costs trade-off for the heat exchanger network (HEN) and waste heat recovery unit (WHRU) in the heating utility system. An industrial case study is used to elucidate the newly proposed technique.

1. Introduction

The oil price has suffered a big drop in recent years from its all-time high price of USD 146/bbl in 2006 (Macrotrends, 2017). As a consequence, oil production companies have to be more prudent either in their new exploration or operation of their existing facility in this uncertain market condition. A few potential improvements in the design of the existing oil and gas platform were studied by Nyugen et al. (2016a) in their research paper. They summarised that modification such as limiting anti-surge recirculation at the gas compression, installation of multi-level (low and high pressure) production manifold, and waste heat recovery as having good energy saving potential. Other energy efficiency improvements such as heat integration by direct heat exchange between the hot and cold process streams was found not viable due to operation reasons (Nyugen et al., 2016b). The installation of organic Rankine cycle - ORC (Pierobon et al., 2014) or steam Rankine cycle - SRC (Nyugen et al., 2014) to recover waste heat is an attractive option in the near future. Another system that has potential for improvement but has been overlooked is the heating utility system. This is reported by de Oilivera and Van Hombeeck (1997) that petroleum heating and separation steps as the most inefficient exergy user in oil and gas platform. The heating utility system is normally used on offshore platform when heavy crude oil is produced from the reservoir. Heating the heavy crude helps to reduce its viscosity thus cutting down the residence time required at the separator and consequently its size. Common heating media used in oil and gas platform are oil and water due to their availability while ethylene glycol is sometimes used at offshore location with freezing temperature. This paper discusses a systematic approach based on superstructure method in designing the optimum heating medium system.

Heating utility system like other central utility systems is a unique HIWN problem, as a single source (heating medium) is used to provide heating requirement to all its users. This is different from the conventional heat exchange network (HEN) whereby heat is integrated between process streams and when there exist insufficient or excess heat, steam or cooling water are used to meet the demand of the overall network. The steam and cooling water is assumed able to be obtained from a source at particular price. However, this is far from true. In a typical chemical plant, the heating or cooling medium is generated from a utility system. Recent superstructure works avoids the consideration of such system. Due to this, their optimisation model cannot be applied directly for design of heating medium system. There are a few handful research works carried out on the design of

central utility systems. Some graphical approaches were proposed to target the minimum flowrate for cooling water network (Kim and Smith, 2001) and chilled water network (Foo et al., 2014), while Ataei et al. (2014) proposed a similar approach for hot oil system which closely resembles heating utility system. It is to be highlighted that their works did not find the optimum overall cost of the system rather only optimum heating medium flowrate. On the other hand, Bade and Bandyopadhyay (2014) proposed an iterative approach to determine the optimum total overall cost solution for the hot oil system. In their approach, they varied the minimum approach temperature (ΔT_{\min}) to calculate the minimum flowrate and the respective area required for the network. The downside of their proposed method is that it is a time-consuming process, as detailed network for different ΔT_{\min} values needs to be determined, before the total cost can be calculated. Besides, their approach does not guarantee global optimum. The proposed new superstructure model that is presented guarantees global optimum for the utility system which is not considered in conventional HEN model.

2. Heating utility system problem statement

For a given set of heating medium user (heat exchangers) $m \in M$, each with a fixed heat load Q_m to be provided by the heating medium (water, hot oil or glycol), and with specified maximum inlet ($T_{in, m}$) and outlet ($T_{out, m}$) temperatures. The heating medium (with return temperature T_{HMR}) is reheated using WHRU using exhaust gas from gas turbine generator and gas turbine compressor at specified maximum inlet ($T_{in, g}$) and outlet ($T_{out, g}$) temperatures. The reheated heating medium at circulation temperature (T_{HM}) is re-circulated among the heating medium users to provide the necessary heating. The main objective is to synthesise an optimum heating medium network, that have the lowest total overall cost while meeting the heat load requirements of all heating medium users.

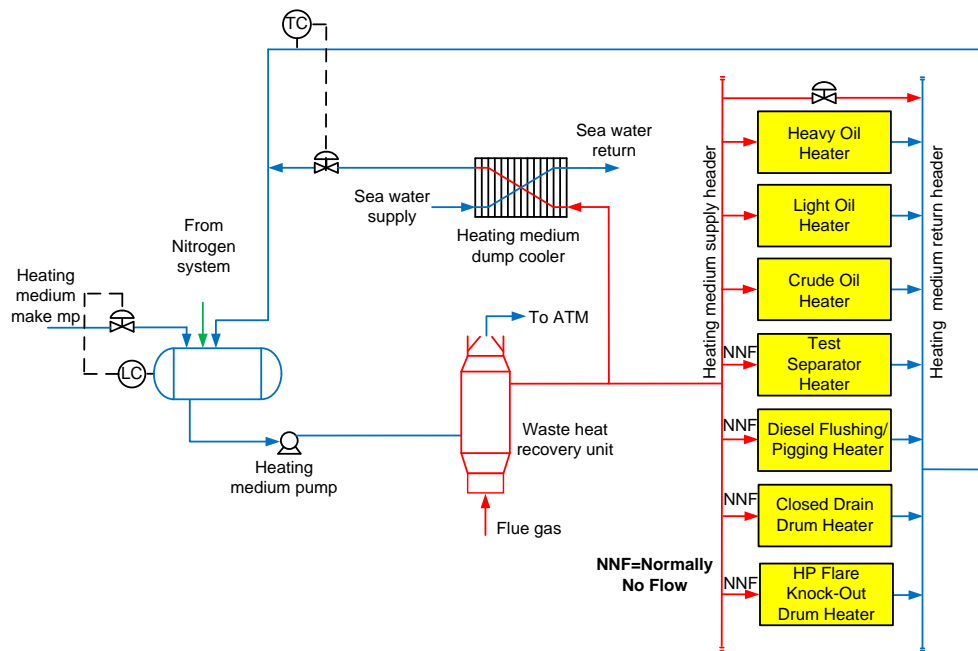


Figure 1: PFD of heating utility system for an offshore platform

3. Superstructure model for HEN

The general superstructure model for heating utility system is shown in Figure 2. The model is a generic representation of a single heating medium user in the system. For every user, the heating medium at supply temperature (F_{HM}) is allowed to mix with the used heating medium from its own or other users ($F_{m',m}$) at the mixing point C. After heat exchange with the process fluid, the heating medium flowrate can be split at the splitting point, S either to WHRU for reheating ($F_{v,m}$) or reused by the users ($F_{m,m}$).

The mass balance at point C and S and the energy balance at point C is given by Eqs(1-3).

$$F_m = \sum_{m' \in M} F_{m',m} + F_{HM,m} \quad \forall m \in M \quad (1)$$

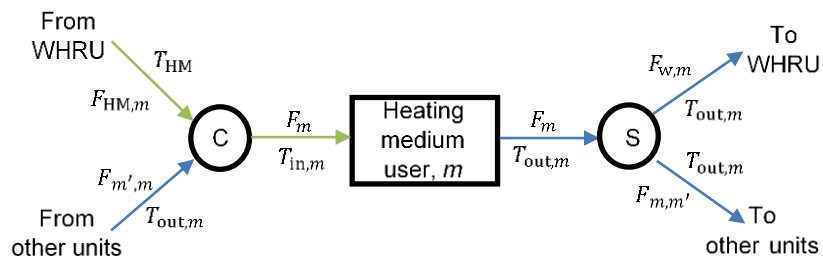


Figure 2: Generic superstructure model for heating utility system

$$F_m = \sum_{m \in M} F_{m,m'} + F_{w,m} \quad \forall m \in M \quad (2)$$

$$F_m T_{in,m} = \sum_{m \in M} F_{m',m} T_{out,m} + F_{HM,m} T_{HM} \quad \forall m \in M \quad (3)$$

where $T_{in,m}$ and $T_{out,m}$ are the inlet and outlet temperature of the heating medium passing through heat exchanger of m user, F_m is the flowrate of the heating medium into the heat exchanger of m user and T_{HM} is heating medium supply temperature. The energy balance at each unit heat exchanger is calculated using Eq.(4).

$$Q_m = F_m (T_{in,m} - T_{out,m}) \quad \forall m \in M \quad (4)$$

where Q_m is the total enthalpy required by the individual user. For determination of heating medium return temperature, T_{HMR} Eqs(5-6) are used.

$$F_w = \sum_{m \in M} F_{w,m} \quad (5)$$

$$F_w T_{HMR} = \sum_{m \in M} F_{w,m} T_{out,m} \quad (6)$$

The limit for the inlet and outlet temperature of the heating medium entering and leaving the heat exchanger are given by Eqs(7-10).

$$T_{in,m} \leq T_{HM} \quad \forall m \in M \quad (7)$$

$$T_{in,m} \geq T_{in,m \text{ Limit}} \quad \forall m \in M \quad (8)$$

$$T_{out,m} \geq T_{out,m \text{ Limit}} \quad \forall m \in M \quad (9)$$

$$T_{out,m} < T_{HM} \quad \forall m \in M \quad (10)$$

In order to reduce the search scope when computing the solution, flow limit for each connection is introduced using Eq.(11). The flow limit is derived based on American Petroleum Institute (API) 14E (1991), which recommends that the flow velocity should not exceed maximum velocity of 4.572 m/s to minimise flashing ahead of control valve. While for the minimum velocity, it is recommended to limit the velocity to 0.9144 m/s to minimise deposition of sand and other solid. Using this information together with the assumption that the biggest and smallest pipe size that are used are 6" and 1/2", the upper and lower flow limit for the connection is calculated to be 432.891 and 3.1408 kW/°C.

$$3.1408 \leq F_{m',m} \leq 432.891 \quad \forall m \in M \quad I[0,1] \quad (11)$$

For HEN area calculation, the log mean temperature difference is determined using Eq.(12).

$$T_{log,m} = \frac{(T_{in,m} - T_{out,m \text{ Limit}}) - (T_{out,m} - T_{in,m \text{ Limit}})}{\text{LN}[(T_{in,m} - T_{out,m \text{ Limit}}) - (T_{out,m} - T_{in,m \text{ Limit}})]} \quad \forall m \in M \quad (12)$$

The area required for the HEN is calculated using Eq(13).

$$A_{HEN} = \sum_{m \in M} \frac{Q_m}{T_{log,m} h_m} \quad (13)$$

where h_m is the overall heat transfer coefficient for user m .

4. Sizing and costing of other equipment in the heating utility system

Besides the HEN, heating utility system of the offshore platform consists of two other major units i.e. WHRU and pump. Design variables of these units, e.g. area of WHRU and power consumption of the pump are to be considered before the cost optimum heating utility system design can be determined. For the WHRU, its log mean temperature (T_{WHRU}) is calculated based on Eq(14) that follows, i.e.,

$$T_{WHRU} = \frac{(T_{in,g} - T_{HM}) - (T_{out,g} - T_{HMR})}{LN[(T_{in,g} - T_{HM}) - (T_{out,g} - T_{HMR})]} \quad (14)$$

where $T_{in,g}$ is the gas turbine generator and/or gas turbine compressor exhaust gas temperature to the WHRU while $T_{out,g}$ is the exhaust gas temperature leaving WHRU after heat transfer with the heating medium. Next, the area of WHRU (A_{WHRU}) is calculated using Eq(15),

$$A_{WHRU} = \frac{Q}{U_e T_{WHRU}} \quad (15)$$

where Q is the total heat load required to be transferred from the exhaust gas to the heating medium and U_e is the enhanced overall heat transfer coefficient. For brevity, the steps involved in calculating these enhanced overall heat transfer is excluded from this paper, however readers can refer to the detailed steps found in Nitsche and Gbadamosi (2016).

The shaft power required by the pump (P_s) to circulate the heating medium in the close loop system is calculated using Eq(16),

$$P_s = \frac{1.1 F_{min} g d}{1 \times 10^3 C_{P_{HM}} \eta} \quad (16)$$

where g is the gravitational force, d is the net differential head required to transfer the heating medium to its required users, $C_{P_{HM}}$ is the specific heat capacity of heating medium and η is the pump efficiency. A design margin of 10 % is included in the heating medium flowrate for pump design purpose. The capital cost of the equipment is annualised based on the lifespan of the offshore platform which is typically between a period of 20-30 y using Eq.(17).

$$AF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (17)$$

where i and n represent the interest rate and number of years respectively. The annualised capital cost of HEN, WHRU and the pump are calculated based on the correlations in Eqs(18-20) (Smith, 2005),

$$C_{HEN} = N AF \left[a + b \left(\frac{A_{HEN}}{N} \right)^c \right] \quad (18)$$

where N = number of units/shells, whichever is appropriate, a = installation cost, b = area cost, c = constant.

$$C_{WHRU} = C_B AF \left(\frac{A_{WHRU}}{D_B} \right)^M \quad (19)$$

where C_{WHRU} = WHRU cost with capacity A_{WHRU} , C_B = known base cost of equipment with capacity D_B , M = constant depending on equipment type

$$C_P = C_B AF \left(\frac{P_s}{D_B} \right)^M \quad (20)$$

where C_P = pump cost with capacity P_s , C_B = known base cost of equipment with capacity D_B , M = constant depending on equipment type

Note that the capital cost correlation for WHRU is based on that for air cooled heat exchanger. The operating cost of the heating medium system (C_U) based on the power consumption of the circulation pump is determined using Eq.(21).

$$C_U = P_s W G \quad (21)$$

where P_s is the pump power, W is the duration of usage and G is the electricity tariff.

The optimisation equation is set to minimise the total annualised cost (TAC) of the heating medium system, given by Eq. 22. The model will also determine the optimum network configuration for the system. To elucidate the proposed superstructure model, an industrial case study is presented in the following section.

$$TAC = C_{HEN} + C_{WHRU} + C_P + C_U \quad (22)$$

5. Case study

In this section, an industrial case study is used to demonstrate the use of the proposed superstructure approach to design a cost-optimum heating utility system. An offshore floating production storage offloading (FPSO) platform is to be installed at Angola (Africa). Its PFD is similar to that in Figure 1, with its limiting data for the cold streams shown in Table 1. The flue gas inlet ($T_{in, g}$) and outlet temperature ($T_{out, g}$) are 433 °C and 130 °C. While the heating medium temperature (T_{HM}) is set at 130 °C. Data for the design of WHRU and pump are as follow: overall heat transfer, U_e (326.5 kWm⁻²°C⁻¹), height, d (51.8m), efficiency, η (60%), heating medium average specific heat capacity, CP_{HM} (4.326 kWm⁻²°C⁻¹).

Table 1: Limiting cold streams data for industrial case study

Unit, m	Inlet Temperature, $T_{in, m}$ (°C)	Outlet Temperature, $T_{out, m}$ (°C)	Cold streams overall heat transfer coefficient, h_m (kWm ⁻² °C ⁻¹)	Load, Q_m (kW)	Limiting heat capacity flowrate, F_m (kW°C ⁻¹)
1	30	65	2	3,630	103.71
2	39	65	1	9,174	352.85
3	57	90	1.5	6,689	202.70
Total				19,493	659.26

Table 2: Data for costing calculation. *Data from Smith (2005). **Data adjusted based on CE index of October 2014 (Chemical Engineering, 2015).

Parameters	Value	Parameters	Value
i	10 %	WHRU*, M	0.89
n	25 y	Pump*, C_B	\$ 9.2594x10 ⁴ **
a^*	260,800**	Pump*, D_B	4 kW
b^*	3260**	Pump*, M	0.55
c^*	1	Duration, W	8,760 h
WHRU*, C_B	\$ 1.0171x10 ⁶ **	Electrical tariff, G	0.12 \$/h
WHRU*, D_B	200 m ²		

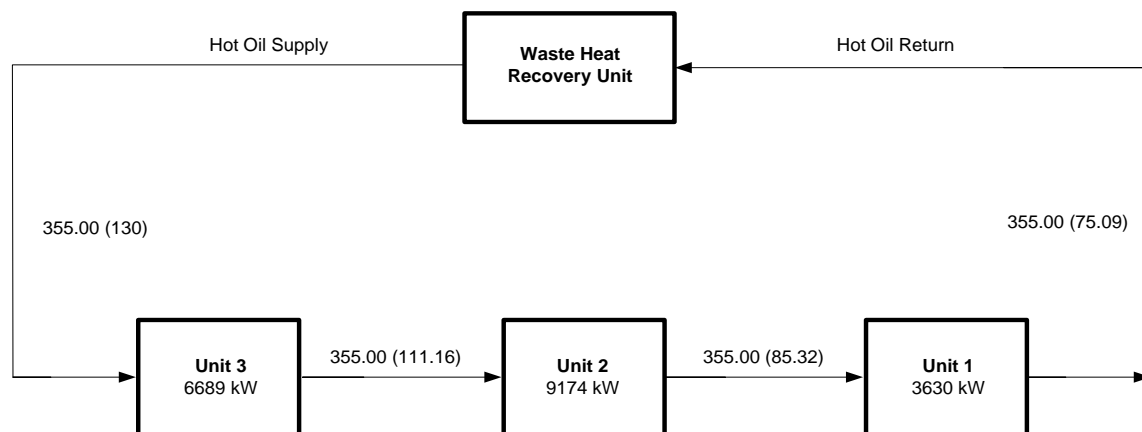


Figure 3: Final configuration of heating utility network for case study (heat capacity flowrate in kW/°C, temperature in °C, given in parenthesis).

Solving the objective function in Eq(22) subject to the constraints in Eqs(1-21) yields the minimum total annualised cost of the heating medium as \$ 632,679. The optimum HEN design obtained from the superstructure solution is shown in Figure 3. The design encompasses a series design of the HEN. Table 3 shows the comparison between the result obtained from the superstructure approach against the conventional design (see Figure 1), where the heating medium is fed to all heat exchangers at 130 °C and returns at 90 °C.

The conventional design TAC is determined as \$ 664,880, thus an annual saving of \$ 32,201 (corresponds to 4.8 % reduction) can be achieved through the series design shown in Figure 3.

Table 3: Comparison of cost between optimum design from superstructure approach and conventional design.

Elements	This work	Conventional design
Annualised capital cost	HEN (\$/y)	295,053
	WHRU (\$/y)	205,596
	Pump (\$/y)	51,680
Total annualised capital cost (\$/y)	552,329	538,822
Total Utility Cost (\$/y)	80,350	126,059
TAC (\$/y)	632,679	664,880

6. Conclusions

This work proposes a novel superstructure approach for the design of heating utility system, which is not covered in conventional HEN design. The proposed method allows the lowest total annualised cost of the system to be determined by weighing the best trade-off between capital and operating cost of the system. The main advantage of this approach as compared to other techniques that has been published for central utility design is that it allows global optimum solution to be obtained. Besides, the proposed superstructure approach provides the solution for optimum HEN which produces the minimum TAC. An industrial case study was used for demonstration; it proves that the total annualised cost of the system is reduced by 4.8 % by changing the existing HEN from parallel to series design.

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