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Analysis and calculation model of energy consumption and product yields of delayed coking units

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Abstract: Delayed coking is an important process used to convert heavy oils to light products. Energy consumption and light oil yield are important factors for evaluating the delayed coking process. This paper analyzes the energy consumption and product yields of delayed coking units in China. The average energy consumption shows a decreasing trend in recent years. The energy consumption of different refineries varies greatly, with the average value of the highest energy consumption approximately twice that of the lowest energy consumption. The factors affecting both energy consumption and product yields were analyzed, and correlation models of energy consumption and product yields were established using a quadratic polynomial. The model coefficients were calculated through least square regression of collected industrial data of delayed coking units. Both models showed good calculation accuracy. The average absolute error of the energy consumption model was approximately 85 MJ/t, and that of the product yield model ranged from 1 wt% to 2.3 wt%. The model prediction showed that a large annual processing capacity and high load rate will result in a reduction in energy consumption.

Key words: Delayed coking, energy consumption, product yield, model

1 Introduction

Energy saving and emission reduction have become common issues with increasing public awareness of the global energy status, energy consumption, and environmental pollution (Szklo and Schaeffer, 2007; Zhuang et al, 2007). Energy efficiency of various processes has been studied (Ji and Bagajewicz, 2002; Dai et al, 2006) and some assessment methods have been proposed and discussed (Lutz et al, 2006; Tanaka, 2008). The petroleum refining industry has a high level of energy consumption and pollutants emission. Therefore, enhancement of energy utilization and reduction of energy consumption and environmental pollution have become urgent tasks for the petroleum refining industry (Ren et al, 2010).

The energy efficiency of refineries has increased over the years, stimulated by increases in the fuel cost. Modern complex refineries can improve energy efficiency, through optimization of a refinery via process unit integration resulting in a reduction of fuel consumption by 10%-15% (Zhang et al, 2010; de Lima and Schaeffer, 2011). Hydrogen-rich multifuel, generated during petroleum refining processes, such as catalytic reforming, catalytic cracking, and delayed coking, can be a low-cost alternative to lower fuel cost and to reduce CO_2 emission (Hsieh and Jou, 2009).

The deep upgrading of petroleum has become inevitable due to increasing heavier and lower-grade crude feedstocks, increasing market requirements for light oils, and more strict environmental quality requirements for oil products (Plantenga and Leliveld, 2003; Song, 2003; Swaty, 2005). Delayed coking technology can process various residua with high carbon residue value and high content of heavy metals. It is characterized by low equipment investment, simple technology and mature technique. Therefore, delayed coking has become one of the most important processes for upgrading heavy oils. Future developments for the delayed coking process include the enhancement of liquid product yield, improvement of unit flexibility and feedstock adaptability, modification of automation control, and reduction of environmental pollution and energy consumption (Shen et al, 2010).

Energy consumption is an important factor for evaluation of delayed coking units. Feedstock properties, unit capacity and operating factors all significantly affect energy consumption. The energy consumption of delayed coking units includes the consumption of fuel gas, water, electricity, steam, and so on. In particular, fuel gas consumption plays a dominant role in unit energy consumption, and power consumption is also significant (Wang and Song, 2008). The consumption of fuel gas is reported to be approximately 77% of the energy consumption of a delayed coking unit, and that of electricity is approximately 17% (Zhen and Jiang, 2007).

Energy saving is always a goal for refineries (Milosevic

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and Rudman, 2009), with the use of advanced technology and equipment as the key to this goal (Wang and Song, 2008). A number of refineries in China have adopted technique modification to reduce their energy consumption. SINOPEC Jiujiang Company has modified its delayed coking unit by expanding unit capacity, enhancing the efficiency of heat exchangers and furnaces, recovering low-temperature heat, and improving the wastewater reuse level to reduce the consumption of fuel gas, steam, electricity, and water, respectively, and the unit energy consumption is reduced by 468 MJ/t compared with the design value (Zou, 2009). Huizhou Refinery of China National Offshore Oil Corporation has modified its delayed coking unit by reducing the recycle ratio, enhancing the energy saving of furnaces, reducing the consumption of fuel gas, optimizing the heat transfer flow, and increasing the heat transfer final temperature of the feedstock, and the unit energy consumption decreased from 1,357 to 1,096 MJ/t (Wang and Chen, 2010).

The current paper analyzes the energy consumption and product yields of 24 delayed coking units in China, and establishes calculation models for energy consumption and product yields.

2 Energy consumption of delayed coking units

2.1 Energy consumption analysis of delayed coking units

Fig. 1 shows the average energy consumption of delayed coking units in China at different years. The average energy consumption decreased in recent years. The average energy consumption was 1,149 MJ/t from 2002 to 2005 and 1,058 MJ/t from 2006 to 2009, a reduction of approximately 8%.

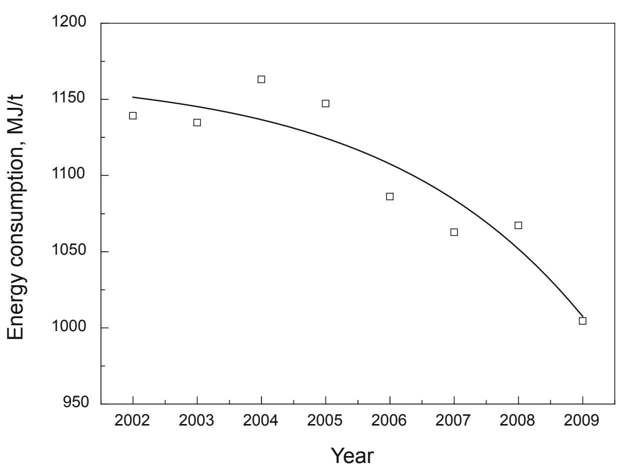

Fig. 1 Average energy consumption of delayed coking units in China

The highest and lowest energy consumption at different years is shown in Fig. 2. The average value of the highest energy consumption from 2002 to 2009 was 1,690 MJ/t, which was approximately twice the average value (838 MJ/t) of the lowest energy consumption for that period. The average value of the highest energy consumptions from 2002 to 2005 and 2006 to 2009 were 1,736 and 1,643 MJ/t, respectively.

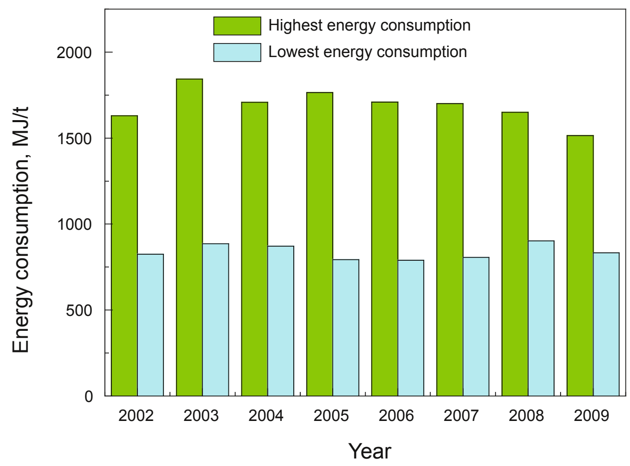

Fig. 2 Highest and lowest energy consumption of delayed coking units in China

While the average value of the lowest energy consumptions from 2002 to 2005 and 2006 to 2009 were 844 and 832 MJ/t, respectively.

Figs. 1 and 2 show that the average energy consumption, average value of the highest energy consumption, and average value of the lowest energy consumption from 2006 to 2009 were lower than those from 2002 to 2005. This phenomenon is important for modeling of energy consumption. Calculating the model coefficients for the two periods, 2002–2005 and 2006–2009, will yield better results.

2.2 Energy consumption model of delayed coking units

2.2.1 Model establishment

The primary factors affecting the energy consumption and product yields of delayed coking units are feedstock properties, operating conditions, and unit factors.

The feedstock properties play an important role in energy consumption, product yields and product properties. Density and carbon residue are two important properties of coking feedstocks. Coke yield usually increases with the increase in density and carbon residue of feedstocks. Therefore, density and carbon residue were selected to describe the effect of feedstocks on energy consumption.

Reaction temperature and pressure are two important operating factors. The outlet temperature of the heating furnace will directly affect the extent of reactions of feedstocks in a coking tower, thereby affecting the product yields and their properties. The pressure and temperature on the top of the coking tower determine the feedstock gasification percentage and extent of reactions. The recycle ratio of a coking tower is another important operating factor. The yield of heavy fraction will increase and that of coke will decrease with a low recycle ratio. Water injection also affects the energy consumption and product yields; the injection of water or steam into a furnace pipeline will increase the flow rate, hence restrain the overcracking and coking reactions in a pipeline.

Unit factors, such as annual processing capacity and load rate, are important parameters affecting energy consumption. With an increase in annual processing capacity and load rate, the energy consumption usually decreases.

Based on the above analyses, a number of parameters were selected to establish the energy consumption model for delayed coking units, namely, annual processing capacity (P_C), load rate (L_R), feedstock density (ρ, g/cm^3), feedstock carbon residue (C_R, wt%), outlet temperature of the heating furnace (T_F, °C), temperature at the top of the coking tower (T_{CT}, °C), pressure at the top of the coking tower (P_{CT}, MPa), recycle ratio (Re), and water injection to oil weight ratio (R_{WO}).

A polynomial regression model is often used to fit or predict data (Xu and Zhang, 1997; Dong et al, 2005). Using the above parameters, this paper establishes a quadratic polynomial model, as shown in Equation (1).

$$Y = a + b\ln P_C + c\ln L_R + d\rho + e\rho^2 + fC_R + gC_R{}^2 + hT_F + iT_F{}^2 + jT_{CT} + kT_{CT}{}^2 + lP_{CT} + mP_{CT}{}^2 + nRe + oRe^2 + pR_{WO} + qR_{WO}{}^2 \quad (1)$$

where, Y is the energy consumption, and a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, p, q are model coefficients.

2.2.2 Model coefficients

Industrial statistical data on delayed coking units were collected. The model coefficients, calculated by using the least square regression, are listed in Table 1.

Table 1 Energy consumption model coefficients of delayed coking units

Coefficient	2002-2009	2002-2005	2006-2009
a	402081.06	834388.48	318456.27
b	-204.50	-276.87	-197.13
c	47.34	175.80	-78.19
d	-6110.95	152599.22	-14882.68
e	2611.89	-78920.23	7264.20
f	-0.0250	-346.42	67.18
g	0.1406	11.12	-1.642
h	-1765.50	-4354.39	-1214.55
i	1.786	4.406	1.229
j	183.93	820.02	-50.22
k	-0.2130	-0.9766	0.0686
l	-1007.14	-1672.38	-1532.97
m	608.84	4688.54	919.10
n	324.25	-958.78	654.42
o	-6.6254	1123.32	-520.09
p	9.742	20.19	4.148
q	-0.3915	-2.493	0.3654

2.2.3 Calculation error analysis

Table 2 lists the average calculation errors of the correlation model of energy consumption. The average absolute error of the single regression model (2002–2009) was 97.69 MJ/t, and those of the piecewise regression models (2002–2005 and 2006–2009) were lower, i.e., 86.83 and 85.45 MJ/t, respectively. The average relative error of the 2002–2009 data set was 8.44%, and those of the 2002–2005 and 2006–2009 data sets were 7.19% and 7.70%, respectively.

Table 2 Average errors of energy consumption correlation models

Error	2002-2009	2002-2005	2006-2009
Average absolute error, MJ/t	97.69	86.83	85.45
Average relative error, %	8.44	7.19	7.70

The average energy consumption showed a decreasing trend in recent years (Fig. 1), which is the result of technique development and equipment innovation. Therefore, the model calculation accuracy increased for the piecewise regression models. The calculation error of the piecewise regression models was approximately 12%, lower than that of the single regression model.

Fig. 3 shows the distribution of the relative calculation error of the correlation model. Approximately 66% of the relative error of the single regression model was below 10%, whereas approximately 70% of those of the piecewise regression models was below 10%. No relative error above 20% was found for the piecewise regression models. These results show that the piecewise regression model had better calculation accuracy.

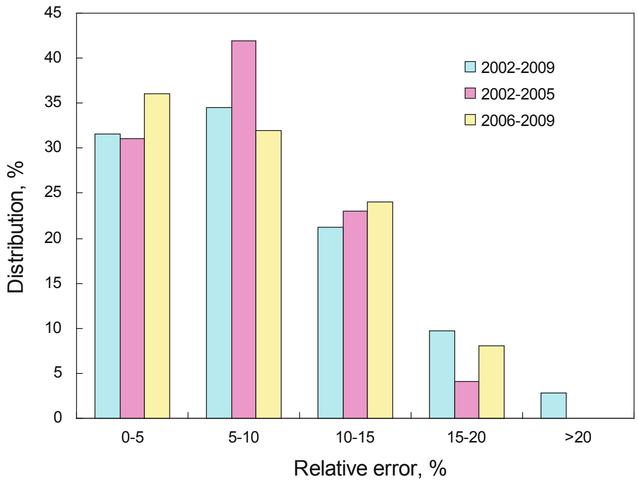

Fig. 3 Distribution of the relative errors of energy consumption correlation models

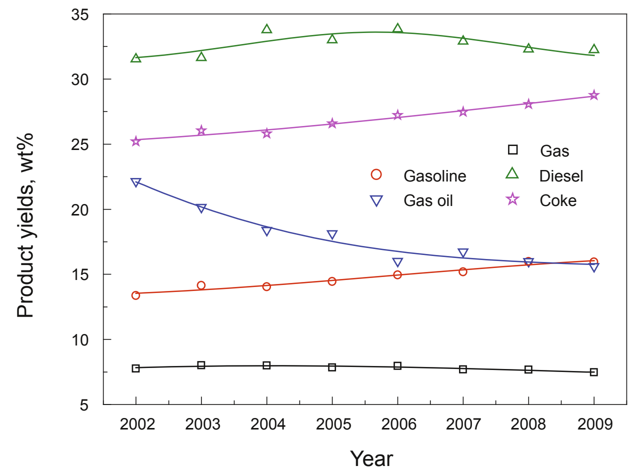

Fig. 5 Average yields of coking products of delayed coking units in China

Fig. 4 shows the calculated energy consumption as a function of annual processing capacity at three load rates using the model coefficients of the piecewise regression model for the 2006–2009 data sets. The calculated energy consumption for delayed coking units decreased with increasing annual processing capacity, and a higher load rate showed a lower value of energy consumption. This result indicates that a large annual processing capacity and high load rate will result in a reduction in energy consumption.

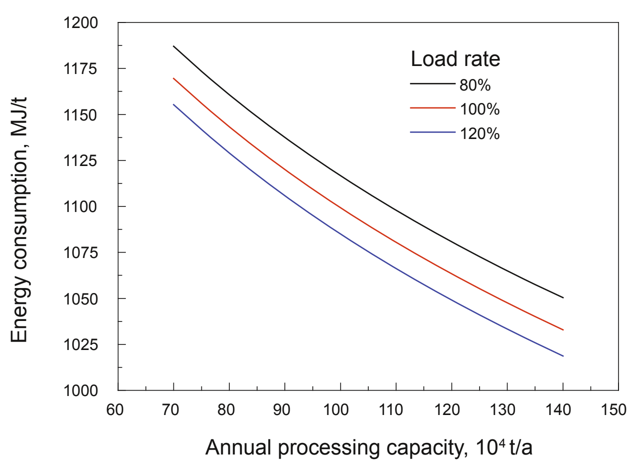

Fig. 4 Calculated energy consumption of delayed coking units as a function of annual processing capacity at three load rates

3 Product yields of delayed coking units

3.1 Analysis of product yields of delayed coking units

Fig. 5 shows the average product yields of the delayed coking units in China for different years. The average gas yield varied slightly, the average gasoline and coke yields increased, the average diesel yield reached its maximum in 2006, and the average gas oil yield showed a decreasing trend.

3.2 Product yield model of delayed coking units

3.2.1 Model establishment

The product yields of delayed coking were dependent on feedstock properties and operating conditions, but almost independent of unit factors. Therefore, the annual processing capacity and load rate can be excluded from the calculation model for product yields. A number of parameters were selected to establish the product yield model of delayed coking units, namely, feedstock density (ρ, g/cm^3), feedstock carbon residue (C_R, wt%), outlet temperature of the heating furnace (T_F, °C), temperature at the top of the coking tower (T_{CT}, °C), pressure at the top of the coking tower (P_{CT}, MPa), recycle ratio (Re), and water injection to oil weight ratio (R_{WO}). Using these parameters, a correlation model of quadratic polynomial was established, as shown in Equation (2).

$$Y = a + b\rho + c\rho^2 + dC_R + eC_R{}^2 + fT_F + gT_F{}^2 + hT_{CT} + iT_{CT}{}^2 + jP_{CT} + kP_{CT}{}^2 + lRe + mRe^2 + nR_{WO} + oR_{WO}{}^2 \quad (2)$$

where, Y is product yield, and a, b, c, d, e, f, g, h, i, j, k, l, m, n, o are model coefficients.

3.2.2 Model coefficients

The error analysis of the energy consumption model showed that the calculation error of the piecewise regression models was lower than that of the single regression model (Fig. 3). Therefore, only the coefficients of the piecewise regression model of product yields were calculated using least square regression, which are listed in Tables 3 and 4.

3.2.3 Calculation error

Tables 5 and 6 list the average calculation errors of the product yield correlation models for the 2002–2005 and 2006–2009 data sets. The average absolute error (about 1-2.3 wt%) is low. The average relative errors of diesel and coke are approximately 5%, those of gasoline and gas oil are approximately 11%, and that of gas is approximately 15%. The average relative error of gas is large because of the low yield of gas products.

Table 3 Product yield model coefficients of delayed coking units of 2002-2005

Coefficient	Gas	Gasoline	Diesel	Gas oil	Coke
a	-1604.84	8204.07	296.17	-17013.22	10217.82
b	2975.15	-1684.88	4195.53	-4142.02	-1343.78
c	-1535.60	902.68	-2156.80	2071.01	718.71
d	-2.0776	0.6467	1.6932	-9.3760	9.1137
e	0.0745	-0.0333	-0.0531	0.2823	-0.2704
f	-2.0453	-23.9931	-13.3962	75.9003	-36.4657
g	0.0022	0.0242	0.0134	-0.0763	0.0366
h	3.2603	-7.0614	4.9307	1.6519	-2.7814
i	-0.00395	0.00849	-0.00581	-0.00216	0.00342
j	-113.08	143.73	-125.82	-9.68	104.85
k	323.99	-430.81	392.27	-5.02	-280.43
l	-0.9040	8.7034	-10.4991	-6.8568	9.5564
m	3.1095	-0.6101	14.2094	-9.3768	-7.3320
n	-0.3115	-0.9956	0.4796	1.4769	-0.6494
o	0.0087	0.0826	-0.0387	-0.1182	0.0656

Table 4 Product yield model coefficients of delayed coking units of 2006-2009

Coefficient	Gas	Gasoline	Diesel	Gas oil	Coke
a	-1295.40	9434.74	9473.60	-21188.63	3675.69
b	-601.43	1210.03	372.71	-1881.39	900.09
c	306.64	-595.90	-212.88	941.96	-439.82
d	-2.3077	-0.3636	2.4185	0.4696	-0.2169
e	0.0614	0.0196	-0.0787	-0.0213	0.0191
f	-0.8704	-42.3152	-16.2679	74.8334	-15.3799
g	0.0009	0.0426	0.0165	-0.0754	0.0154
h	8.7452	2.2979	-26.9595	17.2605	-1.3442
i	-0.0105	-0.0027	0.0324	-0.0208	0.0016
j	9.0004	-6.3651	-4.1848	0.4001	1.1494
k	-5.2939	4.2073	1.7996	0.8774	-1.5904
l	7.7319	19.3972	-29.3159	-10.3157	12.5025
m	-5.0409	-13.0201	49.8331	-13.0937	-18.6784
n	0.1795	-0.2446	0.0842	-0.0802	0.0611
o	-0.01072	0.02044	-0.00666	-0.00146	-0.00160

Table 5 Average errors of product yield correlation model of 2002-2005

Product	Gas	Gasoline	Diesel	Gas oil	Coke
Average absolute error, wt%	1.17	1.35	1.55	2.02	1.19
Average relative error, %	15.28	9.67	4.86	11.12	4.72

Table 6 Average errors of product yield correlation model of 2006-2009

Product	Gas	Gasoline	Diesel	Gas oil	Coke
Average absolute error, wt%	1.09	1.72	2.23	2.07	1.08
Average relative error, %	14.24	11.66	7.05	13.86	3.78

4 Conclusions

1) The energy consumption of delayed coking units in China was analyzed. The average energy consumption showed a decreasing trend in recent years because of technique development and equipment innovation. The mean average energy consumption was 1,149 MJ/t from 2002 to 2005, and 1,058 MJ/t from 2006 to 2009. The energy consumption of different refineries varied significantly, and the average highest energy consumption was approximately twice the average lowest energy consumption.

2) A correlation model of energy consumption was established using a quadratic polynomial with nine parameters, including unit parameters, feed properties, and operating factors. The model coefficients were calculated through least square regression of collected industrial statistical data on delayed coking units. The calculation errors of the model were analyzed. The average relative error of the 2002–2009 data set was 8.44%, and those of the 2002–2005 and 2006–2009 data sets were 7.19% and 7.70%, respectively. The model prediction showed that a large annual processing capacity and high load rate resulted in a reduction in energy consumption.

3) A correlation model of product yields was established using a quadratic polynomial with seven parameters, including feed properties and operating factors. The model coefficients were calculated using least square regression. The product yield model also showed good calculation accuracy, and the average absolute error ranged from 1 to 2.3 wt%.

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