“COMPUTER-IMPLEMENTED METHOD FOR OUTPUTTING THE COKING OF A STEAM CRACKER”

FIELD OF THE INVENTION

The invention relates to a method for determining the coking level of a reactor tube of a steam cracker and to a method for determining the ageing of a reactor tube of a steam cracker.

PRIOR ART

In steam crackers, hydrocarbons consisting, for example, of petroleum fractions are mixed with steam and passed through tubes arranged in a heated furnace. The hydrocarbons are thermally cracked in the reactor tubes. This produces a broad spectrum of hydrocarbon compounds.

During steam cracking, coke is produced as the hydrocarbons are cracked. During the process, the coke is deposited on the walls of the reactor tubes. This deposition is referred to as coking. On the one hand, this results in an increased pressure drop across the reactor tubes. In this case, the steam cracking process must be discontinued when a critical pressure drop is reached. On the other hand, more energy must be expended to heat the reactor tubes as a result of the coking. The amount of energy that can be supplied to heat the reactor tubes is limited by the temperature resistance of the reactor tubes. The energy supply cannot therefore be increased indefinitely. Consequently, when a critical pressure drop is reached or the energy supply is limited, the steam-cracking process must be stopped, in order to remove the coke from the reactor tubes by burn-off.

Coking in the steam cracker is therefore an important and limiting factor in controlling a steam cracker. However, no possible means are known for determining the coking in the steam cracker, in order to optimize control of the steam cracker. A further complicating factor is that the steam-cracking process exhibits transient behaviour, since, during the cracking of hydrocarbons, coking occurs as a result of both pyrolytic coking and catalytic coking. In particular, no method is known that is capable of detecting catalytic coking separately from pyrolytic coking in situ.

While pyrolytic coking is determined primarily by the mixture of petroleum fractions and steam, catalytic coking is significantly influenced by the progression of corrosion of the reactor tubes. Hence, tubes exhibiting advanced corrosion display a higher degree of catalytic coking. Determining the catalytic coking is therefore of particular interest, in order to draw conclusions regarding the progression of corrosion. The progression of corrosion correlates directly with the ageing of the reactor tubes.

The object of the present invention is therefore to propose an efficient and easily implementable method for outputting the coking level of a steam cracker, wherein the coking is determined precisely and control of the steam cracker is facilitated. A further object of the invention is to propose a computer-implemented method for determining the ageing of a steam cracker.

SUMMARY OF THE INVENTION

According to a first aspect of the invention, the object is achieved by a computer-implemented method for outputting the coking level of a steam cracker, characterized by the following steps:

a. detecting a pressure drop of the steam cracker and/or a temperature profile of the steam cracker,
b. defining a coking level of the steam cracker,
c. simulating a pressure drop of the steam cracker and/or simulating a temperature profile of the steam cracker on the basis of the coking level defined in step b.,
d. correcting the coking level defined in step b. in order to match the pressure drop simulated in step c. to the pressure drop detected in step a. and/or correcting the coking level defined in step b. in order to match the temperature profile simulated in step c. to the temperature profile detected in step a.,
e. outputting the coking level of the steam cracker corrected in step d.

The method according to the invention enables the coking level of the steam cracker to be determined precisely. The control of the steam cracker can thereby be facilitated and improved. In particular, the method according to the invention is particularly efficient and easy to implement.

The coking level of a steam cracker may be the deposition of coke on the inner surface of the steam cracker. The coking may have a limiting and significant influence on the control of the steam cracker. In particular, the coking may be described as a function of position along the steam cracker. The coking can thus be described as varying along the steam cracker. The coking may be the thickness of the coke per unit area on the inner

surface of the steam cracker. The coking may also be specified as a coking rate. This may apply, in particular, to all forms of coking disclosed herein.

The pressure drop of the steam cracker may be detected in step a. by measurement using a pressure sensor. The pressure drop detected in step a. may be the difference between the inlet pressure and the outlet pressure of the steam cracker. Detecting the pressure drop encompasses any possible means of determining the pressure drop. In particular, the pressure drop detected in step a. may be the actual pressure drop present in the steam cracker.

The temperature profile of the steam cracker may be detected in step a. by measurement using a temperature sensor, such as a thermostat, a thermocouple, a thermal-imaging camera and/or an infrared camera. In particular, the temperature profile detected in step a. may be detected for the entire steam cracker using at least one temperature sensor. The temperature profile of the steam cracker may be determined from at least one local temperature measurement and interpolation of the temperature profile on the basis of the at least one local temperature measurement.

The temperature profile of the steam cracker may be the temperature profile of the reactor tubes of the steam cracker, in particular of the outer surface of the reactor tubes of the steam cracker.

Defining a coking level of the steam cracker in step b. may involve specifying a value for the coking. The coking may be freely defined in this case. For this purpose, the coking may be defined by estimation, from empirical values and/or on the basis of simulations. In particular, the coking level defined in step b. need not be based on measured values.

Simulating a pressure drop in step c. on the basis of the coking level defined in step b. may involve simulating the pressure drop of the steam cracker, wherein the coking level defined in step b. may be used as an assumption for the simulation. The simulation may be performed on a computer, a server or a similar device. In particular, the pressure drop simulated in step c. need not have been measured at the steam cracker. In particular, the pressure drop simulated in step c. may merely be a calculated value.

Simulating a temperature profile of the steam cracker in step c. on the basis of the coking level defined in step b. may involve simulating the temperature profile of the steam cracker, wherein the coking level defined in step b. may be used as an assumption for the simulation. The simulation may be performed on a computer, a server or a similar device. In particular, the temperature profile simulated in step c. need not have been measured at the steam cracker. In particular, the temperature profile simulated in step c. may merely be a calculated value.

Correcting the coking level defined in step b. in order to match the pressure drop simulated in step c. to the pressure drop detected in step a. and/or correcting the coking level defined in step b. in order to match the temperature profile simulated in step c. to the temperature profile detected in step a. may involve increasing or reducing the coking. In other words, the thickness of the coke per unit area on the inner surface of the steam cracker may be corrected. In this way, the corrected coking may be determined from the coking level defined in step b. The corrected coking may correspond to the actual coking of the steam cracker. The correction of the coking in step d. may merely be calculated. The correction in step d. may be performed independently of the steam cracker.

Outputting the coking level of the steam cracker corrected in step d. may involve reproducing the coking corrected in step d. The output in this case may be provided in a form comprehensible to an operator. The output may be provided, for example, as a number, function or graphic. The output may be provided visually and/or acoustically. The output may involve transmitting information relating to the coking level of the steam cracker corrected in step d. The transmitted information may be used subsequently in another method or for further determinations, for example for determining the catalytic coking.

The method is a computer-implemented method and may therefore be performed on a computer, such as a server, a laptop, a personal computer or the like. A computer-implemented method may be understood, for example, as meaning that the computer performs some or all of the steps of the method. The computer may be understood in this case to be a physical device having hardware components.

Also disclosed is a device configured to perform the method for outputting the coking level of a steam cracker and/or the method for determining the ageing of a steam cracker, wherein the device comprises components configured to perform the disclosed methods. The device is, for example, a device for implementing the method for outputting the coking level of a steam cracker and/or for implementing the method for determining the ageing of a steam cracker.

The means may comprise hardware components and/or software components. The means may comprise, for example, at least one memory containing program instructions of a computer program (e.g. the computer program disclosed below) and at least one processor configured to execute program instructions from the at least one memory. Accordingly, a device comprising at least one processor and at least one memory containing program instructions is also to be understood as disclosed, wherein the at least one memory and the program instructions are configured, together with the at least one processor, to cause the device to implement the disclosed method.

Alternatively, or in addition, the means may further comprise one or more communication interfaces (e.g. one or more wired and/or wireless communication interfaces, such as a wireless communication interface in the form of a radio interface) and/or one or more user interfaces (e.g. a keyboard, a mouse, a screen, a touch-sensitive screen, a loudspeaker, a microphone, etc.). It will be appreciated that the disclosed device may also comprise other means that are not listed.

A computer program is also disclosed, wherein the computer program comprises program instructions that are configured, when executed by at least one processor, to cause a computer to implement the disclosed methods.

The disclosed computer program is contained and/or stored, for example, on a computer-readable storage medium. A computer-readable storage medium is to be understood, for example, as a physical and/or tangible storage medium.

In one exemplary embodiment, the correction according to step d. of the coking level defined in step b. may be performed iteratively, wherein correcting the coking level defined in step b. in order to match the simulated pressure drop to the detected pressure drop according to step d. and/or correcting the coking level defined in step b. in order to match the simulated temperature profile to the detected temperature profile according to step d. may comprise the following steps:

- d.1. comparing the simulated pressure drop with the detected pressure drop and/or comparing the simulated temperature profile with the detected temperature profile,
- d.2. correcting the coking level defined in step b.,
- d.3. simulating the pressure drop of the steam cracker on the basis of the coking corrected in step d.2 and/or simulating the temperature profile of the steam cracker on the basis of the coking corrected in step d.2.

The iterative correction enables the correction, and therefore the method, to determine the coking level of the steam cracker particularly precisely. This may facilitate control of the steam cracker. The method may also be particularly efficient and easy to perform. If the method comprises steps d.1 to d.3, the method may be particularly robust and therefore particularly efficient.

“Iteratively” may mean that the correction can be repeated, for example until the simulated pressure drop corresponds to the detected pressure drop.

In one exemplary embodiment, the coking level defined in step b. may be defined by the pyrolytic coking in the steam cracker.

In this way, the coking level defined in step b. can be determined particularly accurately, since the coking level defined in step b. may be very close to the actual coking level of the steam cracker. The simulation in step c. can therefore be particularly accurate. The method can therefore determine the coking level of the steam cracker particularly precisely and efficiently. This can facilitate and improve the control of the steam cracker.

The pyrolytic coking may be the coking level of the steam cracker caused by the mixture of petroleum fractions and steam.

In one exemplary embodiment, the computer-implemented method may comprise the following method step:

f. determining a catalytic coking level by subtracting the pyrolytic coking level from the coking level corrected in step d., and outputting the catalytic coking level.

In this way, the coking level of the steam cracker can be determined precisely, since the individual components of the coking, in particular the pyrolytic coking and the catalytic coking, can be determined precisely. It is thus possible to determine both the proportion of pyrolytic coking and the proportion of catalytic coking in the total coking. The cause of the coking can therefore be assessed more accurately, thereby facilitating and improving the control of the steam cracker. In particular, the coking level, and especially the pyrolytic coking level and the catalytic coking level, can be determined particularly efficiently and easily in this way.

Catalytic coking may be the formation of coke as a result of the catalytic reaction of the gas at the inner surface of the tubes. For example, the catalytic coking may depend on the chemical composition of the inner surface of the tubes. A catalytically inactive material, such as chromium oxide, silicon oxide and/or aluminium oxide, for example, may reduce the catalytic coking. In particular, the catalytically inactive material may form a layer on the inner surface. Catalytically active materials, such as nickel and/or iron, may promote the catalytic coking.

In particular, when step f. is implemented, the outputting of the coking level of the steam cracker corrected in step d. according to step e. may be replaced by the outputting of the catalytic coking level according to step f. Alternatively, or in addition, the pyrolytic coking level and/or the coking level corrected in step b. may be output.

In one exemplary embodiment, at least one process parameter of the steam cracker may be detected in step a., wherein the simulated pressure drop in step b. and/or the

simulated temperature profile in step b. may additionally be simulated on the basis of the at least one process parameter of the steam cracker.

In this way, the method can be made more precise. The at least one process parameter can also make the method more efficient and easier to implement, since the simulation of the pressure drop in step c. can be improved. This can also facilitate control of the steam cracker.

The at least one process parameter may be a value or a property of the steam cracker or of the steam-cracking process. The at least one parameter may influence the coking and/or the pressure drop of the steam cracker. The at least one parameter may be incorporated into the simulation in step c.

In one exemplary embodiment, the at least one process parameter may represent one of the following variables and/or properties:

- a geometry of the steam cracker;
- an inlet pressure,
  wherein, in particular, the inlet pressure may be determined using a pressure sensor;
- an outlet pressure,
  wherein, in particular, the outlet pressure may be determined using a pressure sensor;
- a mass flow rate,
  wherein, in particular, the mass flow rate may be detected using a mass flow sensor;
- at least one input product,
  wherein, in particular, the at least one input product may be determined using a PIONA analysis and/or gas chromatography, in particular multidimensional gas chromatography;
- at least one output product,
  wherein, in particular, the at least one output product may be determined using residual gas analysis and/or gas chromatography, in particular multidimensional gas chromatography;
- a steam ratio;
- an inlet temperature of the at least one input product,
  wherein, in particular, the inlet temperature may be determined using a temperature sensor;
- an outlet temperature of the at least one output product,
  wherein, in particular, the outlet temperature may be determined using a temperature sensor;
- a heat-flux profile;

- a time,
  wherein, in particular, the time may be measured using a time-measuring device.

In this way, the method can be made more precise, since the at least one process parameter may significantly influence the coking level of the steam cracker. The at least one process parameter can also make the method more efficient and easier to perform, since the pressure drop in step c. can be simulated more quickly and accurately on the basis of the at least one process parameter. This can also facilitate the control of the steam cracker.

The geometry of the steam cracker may be the course of the reactor tubes of the steam cracker. The geometry may be determined from technical drawings or a design file, such as a CAD file, for example. Alternatively, or in addition, the geometry of the steam cracker may be measured.

The temperature profile and the coking profile can be determined with spatial accuracy using the geometry of the steam cracker. This enables the thermal loading and ageing of the individual tubes of the steam cracker to be determined. In this way, the method can make the steam cracker more efficient, for example by adapting the material selection or by replacing only defective reactor tubes.

The inlet pressure may be the pressure of the at least one input product at the inlet of the steam cracker. The inlet pressure may be the pressure at which the at least one input product can be supplied to the steam cracker. The inlet pressure can be determined particularly easily using a pressure sensor.

In this way, the pressure drop across the steam cracker can be calculated, thereby enabling the method to be more precise and efficient.

The outlet pressure may be the pressure of the at least one output product at the outlet of the steam cracker. The outlet pressure may be the pressure at which the at least one output product can exit the steam cracker. The outlet pressure can be determined particularly easily using a pressure sensor.

In this way, the pressure drop across the steam cracker can be calculated, thereby enabling the method to be more precise and efficient.

The mass flow rate may be the volumetric flow rate through the steam cracker. The mass flow rate can be detected using a mass flow sensor. The mass flow rate may be determined, for example, from the pressure drop across metering orifices and/or by measuring Coriolis forces. The mass flow rate may be calculated therefrom.

Alternatively, or in addition, the mass flow rate may be determined from the density as a function of temperature and composition.

The required energy and the flow velocity can be determined from the mass flow rate. These may influence the pressure drop, thereby making the method more accurate.

The at least one input product may be the product introduced into the steam cracker. In particular, a plurality of input products may also be present. The at least one input product may comprise, for example, ethane, butane, other longer-chain paraffins, cycloalkanes or a mixture thereof.

The at least one input product may be determined using a PIONA analysis and/or gas chromatography, in particular multidimensional gas chromatography. The at least one input product may be determined in accordance with DIN EN ISO 22854, ASTM D5134-21 or ASTM D86-23.

The at least one output product may be the product discharged from the steam cracker. In particular, a plurality of output products may also be present. The at least one output product may comprise, for example, an olefin, ethylene, propylene, uncracked ethane or a mixture thereof.

The at least one output product may be determined using residual gas analysis and/or gas chromatography, in particular multidimensional gas chromatography. The at least one output product may be determined in accordance with DIN EN ISO 22854, ASTM D5134-21 or ASTM D86-23.

The steam ratio may be the ratio of steam to hydrocarbons. The steam ratio may be the quotient of the mass flow rate of the steam and the mass flow rate of the at least one input product. The steam ratio may be set by the operator of the steam cracker. The steam ratio may also be the steam-to-oil ratio of the steam cracker.

The inlet temperature of the at least one input product may be the temperature of the at least one input product as it is introduced into the steam cracker. The inlet temperature may be determined using a temperature sensor. The temperature sensor may be a thermocouple, a pyrometer, an optoelectronic sensor and/or a thermal-imaging camera.

The outlet temperature of the at least one output product may be the temperature of the at least one output product as it is discharged from the steam cracker. The outlet temperature may be determined using a temperature sensor. The temperature sensor may be a thermocouple, a pyrometer, an optoelectronic sensor and/or a thermal-imaging camera.

The heat-flux profile may be the thermal energy transported within a period of time from a location at a high temperature to a location at a low temperature. In the steam cracker, the heat-flux profile may represent the transfer of heat from the heated outer side of the reactor tubes to the inner side of the reactor tubes. The heat-flux profile may be determined from surface-temperature measurements. Alternatively, or in addition, the heat-flux profile may be determined on the basis of the outlet temperature and the at least one output product. Alternatively, or in addition, a profile may be estimated from the burner arrangement. Alternatively, or in addition, the heat-flux profile may be determined on the basis of CFD simulations of the burners in the steam cracker.

The time may be the operating period of the steam cracker. The time may be measured using a time-measuring device. A time-measuring device may be a stopwatch, for example. The time enables the amount of coking to be estimated particularly effectively, since the amount of the at least one input product and the at least one output product can be determined.

In one exemplary embodiment, the method may be performed periodically.

In this way, the method enables the coking level of the steam cracker to be monitored continuously. The coking can thus be determined particularly precisely. The efficiency of the method can also be improved in this way. Furthermore, the method may be easy to implement, since the coking level of the steam cracker can be monitored continuously. All of this can, in turn, facilitate the control of the steam cracker.

“Periodically” may mean that the method is performed at regular intervals of time. The intervals of time may be selected in such a manner that a measurable change in the pressure drop detected in step a. as a result of the coking can be identified.

In one exemplary embodiment, the method may be performed daily, preferably hourly.

In this way, the method enables the coking level of the steam cracker to be monitored continuously and at short intervals. The coking can thus be determined particularly precisely. The efficiency of the method can also be improved in this way. Furthermore, the method can be easy to perform, since the coking level of the steam cracker can be monitored daily. All of this can, in turn, facilitate the control of the steam cracker. If the method is performed hourly, the aforementioned advantages are further enhanced.

In one exemplary embodiment, the method may be applied over an entire run of the steam cracker.

In this way, the method enables the coking level of the steam cracker to be simulated over the entire run. The coking level can thus be determined particularly precisely, since the initial coking may be particularly easy to determine because no coking may be present at the beginning of a run. Consequently, the method can be particularly efficient and easy to perform. This then facilitates the control of the steam cracker.

The entire run of a steam cracker may be the operation of the steam cracker between two decoking operations. The run may extend from the beginning of the use of the steam cracker following a decoking operation to the end of the use of the steam cracker for a further decoking operation. Decoking may involve burning coke off the steam cracker. No coking may be present in the steam cracker at the beginning of the run. The maximum coking of the steam cracker may be present at the end of the run.

According to one exemplary embodiment, a method for modelling the steam cracking of hydrocarbons in steam crackers may be used for the method, in particular for steps b. and c.

One example of a method for modelling the steam cracking of hydrocarbons in steam crackers is the COILSIM1D program.

The COILSIM1D program was developed to simulate the steam cracking of hydrocarbons in reactor tubes. A reaction network may be used to model the reactions that may occur during the process. The reaction network may consist of the two schemes of a monomolecular μ-network and a β-network. This may be based, in particular, on Chapters 2.1–2.3 of Kevin van Geem's doctoral thesis entitled "Single Event Microkinetic Model for Steam Cracking of Hydrocarbons" (ISBN 90-8578-077-2).

A steam-cracker model may be additionally required, in order to model the reactors for steam cracking. The model equations may be based on a one-dimensional model in which it can be assumed that there are no gradients in the variables to be calculated in the radial direction. The temperature profile in the region of the very thin film close to the wall may constitute the exception. This gradient cannot be disregarded because it may be significant for heat transfer. The flow may be assumed to be plug flow. The model equations may contain the transport equations for mass, momentum and energy, also known as the Navier–Stokes equations. These equations may be integrated along the coil of the steam cracker and may ultimately yield the product yields and the pressure and temperature profiles across the reactor tubes. This may be based, in particular, on Chapter 4 of Kevin van Geem's doctoral thesis entitled "Single Event Microkinetic Model for Steam Cracking of Hydrocarbons" (ISBN 90-8578-077-2).

The following two coking models may be incorporated into the basic simulation model, in order to simulate the run length of industrial steam crackers. The coking model of Plehiers et al. (Plehiers P.M. Rigoureuze Modellen voor de Simulatie van Fornuizen voor de Thermische Kraking van Lichte Koolwaterstoffen, PhD dissertation, UGent, 1989) was developed to predict coking rates during the steam cracking of light hydrocarbon feedstocks. The model of Reyniers et al. (Reyniers G.C., Froment G.F., Kopinke F.D., Zimmerman G. Coke Formation in the Thermal Cracking of Hydrocarbons. 4. Modeling of Coke Formation in Naphtha Cracking, Ind. Eng. Chem. Res., 33, 2584, 1994) enables the coking rate of heavier feedstocks, ranging from light naphtha fractions to condensates, to be simulated.

However, both coking models can take account only of heterogeneous non-catalytic, or so-called pyrolytic, coking. The coking kinetics may be coupled to the one-dimensional reactor-model equations that can be solved in the program. This may be based, in particular, on Chapter 5, especially Chapter 5.2.4, of Kevin van Geem's doctoral thesis entitled "Single Event Microkinetic Model for Steam Cracking of Hydrocarbons" (ISBN 90-8578-077-2).

According to a second aspect of the invention, the object is achieved by a computer-implemented method for determining the ageing of a steam cracker, characterized by the following steps:

a. determining the catalytic coking level using the method according to the invention for outputting the coking level of a steam cracker;
b. comparing the catalytic coking level with a catalytic reference coking level;
c. outputting the result of the comparison in step b. as the ageing of the steam cracker.

In this way, the ageing, and therefore the condition, of the steam cracker can be determined particularly precisely, thereby facilitating the control of the steam cracker. In addition to the ageing and condition of the steam cracker, the risk of a reactor tube of the steam cracker rupturing can therefore also be determined, so that the method increases the safety of the steam cracker. Furthermore, the method is particularly efficient and easy to implement.

The ageing of a steam cracker may be the condition of the reactor tubes of the steam cracker. In particular, the ageing may correspond to the consumption of the service life of the reactor tubes of the steam cracker. The consumption of the service life of the reactor tubes may be a reduction from the initial wall thickness to a critical wall thickness. The critical wall thickness may be the wall thickness at which failure of the reactor tubes of the steam cracker, such as breaking, bursting and/or cracking of the reactor tubes of the steam cracker, can still be prevented. The remaining wall thickness may be

determined on the basis of carburization and/or nitridation. In particular, the ageing may be output separately for each of the reactor tubes of the steam cracker.

The ageing may be the progression of corrosion. For example, the progression of corrosion may comprise a change in the inner surface of the tubes, in particular a change in the chemical composition of the inner surface of the tubes. For example, the progression of corrosion may comprise an increase in a catalytically active material, such as nickel and/or iron, on the inner surface of the tubes. Alternatively, or in addition, the progression of corrosion may comprise a change in the chemical composition of the material from the inner surface towards the outer surface of the tubes. For example, the change in the chemical composition of the tube material from the inner surface towards the outer surface of the tubes may comprise carburization and/or nitridation.

For example, a certain amount of the catalytically inactive material may be present on the inner surface at the beginning of the service life. The catalytically inactive material may be an oxide layer, such as chromium oxide, silicon oxide and/or aluminium oxide, on the inner surface. In particular, the catalytically inactive material may form a layer on the inner surface. The catalytically inactive material may also prevent carburization and/or nitridation of the tube. As ageing progresses, the amount of the catalytically inactive material on the inner surface may decrease. As ageing progresses, an increasing amount of catalytically active material, such as nickel and/or iron, may be present on the inner surface of the tubes. In this way, the catalytic coking level may increase and/or the carburization and/or nitridation may increase. The catalytically inactive material may reduce catalytic coking. The catalytically active material may promote catalytic coking.

The catalytic reference coking level may be a value representing the coking level at the end of the service life. As the steam cracker ages, the amount of alloying elements in the reactor tubes that are capable of forming a protective oxide layer may decrease. The catalytic coking level may therefore increase as ageing progresses, so that the maximum catalytic coking level at the end of the service life of the steam cracker may constitute the catalytic reference coking level. The catalytic reference coking level may be determined empirically or derived from empirical values.

The comparison in step b. of the catalytic coking level with the catalytic reference coking level may comprise a comparison of their absolute values and/or a ratio between the catalytic coking level and the catalytic reference coking level. In particular, the comparison may be output as the proportion of the catalytic reference coking level represented by the catalytic coking determined in step a., in particular as a percentage.

The result of the comparison in step b. may be output visually and/or acoustically as the ageing of the steam cracker.

According to one exemplary embodiment, the catalytic reference coking level may be determined at the end of the service life of a steam cracker.

In this way, the ageing, and therefore the condition, of the steam cracker can be determined particularly precisely, since the catalytic reference coking level may have been obtained from empirical data. This can facilitate the control of the steam cracker. In addition to the ageing and condition of the steam cracker, the risk of rupture of a reactor tube of the steam cracker can therefore also be determined particularly accurately, so that the method can improve the safety of the steam cracker. Furthermore, the method can be particularly efficient and easy to perform. The steam cracker used to determine the catalytic reference coking level at the end of the service life may be any steam cracker.

The catalytic reference coking level at the end of the service life of a steam cracker may be the maximum catalytic coking level at the end of the service life of the steam cracker.

According to one exemplary embodiment, the catalytic reference coking may be determined from historical data relating to the same steam cracker.

In this way, the ageing, and therefore the condition, of the steam cracker can be determined particularly precisely, since the catalytic reference coking may have been obtained from empirical data relating to the same steam cracker. This can facilitate the control of the steam cracker. In addition to the ageing and condition of the steam cracker, the risk of rupture of a reactor tube of the steam cracker can thus also be determined particularly accurately, so that the method can increase the safety of the steam cracker. Furthermore, the method can be particularly efficient and easy to perform.

The same steam cracker may be the steam cracker whose ageing is to be determined and on which the catalytic reference coking level may also have been determined. It may therefore be the same steam cracker, although individual reactor tubes may have been replaced.

According to a third aspect of the invention, the object is achieved by a device configured to perform the method according to the invention for outputting the coking level of a steam cracker and/or to perform the method according to the invention for determining the ageing of a steam cracker, or comprising respective means for performing the steps of the method according to the invention for outputting the coking level of a steam cracker

and/or respective components for performing the steps of the method according to the invention for determining the ageing of a steam cracker.

According to a fourth aspect of the invention, the object is achieved by a computer program comprising program instructions configured, when executed by at least one processor, to cause a device to perform the method according to the invention for outputting the coking level of a steam cracker and/or the method according to the invention for determining the ageing of a steam cracker.

Further objects, features, advantages and aspects of the present invention will be apparent to a person skilled in the art from the following description and the appended claims. It should be understood, however, that the following description, the appended claims and the specific examples, which illustrate preferred embodiments of the application, are provided solely by way of illustration. Various changes and modifications within the spirit and scope of the disclosed invention will be readily apparent to a person skilled in the art upon reading the following remarks.

DEFINITIONS

As a general rule, the following expressions preferably have the meanings set out below, unless the context in which they are used indicates otherwise.

In addition to its literal meaning, the expression “comprise”, as used herein, also includes and specifically encompasses the expressions “consist essentially of” and “consist of”. Thus, the expression “comprise” refers both to embodiments in which the subject matter that “comprises” specifically listed elements comprises no further elements and to embodiments in which the subject matter that “comprises” specifically listed elements may and/or does comprise further elements. Similarly, the expression “have” is to be understood as the expression “comprise” and also includes and encompasses the expressions “consist essentially of” and “consist of”. Where applicable, the expression “consist essentially of” refers, in particular, to embodiments in which the subject matter comprises, in addition to the specifically listed elements of which the subject matter essentially consists, 20% or less, in particular 15% or less, 10% or less or especially 5% or less, of further elements.

FIGURES

Fig. 1 a flow chart of an embodiment of a computer-implemented method according to the invention for outputting the coking level of a steam cracker;
Fig. 2 a flow chart of an embodiment of step d. of the computer-implemented method according to the invention;
Fig. 3 a schematic view of a steam cracker;
Fig. 4 a flow chart of an embodiment of a computer-implemented method according to the invention for determining the ageing of a steam cracker;
Fig. 5 a cross-section through an aged reactor tube;
Fig. 6 a cross-section through a reactor tube at the end of its service life;
Fig. 7 a schematic representation of an embodiment of a device according to the invention.

DETAILED DESCRIPTION

Fig. 1 shows a flow chart of an embodiment of a computer-implemented method according to the invention.

The computer-implemented method comprises the following steps:

a. detecting a pressure drop of the steam cracker;
b. defining a coking level of the steam cracker;
c. simulating a pressure drop of the steam cracker on the basis of the coking level defined in step b.;
d. correcting the coking level defined in step b. in order to match the pressure drop simulated in step c. to the pressure drop detected in step a.;
e. outputting the coking corrected in step d.;
f. determining a catalytic coking by subtracting the pyrolytic coking level from the coking level corrected in step d., and outputting the catalytic coking level.

In the method, a pressure drop of the steam cracker is first detected in step 100. A coking level of the steam cracker is defined in step 101. A pressure drop of the steam cracker is then simulated in step 103 on the basis of the coking level defined in step 101. In step 104, the coking level defined in step 101 is corrected, in order to match the pressure drop simulated in step 102 to the pressure drop detected in step 100. The coking level corrected in step 103 is then output. Subsequently, a catalytic coking is determined by subtracting the pyrolytic coking level from the coking level corrected in step 103, and the catalytic coking level is output.

However, it is also possible for the method to end with the outputting of the coking level corrected in step 103 according to step 104. Furthermore, when step 105 is performed, the outputting of the coking level of the steam cracker corrected in step 103 according to

step 104 may be replaced by the outputting of the catalytic coking according to step 105. Alternatively, or in addition, the pyrolytic coking level and/or the coking level corrected in step 101 may be output.

The coking level defined in step 101 is defined by the pyrolytic coking in the steam cracker.

Fig. 2 shows a flow chart of an embodiment of step 103 of the method according to the invention.

The correction according to step 103 of the coking level defined in step 101 is performed iteratively. For this purpose, the correction according to step 103 of the coking level defined in step 101, in order to match the simulated pressure drop to the detected pressure drop according to step 103 comprises the following steps:

In step 200, the simulated pressure drop is compared with the detected pressure drop. The coking level defined in step 101 is then corrected in step 201. In the next step 202, the pressure drop of the steam cracker is simulated on the basis of the coking level corrected in step 201.

In the method shown in Fig. 1, at least one process parameter of the steam cracker may be detected in step 100. In step 101, the simulated pressure drop is then additionally simulated on the basis of the at least one process parameter of the steam cracker.

Fig. 3 shows a schematic view of a steam cracker 300. The steam cracker 300 is used to explain how the various process parameters can be determined at the steam cracker 300. The process parameter may be, for example, the geometry of the steam cracker 300, the inlet pressure, the outlet pressure, the mass flow rate, at least one input product, at least one output product, the inlet temperature of the at least one input product, the outlet temperature of the at least one output product, the heat-flux profile and/or the time.

The inlet pressure and the outlet pressure are each determined using a pressure sensor. The mass flow rate is detected using a mass flow sensor. The inlet temperature of the at least one input product and the outlet temperature of the at least one output product are determined using a temperature sensor.

Fig. 3 shows a schematic view of a steam cracker 300. The steam cracker 300 comprises a plurality of burners 301. The steam cracker 300 also comprises the first sensor 301 for determining a process parameter and the second sensor 302 for determining a process parameter.

The first sensor 302 is arranged at the inlet of the steam cracker. The first sensor 302 may be configured to determine the inlet pressure, the mass flow rate, the inlet temperature, the steam ratio or the at least one input product. Instead of one first sensor 302, a plurality of first sensors 302 may also be arranged at the inlet of the steam cracker 300, in order to determine two, three, four, five or more process parameters. For example, a plurality of first sensors 302 may also be used to determine two, three, four or five process parameters selected from the inlet pressure, mass flow rate, inlet temperature, steam ratio and at least one input product.

The second sensor 303 is arranged at the outlet of the steam cracker. The second sensor 303 may be configured to determine the outlet pressure, the outlet temperature or the at least one output product. Instead of one second sensor 303, a plurality of second sensors 303 may also be arranged at the outlet of the steam cracker 300, in order to determine two, three or more process parameters. For example, a plurality of second sensors 303 may also be used to determine two or three process parameters selected from the outlet pressure, outlet temperature and the at least one output product.

The method is performed periodically. In this case, the method is performed daily. Alternatively, the method may also be performed hourly. In this case, the method is applied over an entire run of the steam cracker.

Fig. 4 shows a flow chart of an embodiment of a computer-implemented method according to the invention for determining the ageing of a steam cracker.

The computer-implemented method for determining the ageing of a steam cracker comprises the following steps:

a. determining the catalytic coking level;
b. comparing the catalytic coking level with a catalytic reference coking level;
c. outputting the result of the comparison in step b. as the ageing of the steam cracker.

As shown in the flow chart in Fig. 4, the catalytic coking is first determined in step 400, as explained above with reference to Fig. 1. The catalytic coking level is then compared with the catalytic reference coking level in step 401. Subsequently, the result of the comparison in step 401 is output in step 402 as the ageing of the steam cracker.

The catalytic reference coking level is determined at the end of the service life of a steam cracker. The catalytic reference coking level is also determined from historical data relating to the same steam cracker.

Fig. 5 shows a cross-section through an aged reactor tube. The reactor tube exhibits carburization on the inner side and nitridation on the outer side. The carburization and nitridation increase as ageing progresses. The region between the carburized region and the nitrided region constitutes the remaining wall thickness.

Fig. 6 shows a cross section through a reactor tube at the end of its service life. In comparison with Fig. 5, it can be seen that the carburization and nitridation have progressed further. The remaining wall thickness is so small that the reactor tube should be replaced.

Fig. 7 shows a schematic representation of an embodiment of a device 7 according to the invention.

The device 7 comprises a processor 700 and, connected to the processor 700, a first memory in the form of a program memory 701, a second memory in the form of a main memory 702 and a network interface 703.

A processor 700 is to be understood as meaning, for example, a microprocessor (Central Processing Unit, CPU), a digital signal processor (DSP), an application-specific integrated circuit (ASIC), a microcontroller unit, a microcontroller, a field-programmable gate array (FPGA) or a graphics processor (Graphics Processing Unit, GPU). It will be appreciated that the device 7 may also comprise a plurality of processors 700.

The processor 700 executes program instructions stored in the program memory 701 and stores, for example, intermediate results or the like in the main memory 702. The use of an additional graphics processor may be advantageous, for example, for executing machine-learning algorithms and/or artificial neural networks.

The program memory 701 stores, for example, program instructions which, when executed by the processor 700, cause the processor 700 to at least partially perform and/or control the method according to the first aspect of the invention. The method according to the first aspect of the invention is shown, for example, in Fig. 1. Alternatively, or in addition, the program memory 701 stores, for example, program instructions which, when executed by the processor 700, cause the processor 700 to at least partially perform and/or control the method according to the second aspect of the invention. The method according to the second aspect of the invention is shown, for example, in Fig. 3.

The program memory 701 also contains, for example, the operating system of the device 7, which is loaded at least partially into the main memory 702 when the device 7 is started and is executed by the processor 700.

Examples of operating systems include Windows, UNIX, Linux, Android, Apple iOS and/or Mac OS operating systems. In particular, the operating system enables the device 7 to be used for data processing. For example, it manages resources such as a main memory and a program memory, provides basic functions to other computer programs, inter alia through programming interfaces, and controls the execution of computer programs.

The program memory 701 is, for example, a non-volatile memory such as a flash memory, an EEPROM (electrically erasable programmable read-only memory), a magnetic memory and/or an optical memory. The main memory 702 is, for example, a volatile or non-volatile memory, in particular a random-access memory (RAM), such as a static RAM (SRAM), a ferroelectric RAM (FeRAM), a dynamic RAM (DRAM) and/or a magnetic RAM (MRAM).

The main memory 702 and the program memory 701 may also be formed as a single memory. Alternatively, the main memory 702 and/or the program memory 701 may each be formed by a plurality of memories. Furthermore, the main memory 702 and/or the program memory 701 may also form part of the processor 700.

The processor 700 controls the network interface 703, which is configured, for example, to exchange information with a remote device via a connection in a communication network (e.g. to transmit and/or receive information). In the following, it is assumed by way of example that the network interface 703 is a wired network interface. One example of a wired network interface is an Ethernet interface. For example, the device 7 may use the network interface 703 to output information such as the coking level of the steam cracker or the ageing of the steam cracker. For this purpose, the network interface 703 may be connected, for example, to a screen and/or a loudspeaker.

The components 700 to 703 of the device 7 are communicatively and/or operatively connected to one another, for example, via one or more bus systems (e.g. one or more serial and/or parallel bus connections).

It will be appreciated that, in addition to the components 700 to 703, the device 7 may comprise further components (e.g. a user interface). The device may be connected to an output device, such as a screen and/or a loudspeaker, for example.

PATENT CLAIMS:

1. A computer-implemented method for outputting the coking level of a steam cracker,
   characterized by the following steps:
   a. detecting a pressure drop of the steam cracker (100) and/or a temperature profile of the steam cracker,
   b. defining a coking level of the steam cracker (101),
   c. simulating a pressure drop of the steam cracker and/or simulating a temperature profile of the steam cracker on the basis of the coking level defined in step b. (102),
   d. correcting the coking level defined in step b. in order to match the pressure drop simulated in step c. to the pressure drop detected in step a. (103) and/or correcting the coking level defined in step b. in order to match the temperature profile simulated in step c. to the temperature profile detected in step a.,
   e. outputting the coking level corrected in step d. (104).

2. The computer-implemented method according to claim 1,
   characterized in that
   the correction according to step d. of the coking level defined in step b. is performed iteratively,
   wherein correcting the coking level defined in step b. in order to match the simulated pressure drop to the detected pressure drop according to step d. and/or correcting the coking level defined in step b. in order to match the simulated temperature profile to the detected temperature profile according to step d. comprises the following steps:
   d.1. comparing the simulated pressure drop with the detected pressure drop (200) and/or comparing the simulated temperature profile with the detected temperature profile,
   d.2. correcting the coking level defined in step b. (201),
   d.3. simulating the pressure drop of the steam cracker on the basis of the coking level corrected in step d.2 (202) and/or simulating the temperature profile of the steam cracker on the basis of the coking level corrected in step d.2.

3. The computer-implemented method according to claim 1 or 2,
   characterized in that

the coking level defined in step b. is defined by the pyrolytic coking level in the steam cracker.

4. The computer-implemented method according to any one of claims 1 to 3, comprising the additional method step:
    f. determining a catalytic coking level by subtracting the pyrolytic coking level from the coking level corrected in step d. and outputting the catalytic coking level (105).

5. The computer-implemented method according to any one of claims 1 to 4, **characterized in that**
at least one process parameter of the steam cracker is detected in step a. (100), and
wherein, in step b. (101), the simulated pressure drop and/or, in step b., the simulated temperature profile is additionally simulated on the basis of the at least one process parameter of the steam cracker.

6. The computer-implemented method according to claim 5, **characterized in that**
the at least one process parameter represents one of the following variables and/or properties:
    - a geometry of the steam cracker,
    - an inlet pressure,
      wherein, in particular, the inlet pressure is determined using a pressure sensor,
    - an outlet pressure,
      wherein, in particular, the outlet pressure is determined using a pressure sensor,
    - a mass flow rate,
      wherein, in particular, the mass flow rate is detected using a mass flow sensor,
    - at least one input product,
      wherein, in particular, the at least one input product is determined using a PIONA analysis and/or gas chromatography, in particular multidimensional gas chromatography,
    - at least one output product,
      wherein, in particular, the at least one output product is determined using residual gas analysis and/or gas chromatography, in particular multidimensional gas chromatography,
    - a steam ratio,
    - an inlet temperature of the at least one input product,

wherein, in particular, the inlet temperature is determined using a temperature sensor,

- an outlet temperature of the at least one output product,
  wherein, in particular, the outlet temperature is determined using a temperature sensor,
- a heat-flux profile,
- a time,
  wherein, in particular, the time is measured using a time-measuring device.

7. The computer-implemented method according to any one of claims 1 to 6, **characterized in that**
the method is performed periodically.

8. The computer-implemented method according to claim 7,
characterized in that
the method is performed daily, preferably hourly.

9. The computer-implemented method according to any one of claims 1 to 8,
characterized in that
the method is applied over an entire run of the steam cracker.

10. The computer-implemented method according to any one of claims 1 to 9,
characterized in that
a method for modelling the steam cracking of hydrocarbons in steam crackers is used for the method.

11. The computer-implemented method for determining the ageing of a steam cracker,
characterized by the following steps:
    a. determining the catalytic coking level according to claim 4 (400),
    b. comparing the catalytic coking level with a catalytic reference coking level (401),
    c. outputting the result of the comparison in step b. as the ageing of the steam cracker (402).

12. The computer-implemented method according to claim 11,
characterized in that
the catalytic reference coking level is determined at the end of the service life of a steam cracker.

13. The computer-implemented method according to claim 11 or 12,

characterized in that
the catalytic reference coking level is determined from historical data relating to the same steam cracker.

14. A device configured to perform the method for outputting the coking level of a steam cracker according to any one of claims 1 to 10 and/or to perform the method for determining the ageing of a steam cracker according to any one of claims 11 to 13, or
comprising respective means for performing the steps of the method for outputting the coking level of a steam cracker according to any one of claims 1 to 10 and/or comprising respective means for performing the steps of the method for determining the ageing of a steam cracker according to any one of claims 11 to 13.

15. A computer program comprising program instructions configured, when executed by at least one processor, to cause a device to perform the method for outputting the coking level of a steam cracker according to any one of claims 1 to 10 and/or the method for determining the ageing of a steam cracker according to any one of claims 11 to 13.