FOULING MITIGATION USING ESTIMATED FOULING LAYER THICKNESS IN FINNED TUBE HEAT EXCHANGER

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ABSTRACT

Extending operation period of heat exchanger was performed by mitigation of precipitation fouling. In BPA (bisphenol-A) process, fouling problem has been occurred at finned tube gas cooler of granulation process. Circulation gas in granulation process slightly contains BPA vapor, and it solidifies and adheres to the cooling surface of the finned tube heat exchanger. It causes reduction of cooling performance and/or increasing pressure drop. The fouling layer grows up seriously, reducing the heat exchanger performance and finally becomes impossible to continue operation. It requires shut-down maintenance to remove the fouling layer. In this work, fouling transition and rate is monitored as "fouling thickness" on the fin of the heat exchanger tube by process data analysis, to avoid the influence of operating fluctuation or control. The monitored fouling rate was associated with some operating condition by multiple regression analysis. As a result, important factors for fouling and their sensitivities are revealed. Fouling prediction by the model based on statistical analysis shows good agreement with actual operating performance. The effect of current fouling thickness, one of the important factors, was divided into influence of temperature on cooling surface and gas velocity, and mechanisms of both influence types were studied. Conclusively, some countermeasures, which only require changing operating conditions, were performed in actual plant, and it decreased fouling rate significantly.

INTRODUCTION

BPA (bisphenol-A) is produced from reaction of phenol and acetone. Phenol and other impurities in the reaction liquid are removed by crystallization, solid-liquid separation and distillation to obtain pure BPA. Industrially, the molten BPA is sent to the prilling section, where the spherical prills are produced as final product of BPA.

Fig.1 shows process flow of BPA plant. Molten BPA is cooled and prilled by contacting with countercurrent flow of cooling gas in the tower of prilling section. The cooling gas is circulated in this section through a finned-tube heat exchanger; outlet gas from the top of the prilling tower is cooled by heat exchange with chilled water and is fed to bottom of the tower again. In this process, pressure drop across finned-tube heat exchanger increases with time, and it imposed shut-down maintenance on plant when pressure drop exceeds the tolerance. This problem is one of the bottlenecks of prolonged continuous operation and the challenge which should be conquered. In this study, fouling rate was monitored by estimated fouling layer thickness, and a method to relate fouling rate with operating condition and abstracting influential factor was proposed. Moreover, extended continuous operation by some countermeasures was performed.

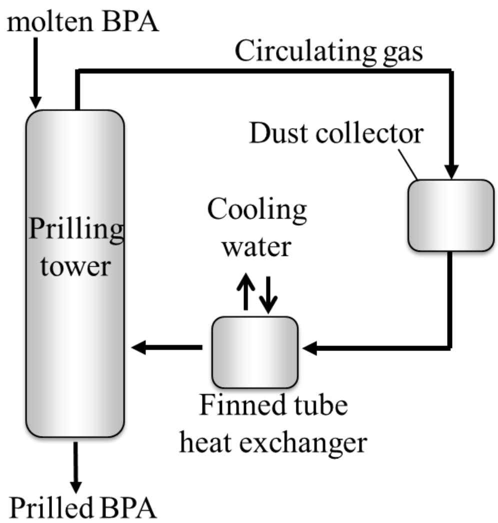

Fig. 1 process flow of prilling section

HEAT EXCHANGER & FOULING SITUATION

Circulating gas is cooled by heat transfer between gas and chilled water in heat exchanger with finned heating surfaces. The external surfaces of finned tubes, which make contact with cooling gas, have significant fouling during operation. Some of the gaps between fins are blocked, and the fouling layer is mostly composed of BPA. Gas analysis of circulating gas reveals existence of BPA in circulating line. On the other hand, construction or pipe wall of upstream of the heat exchanger has no fouling. So, above analysis and observation shows that precipitation fouling occurred by supersaturating of BPA, carried as gas phase from prilling tower. Fig. 2 shows pressure drop trend across heat exchanger. It has asymptotic behavior that fouling rate decreases with time. This trend indicates the presence of factors which promote and inhibit process of fouling and these two influences equilibrate after long time operation.

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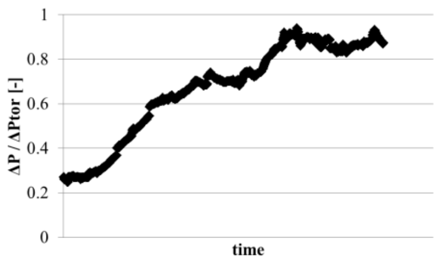

Fig. 2 Profile of pressure drop across heat exchanger

From a standpoint of precipitation fouling, it was supposed that the promotion factor of fouling is carrying of causative substance and cooling situation, and the inhibition factor is shear force by gas flow rate and so on. To get accurate influent factors, data analysis with fouling rate and plant operating condition was performed.

METHODOLOGY

A rough trend of fouling progress could be followed by pressure drop. However, production load is not always constant and circulating gas flow rate and temperatures also fluctuate with that. Kuwahara et al. (2015) presented a method of fouling monitoring by fouling resistance, R_f, which is direct index and applicable for cases with changing operating conditions. In this study, fouling transition was monitored by estimated fouling layer as another direct index.

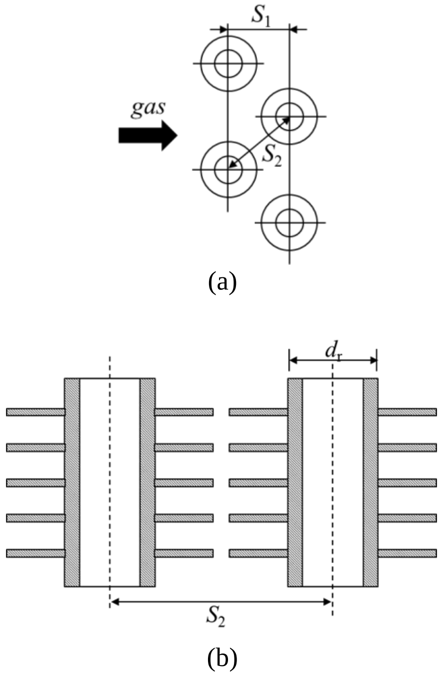

Fig. 3 Tube layout showing the parameters which affect the pressure drop

Finned Tube layout is shown in Fig.3. Robinson et al. (1966) proposed the relation about pressure drop of gas stream through the tube bundles, placed on isosceles triangular arrangement.

$$\Delta P = \eta \frac{nV_{max}^2}{2g\rho} \tag{1}$$

$$\eta = 37.86\left(\frac{d_r V_{max}}{\mu}\right)^{-0.316}\left(\frac{S_1}{d_r}\right)^{-0.927}\left(\frac{S_1}{S_2}\right)^{0.515} \tag{2}$$

S_1, S_2, d_r and n, which are shape factor of heat exchanger, and g is constant. Assuming physical property is almost constant; pressure drop equation (1) is rearranged into (3).

$$\Delta P = aV_{max}^{1.684} \tag{3}$$

V_{max} is velocity at minimum cross section through a row of tubes normal to flow, and is calculated by equation (4).

$$V_{max} = \frac{F}{\rho A_{min}} \tag{4}$$

This means that A_{min} can be calculated if we know flow rate F and pressure drop. The relation is applicable because of that the deposit form an almost uniform layer on the fins.

$$A_{min} = \frac{F}{\rho}\left(\frac{a}{\Delta P}\right)^{1.684} \tag{5}$$

In this case, most of the total heat transfer area consists of fin surface area. Therefore, fouling at the heat transfer area can be considered as increasing of fin (or fouling layer) thickness. Fouling layer thickness can be estimated by geometric calculation from A_{min}.

Furthermore, the fouling rate (= increasing rate of fouling layer thickness) was related to operating conditions. Operating period was divided into periods in which the fouling rate can be considered constant, and fouling rate of each periods were associated with operating conditions by multiple linear regression analysis.

RESULTS & DISCUSSION

Fouling thickness estimation

Examples of pressure drop and circulating gas flow rate trends are shown in Fig.4 and Fig.5. The pressure drop behaviors are different from each other. When fouling progresses, gas flow rate decrease due to increased flow resistance. However, gas flow rate should be kept constant for adequate prilling of BPA, so plant operators have to increase the blower power. This is the reason of the fluctuation of gas flow rate, and pressure drop trend includes this influence. Therefore, analyzing fouling rate from pressure drop did not make sense.

Fig.6 shows estimated fouling thickness. This is direct index of fouling and does not include the effects of disturbance such as circulating gas flow rate. Fouling rate of all cases is almost same at incipient phase. However in later phase, fouling rate, and asymptotic value and period is different. This behavior seems to depend on fundamental difference in the operating conditions, such as temperatures, circulating gas flow rate, and production load.

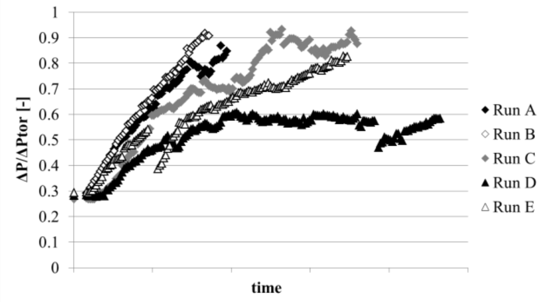

Fig. 4 Profiles of pressure drop

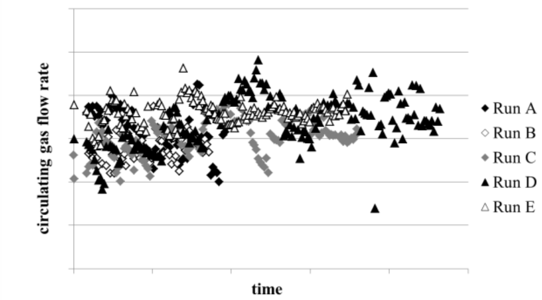

Fig. 5 Profiles of circulating gas flow rate

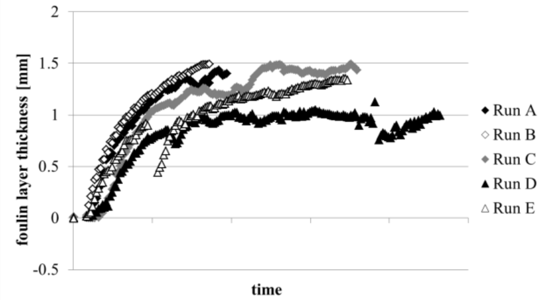

Fig. 6 Profiles of estimated fouling layer thickness

Data analysis & modeling

Based on the estimated values of fouling thickness on the fin surfaces, influential factors and their sensitivities are obtained. Fig.7 shows an example of data partitioning by fouling rate. The data is divided into four periods, and each period has one fouling rate and one set of operating conditions.

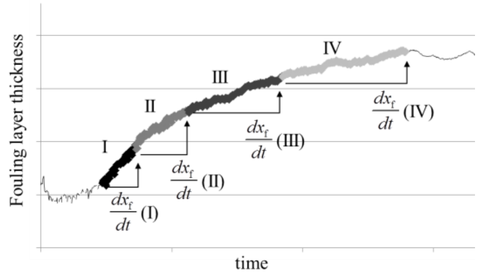

Fig. 7 An example of data partitioning by fouling rate

Operating conditions used for data analysis were chosen as the factor by which influence is assumed (Fig.8). The chosen data are described below and supposed that equation (6) is formed.

No.1 production load F_p
No.2 circulating gas flow rate F_g
No.3 circulating gas temperature (outlet of tower) T_o
No.4 chilled water temperature T_w
No.5 circulating gas temperature (inlet of tower) T_i
No.6 current fouling thickness x_f

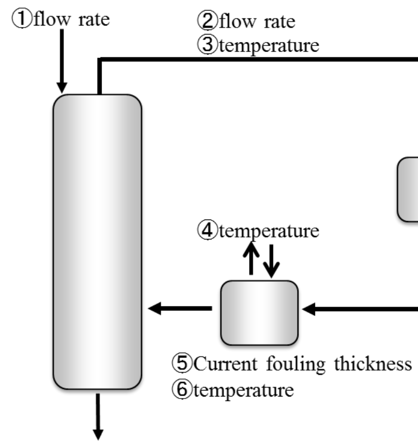

Fig. 8 Parameters used for data analysis

$$\frac{dx_f}{dt} = f\left(F_p, F_g, T_i, T_o, T_w, x_f\right) \quad (6)$$

No.1~5 was measured by actual indicator, and No.6 was obtained from the above method. The operating data of the span (a few years) used for an analysis was divided into 32 periods, and each factor was averaged individually in each period. Eq.7 is fouling model obtained by multiple linear regression analysis with data of each divided period.

$$\frac{dx_f}{dt} = pF_p - qT_w - rx_f \quad (7)$$

Values of the proportional constants *p*, *q*, and r were derived in analysis and they are all positive number. This formula indicates that fouling rate decreases when production load is low, chilled water temperature is high, and current fouling thickness is high. F_g, T_i and T_o are excluded at statistical test. The absence of F_g in Eqn 7 is a little surprising, but it means that an effect on gas velocity of current fouling thickness x_f is greater than one of gas flow rate F_g. The comparison between the value of fouling rate from estimation (by Eqn 4) and calculation (by Epn 5) is shown in Fig.9. A good agreement between two fouling rates suggests that model parameters are suitable for describing fouling layer thickness variation.

The effect of current fouling thickness can be inferred that it includes two factors, influence on temperature of heat transfer surfaces and shear force of gas velocity. The relationship between calculated gas velocity nearby the finned tube bundle and fouling rate is shown in Fig.10. The fouling rate correlates strongly with gas velocity. It means that circulating gas flow rate is also important factor as gas velocity through the minimum cross section area in the heat exchanger, in spite of the fact that it is excluded from fouling model parameter at multiple linear regression analysis.

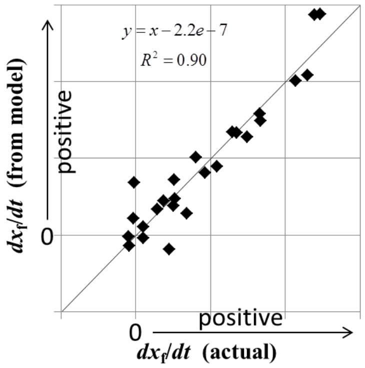

Fig. 9 Comparison between estimated and calculated (by model) fouling rate value

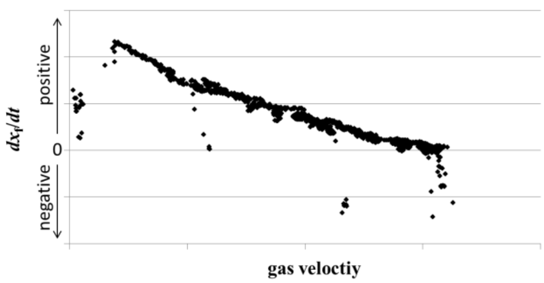

Fig. 10 Correlation between fouling rate and gas velocity calculated with current fouling thickness and flow rate

Countermeasure and effectiveness

In prolonging the operation period of BPA plant, some countermeasures were applied in practice. To be more precise, chilled water temperature and circulating gas flow rate were increased based on process data analysis with estimated fouling layer thickness. Each condition was determined in view of cooling capacity for molten BPA and service temperature limit of the facilities. The comparison between pressure drop trends before and after alteration of operating conditions is shown in Fig.11. It can be observed that countermeasures have well-marked impact for inhibition of fouling layer growth and pressure drop gain. As a result of the study, the pressure drop is no longer the bottleneck of continuous operation, and the longest continuous operation has been achieved.

CONCLUSIONS

A method to analyze the fouling behavior in a finned tube heat exchanger using plant operation data was provided.

1. Fouling layer thickness on finned heat exchanging surface was estimated from pressure drop and flow rate of circulating gas.
2. Key parameters that dictate fouling rate and their sensitivities were obtained by statistical approach.
3. Solution based on fouling model resolved pressure drop problem of heat exchanger.

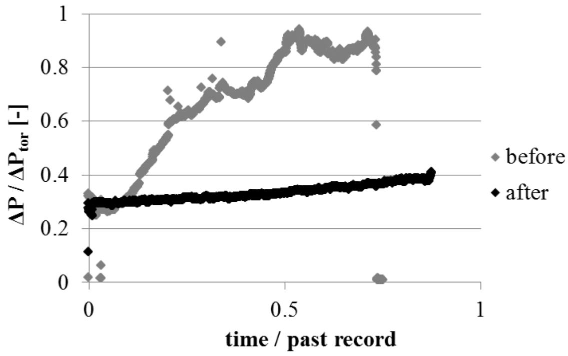

Fig. 11 pressure drop transition before/after

NOMENCLATURE

a	constant
A_{min}	area, m^2
d_r	rood diameter, mm
F	flow rate, kg/hr
g	gravity, m/s^2
n	number of rows of tubes in direction of flow
ΔP	static pressure drop across budle, kPa
p	constant
q	constant
r	constant
S_1	transverse pitch between adjacent tubes in the same row, mm
S_2	longitudinal pitch between adjacent tubes in different rows measured on the diagonal, mm
t	time, hr
T	temperature, K
V_{max}	velocity at minimum cross section through a row of tubes in direction of flow, m/s
x_f	fouling layer thickeness, mm

Greek letters

η	friction factor
μ	gas viscosity, Pas
ρ	gas density, kg/m^3

Subscript

g	gas
i	inlet
o	outlet
p	production
tor	tolerance
w	water

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