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Dynamic modelling of site utility systems

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Process utility systems are complex and have the potential to achieve significant economic benefit by improving their design and operation. There are presents models based on thermodynamic analysis were built to predict the performance of plant equipment as well as searching minimum cost solutions. The objectives in this paper is to propose operating strategies as well as system structure based on transient analysis, while considering system flexibility in industrial operating scenarios. The paper presents analysis in design and optimisation of utility systems. A study of transient analysis has been carried out for boiler breakdown based on dynamic simulation.

1. Introduction

Site utility systems are a feature of all chemical or petrochemical plants. The utility systems transform basic energy of water feed into heating utility and power. Unfortunately, parallel unwanted wastes and greenhouse gases are produced. Building and running site utility systems is expensive and also has big impact onto the environment. That is why improving their design and operation could be a big potential to achieve significant economic benefits.

Site utility systems must fulfil steam and power demands that change significantly according to the process users demands. There are also uncertainties in utility equipment that have to be periodically shutdown for preventive maintenance or may unexpectedly fail.

2. Design of utility system

A typical process utility system comprises of steam generators, a steam distribution network and process users. There are many uncertainty problems, such as demand variations, scheduled maintenance or equipment failures, influence on system design and can be handled with several operation scenarios. As conditions change, the utility system transits from one operating state to another to satisfy processes demand under variable conditions. Traditionally, the design of utility systems has been proposed by considering a constant site configuration and fixed conditions. Some authors (Papoulias and Grossmann, 1983, Petroulas and Reklaitis, 1984) developed linear formulations to model utility units and others employed non-linear models to improve the accuracy of system calculations (Bruno et al., 1998). Recently, more dynamic factors have been introduced into design procedures for utility systems. Multi-period optimisation was applied for retrofit of an existing utility plant (Hui and Natori, 1996); discrete sizes have been accounted for utility units (Shang and Kokossis, 2000); operation scenarios and equipment redundancy also improve the flexibility of process utility systems (Aguilar, 2005, Varbanov, 2006). However, such approaches are based on steady state assumptions and sometimes cause some practical problems in industrial practice. Hence, no equipment can change its load immediately, research on transient behaviour should be applied to check the feasibility of operating scenarios, to improve design operability and enhance the flexibility of utility system design and smoothly and safety running in this periods. To that purpose it is necessary to simulate transient behaviour using dynamic models.

To determine the design of a plant site that considers transient behaviour, the following questions must be answered:

- How many units and what size for spare equipment?
- How to operate in steady state considering multiple scenarios of demand, unit failure and maintenance?
- How to operate in the transient period between scenarios?

3. Equipments modelling and model validation

There are many studies where simulation models of utility equipment have been developed to analyze transient response to the periodic load changes (Kim et al., 2001, Shin et al., 2002). Although dynamic simulation has been performed to analyze transient behaviour of power plant (Wischhusen and Schmitz, 2004, Cao et al., 2005). However, industrial utility systems are more complex for variable steam main levels, different steam paths and many kinds of steam users.

Although utility systems are dynamic, steady state models are popular for their high computational efficiency and accuracy when there are no great changes in system load. However, they cannot be employed in the period when system transits between operation scenarios. Dynamic behaviour of a system can be described by conservation laws and motion equations. Transient characteristics of utility systems may be analyzed by using unsteady calculations. It is, however, inefficient to apply the unsteady simulation directly.

3.1. Dynamic boiler model

Boilers have a key role in transient behaviour because of the long response time when changing the load. In large process plants, drum boilers are used with furnace to generate high temperature and high pressure steam for heating. Water in the water wall becomes steam when receiving heat by radiation from the flame.

The transient behaviours of drum boilers are dominated by differential mass (eq.1) and energy balance (eq.2) equations for drum:

$$\frac{dM}{dt} = w_f - w_s \tag{1}$$

$$\frac{dE}{dt} = w_f \cdot h_f - w_s \cdot h_s + Q \tag{2}$$

Drum boiler model has been validated with published experimental data (Astrom and Bell 2000). Input data is feedwater flowrate, which is random controlled in the experiment. The model predicts drum pressure and water level to be compared with experimental data, shown in Figure 1. There is good agreement between model predictions and experimental data.

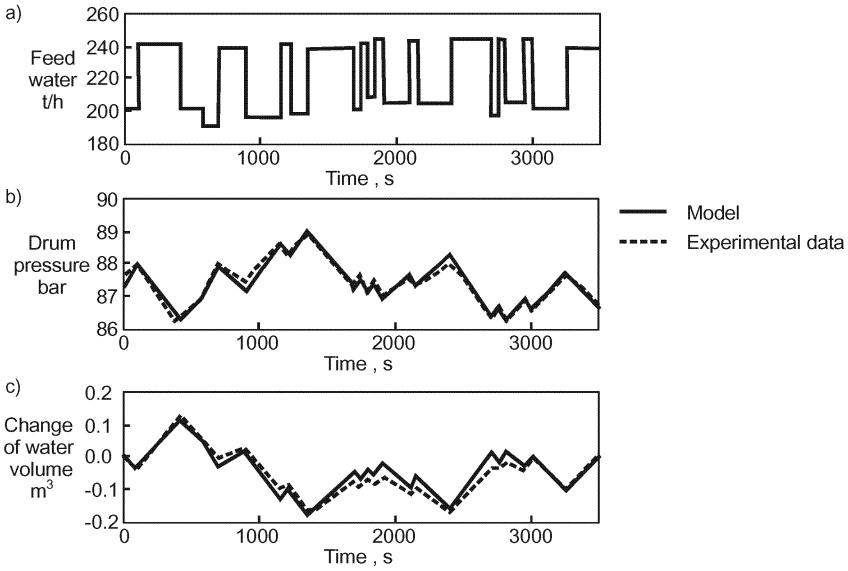

Figure 1. Boiler model validation; a) feedwater flowrate; b) water level in the drum; c) drum pressure. Solid line is model prediction. Dotted line is experiments data.

3.2. Gas and steam turbine

Gas turbines are well recognised to respond faster than boilers. But it would cost hours for gas turbines to start from cold state. Steam turbines also respond relatively fast, compared with boilers. This is the reason why quasi-steady state models can be employed for gas turbines and steam turbines even when studying transient behaviour of utility system.

3.3. Heat recovery steam generator

Heat recovery steam generators (HRSGs) are also important equipment in transient analysis because of the similar structure with boilers. In a HRSG, heat is transferred from the gas turbine exhaust first to superheat steam and then through the evaporator to water flowing through the tubes. After feed water is preheated, the gases are vented.

The mass and energy balance (eqs 3 and 4) equations are defined in HRSG drum:

$$\frac{\mathrm{d}}{\mathrm{dt}}[\rho_s V_s + \rho_w V_w] = q_f - q_s \qquad (3)$$

$$\frac{d}{dt}[\rho_s h_s V_s + \rho_w h_w V_w - pV_t + m_t C_p T_m] = Q + q_f h_f - q_s h_s \qquad (4)$$

The model is based on the following assumptions:

- Drum is thermally insulated. Water and steam are saturated in drum
- Heat transfer is dominated by convection.
- No heat loss from the HRSG.

HRSG model has been validated with a detailed model (Kim, 2000). The validation example is start-up behaviour of a HRSG with the size of 108t/hr. The model predicts steam flowrate to be compared with the detailed model, shown in Fig. 2. There is good agreement between new model and detailed model.

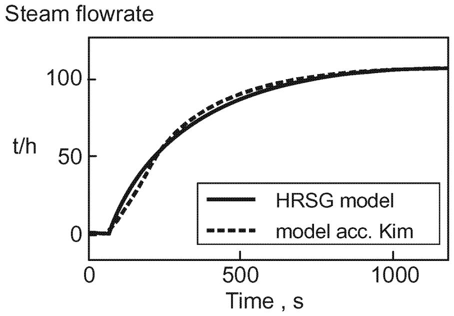

Figure 2. HRSG model validation.

3.4. Steam mains model

Traditionally, pipe pressure drop was neglected in steady state research on utility systems. Even in transient behaviour studies, pipes are also neglected due to their fast response ability. However, in modern process plants, there is a trend that steam would be obtained from cogeneration plant to improve the thermal efficiency. Under certain circumstances, steam users are far away from a steam source, e.g. several hundreds metres or more. In this situation, transient behaviour of steam mains cannot be neglected. Unsteady equation for one-dimension compressible fluid should be employed to calculate the steam flow between the nodes.

4. Optimisation of utility system

Network design and operating scenarios are optimised by using steady state models for high computational efficiency and accuracy. It is necessary to start from setup objectives for utility system design and then collect the site configuration and equipments data. In the next stage, number and size of spare units and operating scenarios are designed by transient analysis. In this step, transient behaviour of the system is simulated by using dynamic models of utility equipment. Steam and power supply must satisfy the process demands and assure the utility system running smoothly and safely in transient period. If the analysis results show that it is infeasible for scenarios transmission, network must be designed again with additional constraints.

Even in the same system, transient behaviour will be different according to different steady state operations. Flowrate or pressure changes may be unacceptable when the system reaches new scenarios from some steady state operation. However, they can be acceptable changing from other steady state operations.

The transient analysis problem is to optimise system operation policy until flowrate or pressure variation within acceptable bounds in transient period. Based on transient analysis, optimised operating strategies and system structure design are developed that considers system flexibility in industrial operation scenarios.

4.1. Operating policy optimisation: case study

A plant with 4 working boilers and 2 spare boilers is studied in case study, where boiler 1 breakdowns due to burner failure in furnace at time 100s. The sizes and optimised working loads are shown in table 1, based on design results from steady state models.

Table 1 Boilers information for case study

Boilers	1	2	3	4	5	6
Size , kg/s	75	75	75	75	50	50
Load , % (option 1 and 2)	100	100	100	0	100	0
Load , % (option 3)	86.7	86.7	86.7	0	80	80

The burner failures decrease the steam generated in boiler 1 sharply. The pressure in steam main is controlled by valves and remains steady. There are some operating options to cover the steam loss in utility systems.

Option 1: only boiler 4 comes online.

Boiler 4 comes online more slowly than boiler 1 deceases its load. The total steam output into the steam mains also drop sharply and maximum steam loss happens at time 950s (Fig. 3b).

Option 2: boiler 4 and boiler 6 come online together.

Boiler 4 and boiler 6 come online together to cover most of steam loss. Finally, boiler 4 runs at full load for high efficiency and boiler 6 offline again (Fig. 3a).

Option 3: optimise the working loads based on transient analysis.

When boiler 1 breakdowns, other working part-load boilers increase loads and spare boiler 4 comes online. The system response is better than Option 1 or 2 (Fig. 3b).

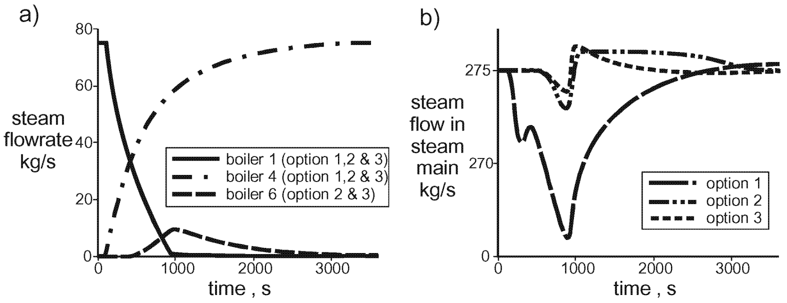

Figure 3. Transient behaviour of a) boilers and b) VHP

5. Conclusions

In the period where the operating state must transit from one state to another to satisfy processes demand under variable conditions is necessary to use transient model. Understanding transients better could lead to capital cost savings through less standby capacity. It has been acknowledged that unsteady one-dimensional simulation gives sufficiently accurate results for utility systems.

Based on the transient analysis, feasibility of equipments network and operating scenarios for site utility system could be checked and optimised operating strategies and carried out as part of the optimised solution for utility systems design.

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7. Symbols

E	energy, J	t	time, s
h	enthalpy, J	T	temperature, K
M	mass, kg	V	volume, m^3
p	pressure, Pa	VHP	very high pressure, -
Q	heat flow from fuel combustion, W	w	mass flowrate, kg/s
		ρ	density, kg/m^3

Subscripts:

f	feed water	out	outlet flow
in	inlet flow	s	steam

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