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Analysis of a Looped Steam Pipe Network

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In this work, we report on analysis of a looped steam pipe network with multi-input steam sources and multi-output background process sinks. Hardy Cross method, which was developed for looped water pipe network analysis, is adopted and modified to determine steam flow distributions in all connecting pipes in the looped steam pipe network with consideration of the heat loss from these pipes to the surroundings and the pressure drop within the pipes. Then, pressure profile, temperature profile, as well as condensate are calculated and used to determine steam flow path within the steam pipe network. Finally, movement of locations of possible stagnation points, where the steam flow rate is significantly smaller than the normal operating conditions, are identified in several network operating scenarios. These analyses will be demonstrated in a large-scale refinery in Taiwan as a basis for optimal operation and plant retrofit. Similar analysis will be also applied on the typical high pressure steam distribution network in an industrial complex in Taiwan.

1. Introduction

Steam pipe networks play an important role in transporting heat energy to process units in chemical industry, such as distillation columns and thermal cracking units. Yet, because pressure drop and heat loss occur when steam flow through pipes, subcooling phenomenon and condensation may take place at the ‘‘stagnation points’’, sections where steam flowrate is significantly low. Moreover, the stagnation points will move after operating conditions of the network are changed. Due to poor quality and instability of steam flow at stagnation points, it is very difficult to operate process units near these points. Due to the above reasons, performing steam network analysis at different operating states is crucial to ensure process safety.

Accordingly, a number of researchers have investigated analysis of single pipeline. Idsinga et al. (1977) investigated the performance of two-phase pressure drop correlations for steam pipelines. Probert et al. (1982) investigated influential factors contributing energy cost of transmitting superheated steam in heat insulated pipes. Bialecki and Kruczek (1996) proposed an iterative algorithm to simulate steam flow through pipe segments and fittings. Verma and co-workers (García-Gutiérrez et al., 2009) developed a numerical model for analysis of the steam network at the Los Azufres geothermal field. Luo et al. (2012) proposed a hydraulic-thermal model and an iterative algorithm to determine steam flowrate in each pipe in a network. Guido et al. (2013) investigated the performance of cubic equations of state and non-analytical equations of state in simulation of carbon dioxide pipelines. Luigi Raimondi (2014) studied the dynamic phenomena in the pipeline transport of carbon dioxide.

However, looped network architecture are preferred because of reliability issues, especially in an integrated chemical plant which has a large number of interconnected process units. The most commonly analysis methods used to determine pipe discharges and nodal heads are the so-called Hardy Cross method (Cross, 1936), the Newton-Raphson method and the linear theory method (Isaacs and Mills, 1980). Manojlović et al. (1994) proposed an algorithm which applies the Hardy Cross method to determine optimal diameters of all pipes in a looped gas pipe network. Brkić (2009) made use of the original Hardy Cross method and the improved simultaneous method to analyze natural gas distribution networks. But, these methods are not applicable to analyse looped steam networks with compressible and non-isothermal flow. According to our knowledge, the method for analysing such networks has never been proposed. That is the purpose of this contribution.

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This manuscript is organized as follows: In Section 2, the method for analysis of looped steam networks are presented. An example of network analysis is presented in Section 3. Finally, conclusions are drawn in Section 4.

2. The Proposed model for pipe network analysis

In this study, we proposed a modified Hardy Cross method which can be applied to analyze looped pipe networks with compressible and non-isothermal steam flows.
To begin with, the following quantities are required to be known for analysis:

- Diameter D, length L and roughness e of pipes.
- Ambient temperature T_e.
- Overall heat transfer coefficient
- Pressure loss factor of fittings ζ.
- Inlet steam temperature, pressure and mass flow rate at each steam source on the network.
- Outlet steam mass flow rate at each steam sink on the network.

Following assumptions are made in the network analysis in this work:

- There is no steam accumulation within pipes.
- The amount of condensed water in the pipe network is very small. So, existence of condensed water does not affect physical properties of the steam flow.
- Speed of steam flows in the pipe network is smaller than 0.3 Mach.
- There are no compressors and turbines in the pipe network.

2.1 Mass balance at each node:
The mass balance equation can be written as follows:

$$\sum m_{in,total} = \sum m_{out,total} \tag{1}$$

where m is the mass flowrate.

2.2 Head balance for each loop:
If the operation of a network reaches its steady state, the sum of head loss around a closed loop should be zero. Eq(2) is the original head balance equation of the Hardy Cross method (Cross, 1936).

$$\sum_{\substack{All\ stream\ i \\ in\ loop\ k}} \frac{8}{\pi^2 D_i^4} \left(\frac{\overline{f_i} L_i}{D_i} \right) Q_i \left| Q_i \right| = 0 \tag{2}$$

Yet, Eq(2) is not applicable to analyze steam network because flow of steam is compressible. Therefore, we use mass flowrate m to substitute volumetric terms Q in Eq(2) and include the head loss in fittings. The modified equation can be written in the following:

$$\sum_{\substack{All\ stream\ i \\ in\ loop\ k}} \frac{8}{\pi^2 D_i^4 g \overline{\rho_i}} \left(\frac{\overline{f_i} L_i}{D_i} + \sum \zeta_i \right) m_i \left| m_i \right| = 0 \tag{3}$$

where ρ is density, f is friction factor, g is gravity constant and ζ is pressure loss factor of fittings. $\overline{\rho}$ and $\overline{f}$ are the mean quantities which are calculated based on the average of steam temperatures and pressures at both ends of the pipe segment.

In general, Eq(3) is not possibly satisfied with the initial guess of the mass flow rates. Similar to the original Hardy Cross method, we have to the apply correction of m, Δm. Therefore, the updated balance equation can be written as follows:

$$\sum_{\substack{All\ stream\ i \\ in\ loop\ k}} \frac{8}{\pi^2 D_i^4 g \overline{\rho_i}} \left(\frac{\overline{f_i} L_i}{D_i} + \sum \zeta_i \right) (m_i + \Delta m_k) \left| m_i + \Delta m_k \right| = 0 \tag{4}$$

Then, we can obtain the corrective term, Δm_k (Eq(5)) via expanding Eq(4) and ignoring the second order of Δm_k.

$$\Delta m_k = \frac{\displaystyle\sum_{\substack{All\ stream\ i \\ in\ loop\ k}} \frac{8}{\pi^2 D_i^4 g \overline{\rho_i}} \left(\frac{\overline{f_i} L_i}{D_i} + \sum \zeta_i \right) m_i \left| m_i \right|}{\displaystyle 2 \sum_{\substack{All\ stream\ i \\ in\ loop\ k}} \frac{8}{\pi^2 D_i^4 g \overline{\rho_i}} \left(\frac{\overline{f_i} L_i}{D_i} + \sum \zeta_i \right) \left| m_i \right|} \tag{5}$$

Updated values of m can be obtained by applying the corrections of m:

$$m_{i,updated} = m_{i,old} + \Delta m_k \qquad for\ all\ steam\ i\ in\ loop\ k \tag{6}$$

2.3 Mass balance at each node:
The procedure for analysis of looped steam networks is stated as follows:

1. Number all pipes, loops and nodes in the network.
2. Assume clockwise (or counter-clockwise) flow direction in all loops as positive direction.
3. Initial guess of pipe discharges: Assume minimum number of arbitrary pipe discharges and use the continuity equation to determine discharges other pipes.
4. Assume arbitrary uniform temperature and pressure in the entire network.
5. Use the initial value of pipe discharges, temperature and pressure to determine the average of density $\overline{\rho}$ and friction factor $\overline{f}$.
6. Use Eq(5) to obtain the correction of pipe discharge Δm_k.
7. Apply the correction of pipe discharge to every pipe in the network.
8. Repeat Step 5 to Step 7 until the correction of pipe discharge is smaller than the defined convergence criterion? (Ex: 0.01 %).
9. Select the node with maximum pressure as the starting point and use momentum balance to calculate pressure at remaining nodes.
10. Use energy balance to calculate temperature and amount of condensed water at each node.
11. Repeat Step 5 to Step 10 until corrections of pressure, temperature and pipe discharge are smaller than convergence criterion.
12. The flow distribution and flow patter of the network are obtained.

The procedures of looped steam networks analysis are summarized in Figure 1.

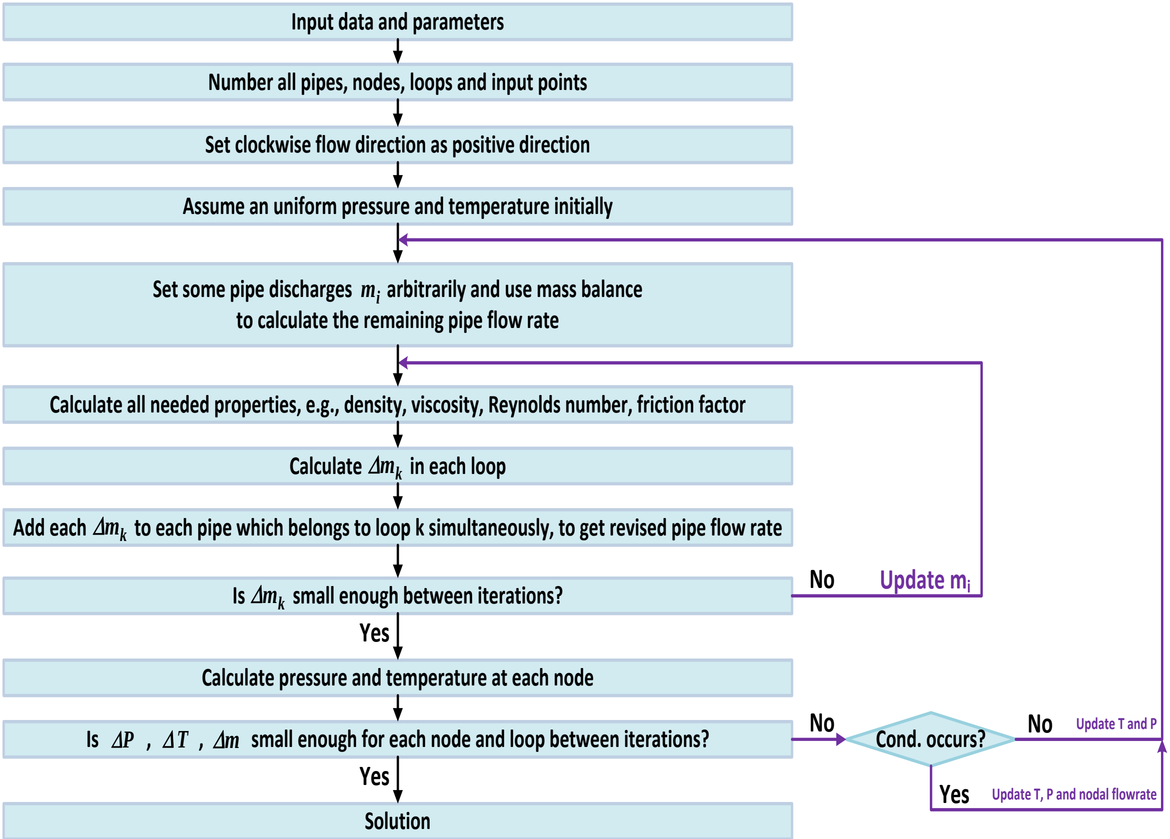

Figure 1: Procedures of steam network analysis

3. An illustrative example

In this section, we apply the proposed analysis method to one network example. This network has totally six pipes, five nodes with two sources and three sinks and two loops. Layout of this network is shown in Figure 2. Parameters for analysis are summarized in Table 1. The overall heat transfer coefficient is calculated based on the inner diameter of pipe. Results of analysis are summarized in Table 2 and flow pattern of the network is shown in Figure 3. The results show that the studied steam network does not have stagnation point. However, the flow rates in pipes 2 and 5 are much higher than other pipes. Whereas the flow rate in pipe 6 is quite small.

Table 1: Parameters for network analysis

Inner diameter of all pipes (m)	Thickness of pipe wall (m)	Thickness of heat insulation (m)	Overall heat transfer coefficient (W/(m^2*K))	Ambient Temperature (K)	Roughness (m)
0.15	0.03	0.15	1.05398	298.15	4.57*10^{-5}

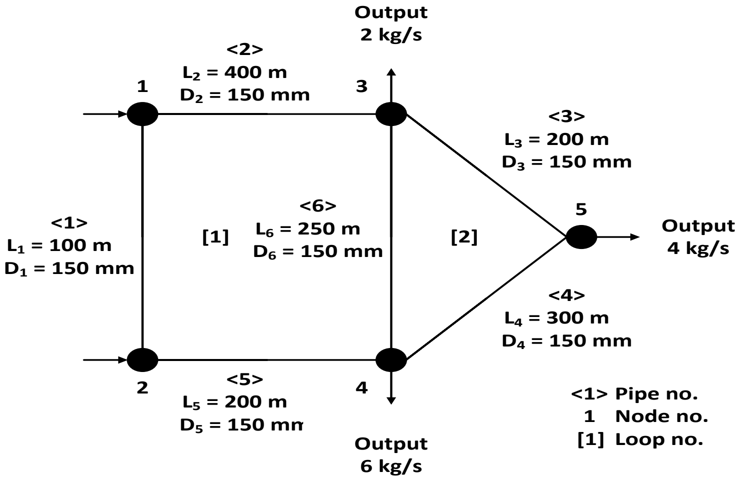

Figure 2: Layout of the network

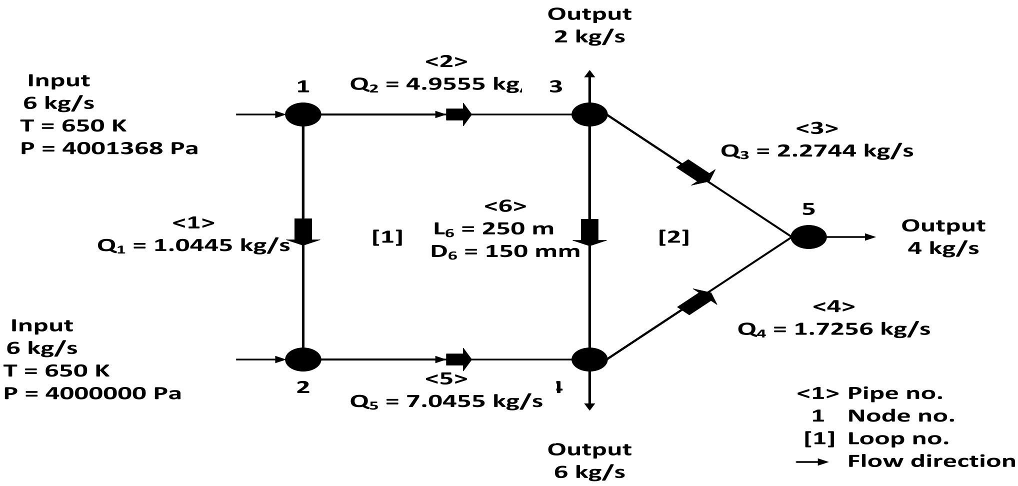

Figure 3: Flow pattern of the network

Table 2: Results of the illustrated network analysis

Pipe No.	Pipe Discharge (kg/s)	Node No.	Nodal Temp. (K)	Nodal Pressure (MPa)
1	1.0445	1	650.01	4.001368
2	4.9555	2	648.96	4.000000
3	2.2744	3	643.23	3.886559
4	1.7256	4	643.41	3.884920
5	7.0445	5	634.41	3.873985
6	0.6811			

4. Conclusions

In this work, a modified Hardy Cross method for analysis of looped steam networks is proposed. This method can be used to predict responses of pipe networks with different operating scenarios. The results are highly valuable to optimize network operation and prevent possible accidents. The analysis is performed in a large scale refinery in Taiwan in an on-going project.

Nomenclature

m mass flowrate
D inner pipe diameter
f friction factor
L length of pipes
T temperature
P pressure
ζ pressure loss factor of fittings
ρ density
g gravity constant
Q volumetric flowrate

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