

PROCESS FOR MAKING CYCLOHEXANONE

PRIORITY CLAIM TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application Serial No. 62/140,702
5 filed March 31, 2015; U.S. Provisional Application Serial No. 62/057,919 filed September 30, 2014;
and European Application No. 15151424.7 filed January 16, 2015, the disclosures of which are
fully incorporated herein by their reference.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] The present application is related to U.S. Provisional Application Serial No. 62/057,919
10 filed September 30, 2014; U.S. Provisional Application Serial No. 62/037,794 filed August 15,
2014; U.S. Provisional Application Serial No. 62/037,801 filed August 15, 2014; U.S. Provisional
Application Serial No. 62/037,814 filed August 15, 2014; and U.S. Provisional Application Serial
No. 62/037,824 filed August 15, 2014, which are incorporated by reference.

FIELD

15 [0003] The present invention relates to processes for making cyclohexanone. In particular, the
present invention relates to processes for making cyclohexanone by phenol hydrogenation. The
present invention is useful, e.g., in making cyclohexanone from cyclohexylbenzene oxidation and
cyclohexylbenzene hydroperoxide cleavage.

BACKGROUND

20 [0004] Cyclohexanone is an important material in the chemical industry and is widely used in,
for example, production of phenolic resins, bisphenol A, ϵ -caprolactam, adipic acid, and
plasticizers. One method for making cyclohexanone is by hydrogenating phenol.

[0005] Currently, a common route for the production of phenol is the Hock process. This is a
three-step process in which the first step involves alkylation of benzene with propylene to produce
25 cumene, followed by oxidation of cumene to the corresponding hydroperoxide, and then cleavage
of the hydroperoxide to produce equimolar amounts of phenol and acetone. The separated phenol
product can then be converted to cyclohexanone by a step of hydrogenation.

[0006] It is known from, e.g., U.S. Patent No. 6,037,513, that cyclohexylbenzene can be
produced by contacting benzene with hydrogen in the presence of a bifunctional catalyst
30 comprising a molecular sieve of the MCM-22 type and at least one hydrogenation metal selected
from palladium, ruthenium, nickel, cobalt, and mixtures thereof. This reference also discloses that
the resultant cyclohexylbenzene can be oxidized to the corresponding hydroperoxide, which can
then be cleaved to produce a cleavage mixture of phenol and cyclohexanone, which, in turn, can be
separated to obtain pure, substantially equimolar phenol and cyclohexanone products. This

cyclohexylbenzene-based process for co-producing phenol and cyclohexanone can be highly efficient in making these two important industrial materials. Given the higher commercial value of cyclohexanone than phenol, it is highly desirable that in this process more cyclohexanone than phenol be produced. While this can be achieved by subsequently hydrogenating the pure phenol product produced in this process to convert a part or all of the phenol to cyclohexanone, a more economical process and system would be highly desirable.

[0007] One solution to making more cyclohexanone than phenol from the above cyclohexylbenzene-based process is to hydrogenate a mixture containing phenol and cyclohexanone obtained from the cleavage mixture to convert at least a portion of the phenol contained therein to cyclohexanone. However, because the phenol/cyclohexanone mixture invariably contains non-negligible amounts of (i) S-containing component(s) that can poison the hydrogenation catalyst, and (ii) cyclohexylbenzene that can be converted into bicyclohexane in the hydrogenation step, and because hydrogenation of the phenol/cyclohexanone/cyclohexylbenzene mixture can also lead to the formation of cyclohexanol, resulting in yield loss, this process is not without challenge.

[0008] As such, there is a need for an improved process for making cyclohexanone from a mixture containing phenol, cyclohexanone, cyclohexylbenzene, and S-containing component(s).

[0009] The present invention satisfies this and other needs.

SUMMARY

[0010] It has been found that S-containing components contained in phenol/cyclohexanone mixtures can be effectively removed by using an anterior sorbent before the first distillation column for separating cyclohexanone from the phenol/cyclohexanone mixture, and/or by using a posterior sorbent after the first distillation column but before the hydrogenation reactor, thereby alleviating the poisoning of the hydrogenation catalyst.

[0011] In a first aspect, the present disclosure relates to a process for making cyclohexanone, the process comprising: (Ia) providing a crude mixture comprising cyclohexanone, phenol, cyclohexylbenzene, and an S-containing component; (Ib) contacting the crude mixture with an anterior sorbent capable of removing at least a portion of the S-containing component to obtain a first mixture comprising cyclohexanone, phenol, and cyclohexylbenzene; (Ic) feeding the first mixture into a first distillation column; (II) obtaining from the first distillation column: a first upper effluent comprising cyclohexanone at a concentration higher than the first mixture; a first middle effluent comprising phenol at a concentration higher than the first mixture, cyclohexanone, cyclohexylbenzene, and bicyclohexane; and a first lower effluent comprising cyclohexylbenzene at a concentration higher than the first mixture; (III) providing hydrogen and at least a portion of the

first middle effluent as at least a portion of a hydrogenation feed to a hydrogenation reaction zone; (IV) contacting the hydrogenation feed with hydrogen in the hydrogenation reaction zone where phenol reacts with hydrogen in the presence of a hydrogenation catalyst under hydrogenation reaction conditions to obtain a hydrogenation reaction product comprising cyclohexanone at a concentration higher than the hydrogenation feed, phenol at a concentration lower than the hydrogenation feed, cyclohexylbenzene, and bicyclohexane; and (V) feeding at least a portion of the hydrogenation reaction product into the first distillation column.

[0012] In a second aspect, the present disclosure relates to a process for making cyclohexanone, the process comprising: (I) feeding a first mixture comprising cyclohexanone, phenol, cyclohexylbenzene, and an S-containing component into a first distillation column; (II) obtaining from the first distillation column: a first upper effluent comprising cyclohexanone at a concentration higher than the first mixture; a first middle effluent comprising phenol at a concentration higher than the first mixture, cyclohexanone, cyclohexylbenzene, bicyclohexane, and a portion of the S-containing component; and a first lower effluent comprising cyclohexylbenzene at a concentration higher than the first mixture; (III) removing at least a portion of the S-containing component from the first middle effluent to obtain a hydrogenation feed; (IV) feeding at least a portion of the hydrogenation feed and hydrogen into a hydrogenation reaction zone where phenol reacts with hydrogen in the presence of a hydrogenation catalyst under hydrogenation reaction conditions to obtain a hydrogenation reaction product comprising cyclohexanone at a concentration higher than the hydrogenation feed, phenol at a concentration lower than the hydrogenation feed, cyclohexylbenzene, and bicyclohexane; and (V) feeding at least a portion of the hydrogenation reaction product into the first distillation column.

[0013] In a specific embodiment of either the first or the second aspect of the processes of the present invention, both an anterior removal mechanism and a posterior removal mechanism are employed to remove at least a portion of the S-containing component from the hydrogenation feed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. 1 is a schematic diagram showing a process/system for making cyclohexanone from a first mixture comprising phenol, cyclohexanone and cyclohexylbenzene including a first distillation column T1, a hydrogenation reactor R1, and a cyclohexanone purification column T2.

[0015] FIG. 2 is a schematic diagram showing a portion of a process/system similar to the process/system shown in FIG. 1, but comprising modified fluid communications between and/or within the first distillation column T1 and the hydrogenation reactor R1.

[0016] FIG. 3 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 and 2, but comprising modified fluid communications and/or heat transfer

arrangement between and/or within the first distillation column T1 and the cyclohexanone purification column T2.

[0017] FIG. 4 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 to 3, but comprising a tubular heat exchanger-type hydrogenation reactor R1, where the hydrogenation reaction occurs primarily in vapor phase.

[0018] FIG. 5 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 to 4, but comprising three hydrogenation reactors R3, R5, and R7 connected in series, where the hydrogenation reaction occurs primarily in liquid phase.

[0019] FIG. 6 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 to 5, but comprising modified fluid communications between and/or within the first distillation column T1 and the hydrogenation reactor R1.

[0020] FIG. 7 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 to 6, but comprising an anterior sorbent bed T4 before the first distillation column T1 configured for removing at least a portion of the S-containing components from the phenol/cyclohexanone/cyclohexylbenzene feed fed to the first distillation column T1 to reduce or prevent catalyst poisoning in the hydrogenation reactor.

[0021] FIG. 8 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 to 7, comprising a posterior sorbent bed T5 after the first distillation column T1 configured for removing at least a portion of the S-containing components from the phenol/cyclohexanone/cyclohexylbenzene feed fed to the hydrogenation reactor to reduce or prevent catalyst poisoning in the hydrogenation reactor.

[0022] FIG. 9 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 to 8, comprising a sorbent bed T6 after the cyclohexanone purification column T2, configured to reduce amounts of S-containing components from the final cyclohexanone product.

DETAILED DESCRIPTION

[0023] Various specific embodiments, versions and examples of the invention will now be described, including preferred embodiments and definitions that are adopted herein for purposes of understanding the claimed invention. While the following detailed description gives specific preferred embodiments, those skilled in the art will appreciate that these embodiments are exemplary only, and that the invention may be practiced in other ways. For purposes of determining infringement, the scope of the invention will refer to any one or more of the appended claims, including their equivalents, and elements or limitations that are equivalent to those that are recited. Any reference to the "invention" may refer to one or more, but not necessarily all, of the inventions defined by the claims.

[0024] In the present disclosure, a process is described as comprising at least one “step.” It should be understood that each step is an action or operation that may be carried out once or multiple times in the process, in a continuous or discontinuous fashion. Unless specified to the contrary or the context clearly indicates otherwise, each step in a process may be conducted sequentially in the order as they are listed, with or without overlapping with one or more other step, or in any other order, as the case may be. In addition, one or more or even all steps may be conducted simultaneously with regard to the same or different batch of material. For example, in a continuous process, while a first step in a process is being conducted with respect to a raw material just fed into the beginning of the process, a second step may be carried out simultaneously with respect to an intermediate material resulting from treating the raw materials fed into the process at an earlier time in the first step. Preferably, the steps are conducted in the order described.

[0025] Unless otherwise indicated, all numbers indicating quantities in the present disclosure are to be understood as being modified by the term “about” in all instances. It should also be understood that the precise numerical values used in the specification and claims constitute specific embodiments. Efforts have been made to ensure the accuracy of the data in the examples. However, it should be understood that any measured data inherently contain a certain level of error due to the limitation of the technique and equipment used for making the measurement.

[0026] As used herein, the indefinite article “a” or “an” shall mean “at least one” unless specified to the contrary or the context clearly indicates otherwise. Thus, embodiments comprising “a light component” include embodiments where one, two or more light components exist, unless specified to the contrary or the context clearly indicates that only one light component exists.

[0027] A “complex” as used herein means a material formed by identified components via chemical bonds, hydrogen bonds, and/or physical forces.

[0028] An “operation temperature” of a distillation column means the highest temperature liquid media inside the column is exposed to during normal operation. Thus, the operation temperature of a column is typically the temperature of the liquid media in the reboiler, if the column is equipped with a reboiler.

[0029] The term “S-containing component” as used herein includes all compounds comprising sulfur.

[0030] In the present application, sulfur concentration in a material is expressed in terms of proportion (ppm, weight percentages, and the like) of the weight of elemental sulfur relative to the total weight of the material, even though the sulfur may be present in various valencies other than zero. Sulfuric acid concentration is expressed in terms of proportion (ppm, weight percentages, and the like) of the weight of H_2SO_4 relative to the total weight of the material, even though the sulfuric

acid may be present in the material in forms other than H_2SO_4 . Thus, the sulfuric acid concentration is the total concentration of H_2SO_4 , SO_3 , HSO_4^- , and R-HSO_4 in the material.

[0031] As used herein, “wt%” means percentage by weight, “vol%” means percentage by volume, “mol%” means percentage by mole, “ppm” means parts per million, and “ppm wt” and “wppm” are used interchangeably to mean parts per million on a weight basis. All “ppm” as used herein are ppm by weight unless specified otherwise. All concentrations herein are expressed on the basis of the total amount of the composition in question. Thus, the concentrations of the various components of the first mixture are expressed based on the total weight of the first mixture. All ranges expressed herein should include both end points as two specific embodiments unless specified or indicated to the contrary.

[0032] In the present disclosure, a location “in the vicinity of” an end (top or bottom) of a column means a location within a distance of $a \cdot H_c$ from the end (top or bottom) of the column, where H_c is the height of the column from the bottom to the top, and $a_1 \leq a \leq a_2$, where a_1 and a_2 can be, independently: 0, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17, 0.18, 0.19, 0.20, as long as $a_1 < a_2$. For example, a location in the vicinity of an end of a column can have an absolute distance from the end (top or bottom) of at most D meters, where D can be 5.0, 4.5, 4.0, 3.5, 3.0, 2.5, 2.0, 1.5, 1.0, 0.8, 0.5, 0.4, 0.3, 0.2, 0.1, or 0.

[0033] An “upper effluent” as used herein may be at the very top or the side of a vessel such as a distillation column or a reactor, with or without an additional effluent above it. Preferably, an upper effluent is drawn at a location in the vicinity of the top of the column. Preferably, an upper effluent is drawn at a location above at least one feed. A “lower effluent” as used herein is at a location lower than the upper effluent, which may be at the very bottom or the side of a vessel, and if at the side, with or without additional effluent below it. Preferably, a lower effluent is drawn at a location in the vicinity of the bottom of the column. Preferably, a lower effluent is drawn at a location below at least one feed. As used herein, a “middle effluent” is an effluent between an upper effluent and a lower effluent. The “same level” on a distillation column means a continuous segment of the column with a total height no more than 5% of the total height of the column.

[0034] Nomenclature of elements and groups thereof used herein are pursuant to the Periodic Table used by the International Union of Pure and Applied Chemistry after 1988. An example of the Periodic Table is shown in the inner page of the front cover of Advanced Inorganic Chemistry, 6th Edition, by F. Albert Cotton et al. (John Wiley & Sons, Inc., 1999).

[0035] As used herein, the term “methylcyclopentanone” includes both isomers 2-methylcyclopentanone (CAS Registry No. 1120-72-5) and 3-methylcyclopentanone (CAS Registry No. 1757-42-2), at any proportion between them, unless it is clearly specified to mean only one of

these two isomers or the context clearly indicates that is the case. It should be noted that under the conditions of the various steps of the present processes, the two isomers may undergo isomerization reactions to result in a ratio between them different from that in the raw materials immediately before being charged into a vessel such as a distillation column.

5 [0036] As used herein, the generic term “dicyclohexylbenzene” (“DiCHB”) includes, in the aggregate, 1,2-dicyclohexylbenzene, 1,3-dicyclohexylbenzene, and 1,4-dicyclohexylbenzene, unless clearly specified to mean only one or two thereof. The term cyclohexylbenzene, when used in the singular form, means mono substituted cyclohexylbenzene. As used herein, the term “C12” means compounds having 12 carbon atoms, and “C12+ components” means compounds having at least 12
10 carbon atoms. Examples of C12+ components include, among others, cyclohexylbenzene, biphenyl, bicyclohexane, methylcyclopentylbenzene, 1,2-biphenylbenzene, 1,3-biphenylbenzene, 1,4-biphenylbenzene, 1,2,3-triphenylbenzene, 1,2,4-triphenylbenzene, 1,3,5-triphenylbenzene, and corresponding oxygenates such as alcohols, ketones, acids, and esters derived from these compounds. As used herein, the term “C18” means compounds having 18 carbon atoms, and the
15 term “C18+ components” means compounds having at least 18 carbon atoms. Examples of C18+ components include, among others, dicyclohexylbenzenes (“DiCHB,” described above), tricyclohexylbenzenes (“TriCHB,” including all isomers thereof, including 1,2,3-tricyclohexylbenzene, 1,2,4-tricyclohexylbenzene, 1,3,5-tricyclohexylbenzene, and mixtures of two or more thereof at any proportion). As used herein, the term “C24” means compounds having 24
20 carbon atoms.

[0037] As used herein, the term “light component” means compound having a normal boiling point (i.e., boiling point at a pressure of 101,325 Pa) lower than cyclohexanone. Examples of the light component include, but are not limited to: (i) methylcyclopentanone; (ii) water; (iii) hydrocarbons comprising 4, 5, 6, 7, 8, 9, 10, 11, or 12 carbon atoms, including but not limited to
25 linear, branched linear, cyclic, substituted cyclic, alkanes, alkenes, and dienes; (iv) oxygenates such as alcohols, aldehydes, ketones, carboxylic acids, ethers, and the like, of hydrocarbons; (v) N-containing compounds, such as amines, amides, imides, NO₂- substituted compounds, and the like; (vi) S-containing compounds, such as sulfides, sulfites, sulfates, sulfones, and the like. It has been found that S-containing compounds, N-containing compounds, dienes, alkenes, cyclic alkenes, and
30 cyclic dienes, and carboxylic acids comprising 1, 2, 3, 4, 5, 6, 7, or 8 carbon atoms can be present in the phenol/cyclohexanone mixture produced by hydroperoxide cleavage reactions described in greater detail below, and they can be particularly detrimental to the performance of the hydrogenation catalyst, leading to catalyst poisoning and undesirable, premature catalyst performance reduction.

[0038] The term "MCM-22 type material" (or "material of the MCM-22 type" or "molecular sieve of the MCM-22 type" or "MCM-22 type zeolite"), as used herein, includes one or more of:

- molecular sieves made from a common first degree crystalline building block unit cell, which unit cell has the MWW framework topology. A unit cell is a spatial arrangement of atoms which if tiled in three-dimensional space describes the crystal structure. Such crystal structures are discussed in the "Atlas of Zeolite Framework Types," Fifth Edition, 2001, the entire content of which is incorporated as reference;
- molecular sieves made from a common second degree building block, being a 2-dimensional tiling of such MWW framework topology unit cells, forming a monolayer of one unit cell thickness, desirably one c-unit cell thickness;
- molecular sieves made from common second degree building blocks, being layers of one or more than one unit cell thickness, wherein the layer of more than one unit cell thickness is made from stacking, packing, or binding at least two monolayers of one unit cell thickness. The stacking of such second degree building blocks can be in a regular fashion, an irregular fashion, a random fashion, or any combination thereof; and
- molecular sieves made by any regular or random 2-dimensional or 3-dimensional combination of unit cells having the MWW framework topology.

[0039] Molecular sieves of the MCM-22 type include those molecular sieves having an X-ray diffraction pattern including d-spacing maxima at 12.4 ± 0.25 , 6.9 ± 0.15 , 3.57 ± 0.07 , and 3.42 ± 0.07 Angstrom. The X-ray diffraction data used to characterize the material are obtained by standard techniques such as using the K-alpha doublet of copper as incident radiation and a diffractometer equipped with a scintillation counter and associated computer as the collection system.

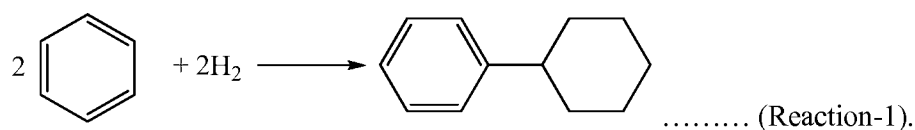
[0040] Materials of the MCM-22 type include MCM-22 (described in U.S. Patent No. 4,954,325), PSH-3 (described in U.S. Patent No. 4,439,409), SSZ-25 (described in U.S. Patent No. 4,826,667), ERB-1 (described in European Patent No. 0293032), ITQ-1 (described in U.S. Patent No. 6,077,498), ITQ-2 (described in International Patent Publication No. WO97/17290), MCM-36 (described in U.S. Patent No. 5,250,277), MCM-49 (described in U.S. Patent No. 5,236,575), MCM-56 (described in U.S. Patent No. 5,362,697), and mixtures thereof. Other molecular sieves, such as UZM-8 (described in U.S. Patent No. 6,756,030), may be used alone or together with the MCM-22 type molecular sieves as well for the purpose of the present disclosure. Desirably, the molecular sieve used in the catalyst of the present disclosure is selected from (a) MCM-49; (b) MCM-56; and (c) isotypes of MCM-49 and MCM-56, such as ITQ-2.

[0041] The process and systems for making cyclohexanone disclosed herein can be advantageously used for making cyclohexanone from any feed mixture comprising phenol,

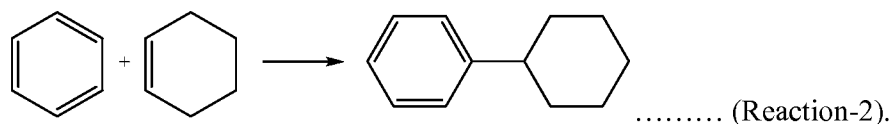
cyclohexanone and cyclohexylbenzene. While the feed may be derived from any process or source, it is preferably obtained from the acid cleavage of a mixture comprising cyclohexylbenzene hydroperoxide and cyclohexylbenzene, which, in turn, is preferably obtained from aerobic oxidation of cyclohexylbenzene, which, in turn, is preferably obtained from benzene hydroalkylation. Steps of these preferred processes are described in detail below.

Supply of Cyclohexylbenzene

[0042] The cyclohexylbenzene supplied to the oxidation step can be produced and/or recycled as part of an integrated process for producing phenol and cyclohexanone from benzene. In such an integrated process, benzene is initially converted to cyclohexylbenzene by any conventional technique, including oxidative coupling of benzene to make biphenyl followed by hydrogenation of the biphenyl. However, in practice, the cyclohexylbenzene is desirably produced by contacting benzene with hydrogen under hydroalkylation conditions in the presence of a hydroalkylation catalyst whereby benzene undergoes the following Reaction-1 to produce cyclohexylbenzene (CHB):



[0043] Alternatively, cyclohexylbenzene can be produced by direct alkylation of benzene with cyclohexene in the presence of a solid-acid catalyst such as molecular sieves in the MCM-22 family according to the following Reaction-2:



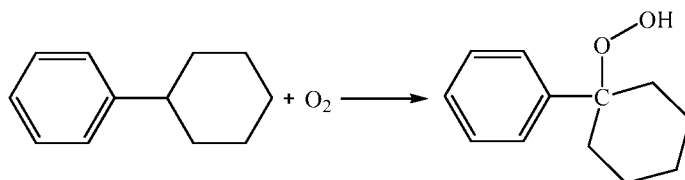
[0044] Side reactions may occur in Reaction-1 or Reaction-2 to produce some polyalkylated benzenes, such as dicyclohexylbenzenes (DiCHB), tricyclohexylbenzenes (TriCHB), methylcyclopentylbenzene, unreacted benzene, cyclohexane, bicyclohexane, biphenyl, and other contaminants. Thus, typically, after the reaction, the hydroalkylation reaction product mixture is separated by distillation to obtain a C6 fraction containing benzene, cyclohexane, a C12 fraction containing cyclohexylbenzene and methylcyclopentylbenzene, and a heavies fraction containing, e.g., C18s such as DiCHBs and C24s such as TriCHBs. The unreacted benzene may be recovered by distillation and recycled to the hydroalkylation or alkylation reactor. The cyclohexane may be sent to a dehydrogenation reactor, with or without some of the residual benzene, and with or without co-fed hydrogen, where it is converted to benzene and hydrogen, which can be recycled to the hydroalkylation/alkylation step. Depending on the quantity of the heavies fraction, it may be desirable to either (a) transalkylate the C18s such as DiCHB and C24s such as TriCHB with

additional benzene or (b) dealkylate the C18s and C24s to maximize the production of the desired monoalkylated species.

[0045] Details of feed materials, catalyst used, reaction conditions, and reaction product properties of benzene hydroalkylation, and transalkylation and dealkylation can be found in, e.g., the following copending, co-assigned patent applications: U.S. Provisional Patent Application Serial Nos. 61/972877, entitled "Process for Making Cyclohexylbenzene and/or Phenol and/or Cyclohexanone;" and filed on March 31, 2014; U.S. Provisional Patent Application Serial No. 62/037794, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037801, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037814, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037824, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/057919, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014; U.S. Provisional Patent Application Serial No. 62/057947, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014; and U.S. Provisional Patent Application Serial No. 62/057980, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014, the contents of all of which are incorporated herein by reference in their entirety.

Oxidation of Cyclohexylbenzene

[0046] In the oxidation step, at least a portion of the cyclohexylbenzene contained in the oxidation feed is converted to cyclohexyl-1-phenyl-1-hydroperoxide, the desired hydroperoxide, according to the following Reaction-3:



..... (Reaction-3).

[0047] The cyclohexylbenzene freshly produced and/or recycled may be purified before being fed to the oxidation step to remove at least a portion of, among others, methylcyclopentylbenzene, olefins, phenol, acid, and the like. Such purification may include, e.g., distillation, hydrogenation, caustic wash, and the like.

[0048] In exemplary processes, the oxidation step may be accomplished by contacting an oxygen-containing gas, such as air and various derivatives of air, with the feed comprising cyclohexylbenzene. For example, a stream of pure O₂, O₂ diluted by inert gas such as N₂, pure air,

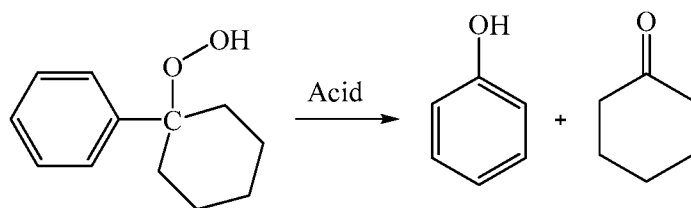
or other O₂-containing mixtures can be pumped through the cyclohexylbenzene-containing feed in an oxidation reactor to effect the oxidation.

[0049] The oxidation may be conducted in the absence or presence of a catalyst, such as a cyclic imide type catalyst (e.g., N-hydroxyphthalimide).

5 [0050] Details of the feed material, reaction conditions, reactors used, catalyst used, product mixture composition and treatment, and the like, of the oxidation step can be found in, e.g., the following copending, co-assigned patent applications: U.S. Provisional Patent Application Serial Nos. 61/972877, entitled "Process for Making Cyclohexylbenzene and/or Phenol and/or Cyclohexanone;" and filed on March 31, 2014; U.S. Provisional Patent Application Serial No. 10 62/037794, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037801, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037814, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037824, entitled "Process and System for 15 Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/057919, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014; U.S. Provisional Patent Application Serial No. 62/057947, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014; and U.S. Provisional Patent Application Serial No. 62/057980, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014, the contents of all of which are incorporated herein by reference in their entirety.

Cleavage Reaction

[0051] In the cleavage reaction, at least a portion of the cyclohexyl-1-phenyl-1-hydroperoxide decomposes in the presence of an acid catalyst in high selectivity to cyclohexanone and phenol according to the following desired Reaction-4:



..... (Reaction-4).

[0052] The cleavage product mixture may comprise the acid catalyst, phenol, cyclohexanone, cyclohexylbenzene, and contaminants.

[0053] The acid catalyst can be at least partially soluble in the cleavage reaction mixture, is stable at a temperature of at least 185°C and has a lower volatility (higher normal boiling point) 30 than cyclohexylbenzene.

[0054] Feed composition, reaction conditions, catalyst used, product mixture composition and treatment thereof, and the like, of this cleavage step can be found in, e.g., the following copending, co-assigned patent applications: : U.S. Provisional Patent Application Serial Nos. 61/972877, entitled "Process for Making Cyclohexylbenzene and/or Phenol and/or Cyclohexanone;" and filed
5 on March 31, 2014; U.S. Provisional Patent Application Serial No. 62/037794, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037801, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/037814, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional
10 Patent Application Serial No. 62/037824, entitled "Process and System for Making Cyclohexanone," and filed on August 15, 2014; U.S. Provisional Patent Application Serial No. 62/057919, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014; U.S. Provisional Patent Application Serial No. 62/057947, entitled "Process for Making Cyclohexanone," and filed on September 30, 2014; and U.S. Provisional Patent Application Serial No. 62/057980, entitled
15 "Process for Making Cyclohexanone," and filed on September 30, 2014, the contents of all of which are incorporated herein by reference in their entirety.

Separation and Purification

[0055] A portion of the neutralized cleavage reaction product can then be separated by methods such as distillation. In one example, in a first distillation column after the cleavage reactor, a
20 heavies fraction comprising heavies (such as amine sulfuric acid complex, which can be regarded as an amine sulfate salt, if an organic amine is used to neutralize at least a portion of the sulfuric acid present in the cleavage reaction product before it is fed into the first distillation column) is obtained at the bottom of the column, a side fraction comprising cyclohexylbenzene is obtained in the middle section, and an upper fraction comprising cyclohexanone, phenol,
25 methylcyclopentanone, and water is obtained.

[0056] The separated cyclohexylbenzene fraction can then be treated and/or purified before being delivered to the oxidation step. Since the cyclohexylbenzene separated from the cleavage product mixture may contain phenol and/or olefins such as cyclohexenylbenzenes, the material may be subjected to treatment with an aqueous composition comprising a base and/or a hydrogenation
30 step as disclosed in, for example, WO2011/100013A1, the entire contents of which are incorporated herein by reference.

[0057] In one example, the fraction comprising phenol, cyclohexanone, and water can be further separated by simple distillation to obtain an upper fraction comprising primarily cyclohexanone and methylcyclopentanone and a lower fraction comprising primarily phenol, and

some cyclohexanone. Cyclohexanone cannot be completely separated from phenol without using an extractive solvent due to an azeotrope formed between these two. Thus, the upper fraction can be further distilled in a separate column to obtain a pure cyclohexanone product in the vicinity of the bottom and an impurity fraction in the vicinity of the top comprising primarily methylcyclopentanone, which can be further purified, if needed, and then used as a useful industrial material. The lower fraction can be further separated by a step of extractive distillation using an extractive solvent (e.g., sulfolane, and glycols such as ethylene glycol, propylene glycol, diethylene glycol, triethylene glycol, and the like) described in, e.g., co-assigned, co-pending patent applications WO2013/165656A1 and WO2013/165659, the contents of which are incorporated herein by reference in their entirety. An upper fraction comprising cyclohexanone and a lower fraction comprising phenol and the extractive solvent can be obtained. In a subsequent distillation column, the lower fraction can then be separated to obtain an upper fraction comprising a phenol product and a lower fraction comprising the extractive solvent.

[0058] Where an acid, such as sulfuric acid, is used as the catalyst in the cleavage step, and a liquid amine is used as the neutralizing agent to neutralize at least a portion of the acid before the cleavage product mixture is fed into the first distillation column, the acid will react with the amine to form a complex that is fed into the first distillation column as well. It had been hoped that given the high boiling point of the complex, it would stay in the bottom fraction of the first distillation column, and therefore all sulfur would be removed completely from the bottoms of the first distillation column. However, in a very surprising manner, it has been found that sulfur was present in the fraction comprising cyclohexanone and phenol exiting the first distillation column.

[0059] Without intending to be bound by a particular theory, it is believed that the complex between the acid catalyst and the organic amine, if present in the feed to the first distillation column, can decompose at least partially in the first distillation column, due to the high operating temperature therein (i.e., the highest temperature the liquid media is exposed to in the first distillation column, typically in the vicinity of the bottom of the column and/or in the reboiler) of at least 120°C (even 130°C, 140°C, 150°C, 160°C, 170°C, 180°C, 190°C, 200°C, 210°C, 220°C, 230°C, 240°C, or even 250°C) is used, necessitated by the separation of cyclohexylbenzene present therein at high concentrations (e.g., at least 5 wt%, or 10 wt%, or 15 wt%, or 20 wt%, or 25 wt%, or 30 wt%, or 35 wt%, or 40 wt%, or 45 wt%, or even 50 wt%, based on the total weight of the cleavage product mixture), which has a very high normal boiling temperature (240°C, compared to the normal boiling temperature of cumene of 152°C). The decomposition of the complex likely produces, among others, SO₃, which can easily travel upwards along the first distillation column to upper locations, where it can recombine at least partially with water to form H₂SO₄. This operation

temperature can be significantly higher than the distillation temperature the mixture of cumene, phenol, and acetone is exposed to in the first distillation column in the cumene process for making phenol and acetone.

[0060] Thus, the presence of acid, especially strong acid such as SO_3 , HSO_4^- , R-HSO_4 , and/or sulfuric acid in the first distillation column, can catalyze many undesirable side reactions between and among the many components present in the distillation mixture, leading to the formation of byproducts and/or premature malfunction of the distillation column. Furthermore, at high operation temperature, prolonged exposure to the acid can cause significant corrosion to the column equipment. The acid species can also make their way into the various fractions drawn from the different locations of the first distillation column, causing different problems in subsequent steps where the fractions are further processed. If the acid species and/or S-containing component enter into a down-stream hydrogenation reactor (described below) where phenol is hydrogenated to make additional cyclohexanone, the hydrogenation catalyst can be easily deactivated.

[0061] Therefore, treating the cleavage product mixture before it enters into the first distillation column using a solid-phase basic material according to the present invention is highly advantageous and desirable. Doing so would reduce or eliminate the presence of acid species in media inside the first distillation column, avoid undesirable side reactions and byproducts formed as a result of contact with the acid species, reduce corrosion of the first distillation column caused by the acid species and the associated repair and premature replacement, and prevent undesirable side reactions and byproduct formation in subsequent steps.

[0062] Such basic materials useful for the present invention, advantageously in solid-phase under the operation conditions, can be selected from (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v) complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more of (i), (ii), (iii), (iv), (v), (vi), and (vii). Oxides, hydroxides, carbonates and bicarbonates of alkali and alkaline earth metals and zinc can react with acid to form salts thereof, which preferably, are also in solid-phase under the operation conditions. Preferably, an ion exchange resin is used. Such ion exchange resin preferably comprise groups on the surface thereof capable of adsorbing and/or binding with protons, SO_3 , HSO_4^- , H_2SO_4 , complexes of sulfuric acid, and the like. The ion exchange resin can comprise a strong and/or a weak base resin. Weak base resins primarily function as acid adsorbers. These resins are capable of sorbing strong acids with a high capacity. Strong base anion resins can comprise quarternized amine-based products capable of sorbing both strong and weak acids.

Commercial examples of basic ion exchange resins useful in the present invention include but are not limited to: Amberlyst® A21 basic ion exchange resin available from Dow Chemical Company.

[0063] Desirably, as a result of the treatment of the cleavage product mixture using the present invention, substantially all sulfur and/or acid is removed from the cleavage product mixture before being fed into the first distillation column. Thus, the feed supplied to the first distillation column may exhibit one or more of the following traits (i), (ii), (iii), (iv), and (v):

(i) total acid concentration, based on the total weight of the mixture fed into the first distillation column, of at most 50 ppm, such as no higher than 40 ppm, 30 ppm, 20 ppm, 10 ppm, 8 ppm, 6 ppm, 5 ppm, 4 ppm, 3 ppm, 2 ppm, or even 1 ppm;

(ii) total sulfuric acid concentration, based on the total weight of the mixture fed into the first distillation column, of at most 50 ppm, such as no higher than 40 ppm, 30 ppm, 20 ppm, 10 ppm, 8 ppm, 6 ppm, 5 ppm, 4 ppm, 3 ppm, 2 ppm, or even 1 ppm;

(iii) total sulfur concentration, based on the total weight of the mixture fed into the first distillation column, of at most 50 ppm, such as no higher than 40 ppm, 30 ppm, 20 ppm, 10 ppm, 8 ppm, 6 ppm, 5 ppm, 4 ppm, 3 ppm, 2 ppm, or even 1 ppm;

(iv) total acid concentration in the feed supplied to the first distillation column is at most 10%, or 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2%, or even 1%, of the total acid concentration in the cleavage product mixture prior to being treated by using the method of the present invention; and

(v) total sulfur concentration in the feed supplied to the first distillation column is at most 10%, or 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2%, or even 1%, of the total sulfur concentration in the cleavage product mixture prior to being treated by using the method of the present invention.

[0064] Cleavage of cyclohexylbenzene hydroperoxide in a media comprising cyclohexylbenzene hydroperoxide, cyclohexanone, phenol, and cyclohexylbenzene typically uses acid catalyst, such as sulfuric acid, at concentrations higher than in the cleavage of cumene hydroperoxide in a media comprising cumene hydroperoxide, phenol, acetone, and cumene. Thus, in cyclohexylbenzene hydroperoxide cleavage, sulfuric acid concentration in the media can range from, e.g., 50 (or 60, 80, 100, 150, 200, 250, 300, 350, 400, 450, 500) ppm to 2000 (or 1800, 1600, 1500, 1400, 1200, 1000, 800, 600) ppm, based on the total weight of the cleavage reaction media. If an organic amine is used to neutralize the acid in the cyclohexylbenzene hydroperoxide cleavage product mixture, a large quantity of the amine would be consumed, which would represent quite substantial costs to the overall process. In the present invention, either inexpensive solid-phase bases such as hydroxides, carbonates and bicarbonates (e.g., NaOH, KOH, Na₂CO₃, NaHCO₃, CaCO₃, and the like), or regenerable ion exchange resins, can be used, thereby reducing the overall costs to the process. Furthermore, where a large quantity of amine is used, a large quantity of amine

acid complex material would be produced and delivered to the first distillation column. Even at relatively low distillation column operation temperature where only a very small percentage of the complex decomposes, because of the large quantity of the complex supplied to the first distillation column, a non-negligible quantity of SO_3 , HSO_4^- , R-HSO_4 and/or H_2SO_4 may nonetheless be produced and travel along the column to the various fractions drawn from the column. Therefore, using the process of the present invention to treat cleavage product mixture comprising acid at a high concentration to remove substantially all of the acid before the first distillation column is particularly advantageous.

[0065] Total sulfur concentration in the organic media can be determined by using conventional methods such as gas chromatography followed by mass spectrometry (GC-MS), liquid chromatography, ICP-AES, ICP-MS, and the like. For example, total sulfur measurement techniques may include ASTM Standard Test Method D 5504: Determination of Sulfur Compounds in Natural Gas and Gaseous Fuels by Gas Chromatography and Chemiluminescence; ASTM D 5623: Sulfur Compounds in Light Petroleum Liquids by Gas Chromatography and Sulfur Selective Detection; ASTM D 7011: Determination of Trace Thiophene in Refined Benzene by Gas Chromatography and Sulfur Selective Detection; and ASTM D5453 Standard Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence. Total sulfur measurement instruments may include those utilizing the principles of Energy Dispersive X-Ray Fluorescence, (Pulsed) Ultra Violet Fluorescence ((P)UVF), and Sulfur Chemiluminescence Detection (SCD), for example utilizing the combustion of sulfur compounds to form sulfur monoxide (SO) and the chemiluminescence reaction of SO with ozone (O_3), and other pyro-fluorescence and pyro-chemiluminescence technologies.

[0066] Sulfuric acid concentration in the organic media can be determined by using conventional methods such as titration, gas chromatography followed by mass spectrometry (GC-MS), liquid chromatography, ICP-AES, ICP-MS, and the like. Sulfuric acid concentration may be derived from the measured total sulfur concentration, or vice versa.

[0067] Total sulfur concentration in the organic media can be determined by using conventional methods such as gas chromatography followed by mass spectrometry (GC-MS), liquid chromatography, ICP-AES, ICP-MS, and the like.

[0068] After treatment using the method of the present invention, both total acid concentration and acid precursor concentration in the feed supplied to the first distillation column can be exceedingly low. Accordingly, the first distillation column can be operated at a high operation temperature, such as temperatures higher than the disassociation temperatures of complex materials

formed between the acid catalyst used in the cleavage step, such as sulfuric acid, and the following organic amines: (i) pentane-1,5-diamine; (ii) 1-methylhexane-1,5-diamine; (iii) hexane-1,6-diamine; (iv) 2-methylpentane-1,5-diamine; (v) ethylene diamine; (vi) propylene diamine; (vii) diethylene triamine; and (viii) triethylene tetramine, without the concern of issues associated with acid
5 produced from thermal dissociation thereof under such high operation temperature.

Separation and Hydrogenation

[0069] At least a portion, preferably the entirety, of the neutralized cleavage effluent (cleavage reaction product), may be separated and a phenol-containing fraction thereof can be hydrogenated to covert a portion of the phenol to cyclohexanone in accordance with the present invention.

10 [0070] It has been found that hydrogenation catalyst used for hydrogenating phenol to make additional quantities of phenol is highly susceptible to poisoning by S-containing components and/or acids in the feed to the hydrogenation reactor. As such, it is highly desirable that acids and/or S-containing components are removed from the feed fed into the hydrogenation reactor.

[0071] Examples of the separation and hydrogenation process and/or system are illustrated in
15 the attached drawings and described in detail below. It should be understood that process and/or systems shown in the schematic, not-to-scale drawings are only for the purpose of illustrating the general material and/or heat flows and general operating principles. To simplify illustration and description, some routine components, such as pumps, valves, reboilers, pressure regulators, heat exchangers, recycling loops, condensers, separation drums, sensors, rectifiers, fillers, distributors,
20 stirrers, motors, and the like, are not shown in the drawings or described herein. One having ordinary skill in the art, in light of the teachings herein, can add those components where appropriate.

[0072] FIGs. 1, 2, 3, 4, 5, 6, and 9 illustrate processes and systems that do not include an anterior or posterior sorbent beds before or after the first distillation column for separating
25 cyclohexanone from phenol for the purpose of poison removal from the hydrogenation feed. Nonetheless, because these drawings show systems and processes on which the present invention is based, they are included and described herein.

[0073] FIG.1 is a schematic diagram showing a process/system 101 for making cyclohexanone from a mixture comprising phenol, cyclohexanone and cyclohexylbenzene including a first
30 distillation column T1 (i.e., the first distillation column), a hydrogenation reactor R1, and a cyclohexanone purification column T2 (i.e., the second distillation column). Feed 103 from storage S1, comprising phenol, cyclohexanone, and cyclohexylbenzene, is fed into the first distillation column T1.

[0074] Feed 103 can be produced by any method. A preferred method is by cleaving a cyclohexylbenzene hydroperoxide in the presence of an acid catalyst such as sulfuric acid and cyclohexylbenzene as described above. Feed 103 may further comprise impurities other than cyclohexylbenzene such as: hydrogenation catalyst poisons; light components (defined above) such as water, methylcyclopentanone, pentanal, hexanal, benzoic acid, and the like, and heavy components such as methylcyclopentylbenzene, bicyclohexane, sulfate of an organic amine (such as 1,6-hexamethylenediamine, 2-methyl-1,5-pentamethylenediamine, ethylenediamine, propylenediamine, diethylenetriamine, and the like) produced by injecting the amine into the cleavage mixture to neutralize the liquid acid catalyst used. Feed 103 may further comprise olefins heavier than cyclohexanone such as phenylcyclohexene isomers, hydroxycyclohexanone, cyclohexenone, and the like. The cyclohexylbenzene hydroperoxide may be produced by aerobic oxidation of cyclohexylbenzene in the presence of a catalyst such as NHPI as described above. The cyclohexylbenzene may be produced by hydroalkylation of benzene in the presence of a hydrogenation/alkylation bi-functional catalyst as described above.

[0075] Thus, feed 103 (the first mixture) may comprise, based on the total weight thereof:

- cyclohexanone at a concentration of $C_{xnone}(FM1)$ in a range from x_{11} wt% to x_{12} wt%, where x_{11} and x_{12} can be, independently: 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 82, 84, 85, 86, 88, or 90, as long as $x_{11} < x_{12}$; preferably, $20 \text{ wt}\% \leq C_{xnone}(FM1) \leq 30 \text{ wt}\%$;
- phenol at a concentration of $C_{phol}(FM1)$ in a range from x_{21} wt% to x_{22} wt%, where x_{21} and x_{22} can be, independently: 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 82, 84, 85, 86, 88, or 90, as long as $x_{21} < x_{22}$; preferably, $20 \text{ wt}\% \leq C_{phol}(FM1) \leq 30 \text{ wt}\%$; preferably, $0.3 \leq C_{xnone}(FM1)/C_{phol}(FM1) \leq 2.0$; more preferably $0.5 \leq C_{xnone}(FM1)/C_{phol}(FM1) \leq 1.5$; even more preferably $0.8 \leq C_{xnone}(FM1)/C_{phol}(FM1) \leq 1.2$;
- cyclohexylbenzene at a concentration of $C_{chb}(FM1)$ in a range from x_{31} wt% to x_{32} wt%, where x_{31} and x_{32} can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, 32, 34, 35, 36, 38, 40, 42, 44, 45, 46, 48, 50, 52, 54, 55, 56, 58, 60, 62, 64, 65, 66, 68, 70, 72, 74, 75, 76, 77, 78, 79, or 80, as long as $x_{31} < x_{32}$; preferably $30 \text{ wt}\% \leq C_{chb}(FM1) \leq 60 \text{ wt}\%$;
- bicyclohexane at a concentration of $C_{bch}(FM1)$ in a range from x_{41} wt% to x_{42} wt%, where x_{41} and x_{42} can be, independently: 0, 0.00001, 0.0001, 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, or 30, as long as $x_{41} < x_{42}$; preferably, $0.001 \text{ wt}\% \leq C_{bch}(FM1) \leq 1 \text{ wt}\%$; and

- light components (e.g., benzoic acid, and other carboxylic acids comprising 1, 2, 3, 4, 5, 6, 7, or 8 carbon atoms), S-containing compounds, and N-containing compounds each at a concentration of $Clc(FM1)$ in a range from $x51$ ppm to $x52$ ppm, where $x51$ and $x52$ can be, independently, 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, or 10,000, as long as $x51 < x52$, preferably $1 \text{ ppm} \leq Clc(FM1) \leq 5000$.

[0076] From the first distillation column T1, a first upper effluent 105 comprising a portion of the cyclohexanone and a portion of light components such as water, methylcyclopentanone, and the like, is produced in the vicinity of the top of the column T1. Effluent 105 may comprise, based on the total weight thereof:

- cyclohexanone at a concentration of $Cxnone(UE1)$, where $z11 \text{ wt\%} \leq Cxnone(UE1) \leq z12 \text{ wt\%}$, $z11$ and $z12$ can be, independently: 60, 65, 70, 75, 80, 85, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 99.5, or 99.9, as long as $z11 < z12$; preferably $75 \leq Cxnone(UE1) \leq 95$;
- phenol at a concentration of $Cphol(UE1)$, where $z21 \leq Cphol(UE1) \leq z22$, $z21$ and $z22$ can be, independently: 0, 0.00001, 0.00005, 0.0001, 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, or 1, as long as $z21 < z22$;
- cyclohexylbenzene at a concentration of $Cchb(UE1)$, where $y31 \text{ wt\%} \leq Cchb(UE1) \leq y32 \text{ wt\%}$, where $y31$ and $y32$ can be, independently: 0, 0.00001, 0.00005, 0.0001, 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, or 1, as long as $y31 < y32$;
- bicyclohexane at a concentration of $Cbch(UE1)$, where $y41 \text{ wt\%} \leq Cbch(UE1) \leq y42 \text{ wt\%}$, $y41$ and $y42$ can be, independently: 0, 0.00001, 0.00005, 0.0001, 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, or 1, as long as $y41 < y42$;
- cyclohexanol at a concentration of $Cxnol(UE1)$, where $z51 \text{ wt\%} \leq Cxnol(UE1) \leq z52 \text{ wt\%}$, based on the total weight of the first upper effluent, where $z51$ and $z52$ can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, or 10, as long as $z51 < z52$; preferably $0.1 \text{ wt\%} \leq Cxnol(UE1) \leq 5.0 \text{ wt\%}$; and
- light components at a total concentration of $Clc(UE1)$, where $a61 \text{ wt\%} \leq Clc(UE1) \leq a62 \text{ wt\%}$, where $a61$ and $a62$ can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, or 5.0, as long as $a61 < a62$; preferably $0.001 \text{ wt\%} \leq Clc(UE1) \leq 1.0 \text{ wt\%}$.

[0077] The first upper effluent 105 is then sent to a cyclohexanone purification column T2, from which a third upper effluent 121 comprising light components such as water,

methylcyclopentanone, and the like, is produced at a location in the vicinity of the top of column T2 and then delivered to storage S5. A second upper effluent 123 comprising essentially pure cyclohexanone is produced and sent to storage S7. In the vicinity of the bottom of column T2, a second lower effluent 125 is produced and delivered to storage S9. The second lower effluent can be, e.g., a KA oil comprising both cyclohexanone and cyclohexanol. Thus, the second upper effluent 123 may comprise, based on the total weight thereof, cyclohexanone at a concentration of $C_{xnone}(UE2)$, where $C_{xnone}(UE2) \geq y_{11}$ wt%, y_{11} can be 95, 95.5, 96, 96.5, 97, 97.5, 98, 98.5, 99, 99.5, 99.8, or 99.9. The second lower effluent 125 may comprise, based on the total weight thereof: cyclohexanol at a concentration of $C_{xnol}(LE2)$, y_{51} wt% $\leq C_{xnol}(LE2) \leq y_{52}$ wt%, y_{51} and y_{52} can be, independently: 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, 32, 34, 35, 36, 38, 40, 42, 44, 45, 46, 48, 50, 52, 54, 55, 56, 58, 60, 62, 64, 65, 66, 68, 70, 72, 74, 75, 76, 78, or 80, as long as $y_{51} < y_{52}$; and cyclohexanone at a concentration of $C_{xnone}(LE2)$, e_{11} wt% $\leq C_{xnone}(LE2) \leq e_{12}$ wt%, e_{11} and e_{12} can be, independently: 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, 32, 34, 35, 36, 38, 40, 42, 44, 45, 46, 48, 50, 52, 54, 55, 56, 58, 60, 62, 64, 65, 66, 68, 70, 72, 74, 75, 76, 78, or 80, as long as $e_{11} < e_{12}$.

[0078] The first middle effluent 107 produced from the first distillation column T1 comprises phenol at a concentration higher than in feed 103 and higher than in the first upper effluent 105, cyclohexanone at a concentration lower than in both feed 103 and the first upper effluent 105, cyclohexylbenzene at a concentration desirably lower than in feed 103 and higher than in the first upper effluent 105, and one or more of other impurities such as bicyclohexane and cyclohexenone. Thus, effluent 107 may comprise, based on total weight thereof:

- cyclohexanone at a concentration of $C_{xnone}(ME1)$, where a_{11} wt% $\leq C_{xnone}(ME1) \leq a_{12}$ wt%, a_{11} and a_{12} can be, independently: 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, 35, 40, 45, or 50, as long as $a_{11} < a_{12}$;
- phenol at a concentration of $C_{phol}(ME1)$, where a_{21} wt% $\leq C_{phol}(ME1) \leq a_{22}$ wt%, based on the total weight of the first middle effluent, where a_{21} and a_{22} can be, independently: 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, as long as $a_{21} < a_{22}$; preferably, $1.0 \leq C_{phol}(ME1)/C_{xnone}(ME1) \leq 3.0$; more preferably, $2.0 \leq C_{phol}(ME1)/C_{xnone}(ME1) \leq 3.0$, close to the ratio in a phenol/cyclohexanone azeotrope;
- cyclohexylbenzene at a concentration of $C_{chb}(ME1)$, where a_{31} wt% $\leq C_{chb}(ME1) \leq a_{32}$ wt%, a_{31} and a_{32} can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, or 30, as long as $a_{31} < a_{32}$;

- bicyclohexane at a concentration of $C_{bch}(ME1)$, where $a41 \text{ wt}\% \leq C_{bch}(ME1) \leq a42 \text{ wt}\%$, $a41$ and $a42$ can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, or 30, as long as $a41 < a42$;
- cyclohexanol at a concentration of $C_{xnol}(ME1)$, where $a51 \text{ wt}\% \leq C_{xnol}(ME1) \leq a52 \text{ wt}\%$, $a51$ and $a52$ can be, independently: 0.01, 0.02, 0.04, 0.05, 0.06, 0.08, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, or 30, as long as $a51 < a52$; preferably $0.01 \text{ wt}\% \leq C_{xnol}(ME1) \leq 5 \text{ wt}\%$; and
- light components (e.g., benzoic acid, and other organic acid comprising 1, 2, 3, 4, 5, 6, 7, or 8 carbon atoms), S-containing compounds, and N-containing compounds each at a concentration of $Clc(ME1)$, where $a71 \text{ ppm} \leq Clc(ME1) \leq a72 \text{ ppm}$, where $a71$ and $a72$ can be, independently: 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 2000, 3000, 4000, 5000, as long as $a71 < a72$, preferably $1 \text{ ppm} \leq Clc(ME1) \leq 1000$.

[0079] Preferably, effluent 107 is essentially free of S-containing components that may poison the hydrogenation catalyst used in the hydrogenation reactor(s). However, depending on the quality of feed 103, effluent 107 may comprise S-containing components at concentrations capable of leading to poisoning of the hydrogenation catalyst, as discussed above. In such case, the present invention (exemplified and illustrated in FIGs. 7 and 8 and described in detail below) may be advantageously used to reduce the S-containing components from effluent 107 before it is fed into the hydrogenation reactor as the whole or a portion of the hydrogenation feed.

[0080] Effluent 107, if containing S-containing components capable of poisoning the hydrogenation catalyst at acceptable concentration(s), can be directly delivered to a hydrogenation reactor R1, where it is mixed with a hydrogen gas feed 112 comprising fresh make-up hydrogen stream 111 from storage S3 and recycle hydrogen 117. The phenol contained in feed 107 and hydrogen reacts with each other in the presence of a catalyst bed 113 inside reactor R1 to produce cyclohexanone. Some of the cyclohexanone inside the reactor R1 reacts with hydrogen in the presence of the catalyst bed 113 as well to produce cyclohexanol. In the exemplary process shown in FIG. 1, surplus hydrogen is fed into reactor R1. It is contemplated that a second phenol-containing stream (not shown), separate from and independent of effluent 107, may be fed into the hydrogenation reactor R1. Such additional feed can advantageously contain phenol at a concentration of $C_{phol}(FP)$, $d21 \text{ wt}\% \leq C_{phol}(FP) \leq d22 \text{ wt}\%$, based on the total weight of the second phenol-containing stream, where $d21$ and $d22$ can be, independently: 50, 55, 60, 65, 70, 75, 80, 85, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, or 100, as long as $d21 < d22$. Preferably, the second

phenol-containing stream comprises substantially pure phenol produced by any process, such as the conventional cumene process, coal-based processes, and the like.

[0081] The total hydrogenation feed, including stream 107 and optional additional streams, delivered to the hydrogenation reactor R1, if blended together before being fed into R1, may have an overall composition containing phenol at a concentration of $C_{phol}(A)$, cyclohexanone at a concentration of $C_{xnone}(A)$, cyclohexylbenzene at a concentration of $C_{chb}(A)$, and bicyclohexane at a concentration of $C_{bch}(A)$, wherein the concentrations are in the following ranges, based on the total weight of the hydrogenation feed:

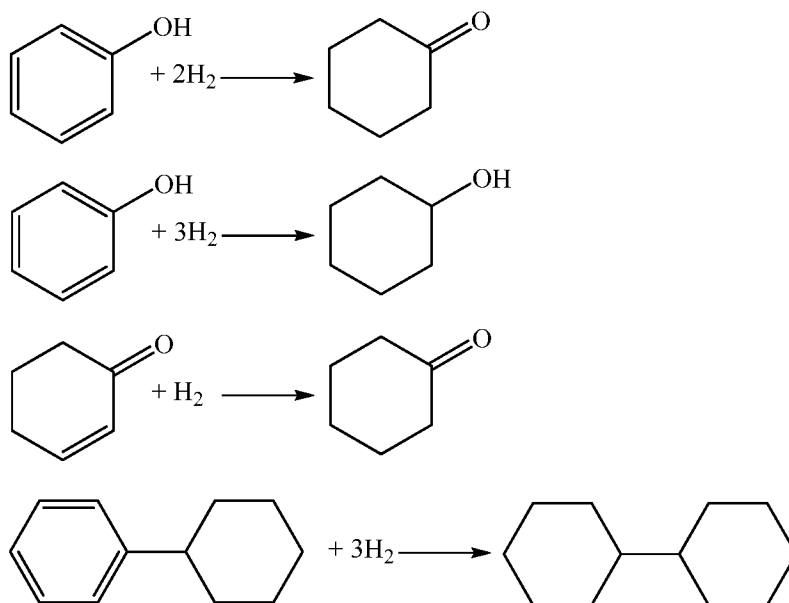
$a1 \text{ wt}\% \leq C_{xnone}(A) \leq a2 \text{ wt}\%$, where $a1$ and $a2$ can be, independently: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, 32, 34, 35, 36, 38, 40, 42, 44, 45, 46, 48, 50, as long as $a1 < a2$;

$b1 \text{ wt}\% \leq C_{phol}(A) \leq b2 \text{ wt}\%$, where $b1$ and $b2$ can be, independently: 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 82, 84, 85, 86, 88, 90, 91, 92, 93, 94, 95, 96, 97, 98, or 99, as long as $a21 < a22$;

$c1 \text{ wt}\% \leq C_{chb}(A) \leq c2 \text{ wt}\%$, where $c1$ and $c2$ can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, or 30, as long as $c1 < c2$; preferably, $1 \text{ wt}\% \leq C_{chb}(A) \leq 20 \text{ wt}\%$; and

$d1 \text{ wt}\% \leq C_{bch}(A) \leq d2 \text{ wt}\%$, where $d1$ and $d2$ can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, or 30, as long as $d1 < d2$; preferably, $1 \text{ wt}\% \leq C_{bch}(A) \leq 20 \text{ wt}\%$.

[0082] In the hydrogenation reaction zone, the following reactions can take place, resulting in an increase of concentrations of cyclohexanone, cyclohexanol, and bicyclohexane, and a decrease of concentrations of phenol, cyclohexanone, and cyclohexylbenzene:



[0083] Cyclohexanone may hydrogenate to make cyclohexanol in the hydrogenation reactor R1. Because the net effect of the reaction is an overall increase of cyclohexanone concentration, this reaction is not included in the above paragraph. Nonetheless, cyclohexanone can engage in competition against phenol for hydrogen, which should be reduced or inhibited.

[0084] The total amount of hydrogen, including fresh, make-up hydrogen and recycled hydrogen, fed into the reactor R1, and the total amount of phenol fed into the hydrogenation reaction zone desirably exhibit a hydrogen to phenol molar ratio of $R(H_2/phol)$, where $R1 \leq R(H_2/phol) \leq R2$, $R1$ and $R2$ can be, independently: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, or 10, as long $R1 < R2$. While a higher $R(H_2/phol)$ ratio can result in higher overall conversion of phenol, it tends to result in higher conversion of cyclohexanone, higher selectivity of phenol to cyclohexanol, and higher conversion of cyclohexylbenzene, as well. Therefore, it is generally desirable that in the hydrogenation reactor R1, the reaction conditions, including but not limited to temperature, pressure, and $R(H_2/phol)$ ratio, and catalysts, are chosen such that the overall conversion of phenol is not too high.

[0085] The hydrogenation reactions take place in the presence of a hydrogenation catalyst. The hydrogenation catalyst may comprise a hydrogenation metal performing a hydrogenation function supported on a support material. The hydrogenation metal can be, e.g., Fe, Co, Ni, Ru, Rh, Pd, Ag, Re, Os, Ir, and Pt, and mixtures and combinations of one or more thereof. The support material can be advantageously an inorganic material, such as oxides, glasses, ceramics, molecular sieves, and the like. For example, the support material can be activated carbon, Al_2O_3 , Ga_2O_3 , SiO_2 , GeO_2 , SnO , SnO_2 , TiO_2 , ZrO_2 , Sc_2O_3 , Y_2O_3 , alkali metal oxides, alkaline earth metal oxides, and mixtures, combinations, complexes, and compounds thereof. The concentration of the

hydrogenation metal can be, e.g., in a range from Cm1 wt% to Cm2 wt%, based on the total weight of the catalyst, where Cm1 and Cm2 can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, as long as Cm1 < Cm2.

[0086] Without intending to be bound by any particular theory, it is believed that the above
5 hydrogenation reactions occur quickly in the presence of the hydrogenation metal. Therefore, it is highly desirable that the hydrogenation metal is preferentially distributed in the outer rim of the catalyst particles, i.e., the concentration of the hydrogenation metal in the catalyst particle surface layer is higher than in the core thereof. Such rimmed catalyst can reduce the overall hydrogenation metal loading, reducing cost thereof, especially if the hydrogenation metal comprises a precious
10 metal such as Pt, Pd, Ir, Rh, and the like. The low concentration of hydrogenation metal in the core of the catalyst particle also leads to a lower chance of hydrogenation of cyclohexanone, which may diffuse from the surface to the core of the catalyst particles, resulting in higher selectivity of cyclohexanone in the overall process.

[0087] Certain light components, such as organic acids (e.g., formic acid, acetic acid,
15 propanoic acid, linear, linear branched and cyclic carboxylic acids comprising 5, 6, 7, or 8 carbon atoms such as benzoic acid), N-containing compounds (e.g., amines, imides, amides, NO₂-substituted organic compounds), and S-containing compounds (e.g., sulfides, sulfites, sulfates, sulfones, SO₃, SO₂), if contained in the reaction mixture in the hydrogenation reactor and allowed to contact the hydrogenation metal under the hydrogenation reaction conditions, poisoning of the
20 hydrogenation catalyst can occur, leading to reduction of performance or premature failure of the catalyst. To avoid catalyst poisoning, it is highly desirable that the hydrogenation feed comprises such S-containing components at low concentrations described above.

[0088] It is believed that the catalyst surface can have different degrees of adsorption affinity to the different components in the reaction media such as phenol, cyclohexanone, cyclohexanol,
25 cyclohexenone, cyclohexylbenzene, and bicyclohexane. It is highly desired that the catalyst surface has higher adsorption affinity to phenol than to cyclohexanone and cyclohexylbenzene. Such higher phenol adsorption affinity will give phenol competitive advantages in the reactions, resulting in higher selectivity to cyclohexanone, lower selectivity of cyclohexanol, and lower conversion of cyclohexylbenzene, which are all desired in a process designed for making cyclohexanone. In
30 addition, in order to favor the conversion of phenol to cyclohexanone over the conversion of cyclohexylbenzene to bicyclohexane and the conversion of cyclohexanone to cyclohexanol, it is highly desired that the phenol concentration in the reaction medium in the hydrogenation reactor R1 is relatively high, so that phenol molecules occupy most of the active catalyst surface area. Therefore, it is desired that the overall conversion of phenol in the reactor R1 is relatively low.

[0089] As such, it is desired that in the hydrogenation reactor R1, the selectivity of phenol to cyclohexanone is Sel(phol)a, the selectivity of phenol to cyclohexanol is Sel(phol)b, and at least one of the following conditions (i), (ii), (iii), and (iv) is met:

(i) $30\% \leq \text{Con(phol)} \leq 95\%$;

5 (ii) $0.1\% \leq \text{Con(chb)} \leq 20\%$;

(iii) $80\% \leq \text{Sel(phol)a} \leq 99.9\%$; and

(iv) $0.1\% \leq \text{Sel(phol)b} \leq 20\%$.

[0090] The feed(s) to the hydrogenation reactor R1 may further comprise cyclohexenone at a concentration of Cxenone(A), where $e1 \text{ wt}\% \leq \text{Cxenone(A)} \leq e2 \text{ wt}\%$, based on the total weight of the hydrogenation feed, e1 and e2 can be, independently: 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.5, 2, 2.5, 3.5, 4, 4.5, or 5, as long as $e1 < e2$. It is highly desired that in step (B), the conversion of cyclohexenone is $\text{Con(xenone)} \leq \text{Con5}\%$ or $\text{Con(xenone)} \leq \text{Con6}\%$, where Con5 and Con6 can be, independently: 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, as long as $\text{Con5} < \text{Con6}$. Thus, a great majority of the cyclohexenone contained in the feed(s) is converted into cyclohexanone in the hydrogenation reactor R1.

[0091] At the bottom of reactor R1, a hydrogenation reaction product stream 115 comprising phenol at a concentration lower than in stream 107, cyclohexanone at a concentration higher than in stream 107, cyclohexylbenzene, bicyclohexane, and surplus hydrogen is taken. Stream 115 may comprise, based on the total weight thereof:

- Cyclohexanone at a concentration of Cxnone(HRP), where $b11 \text{ wt}\% \leq \text{Cxnone(HRP)} \leq b12 \text{ wt}\%$, b11 and b12 can be, independently: 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, as long as $b11 < b12$;
- Phenol at a concentration of Cphol(HRP), where $b21 \text{ wt}\% \leq \text{Cphol(HRP)} \leq b22 \text{ wt}\%$, b21 and b22 can be, independently: 1, 2, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, 40, 50, as long as $b21 < b22$;
- cyclohexylbenzene at a concentration of Cchb(HRP), where $b31 \text{ wt}\% \leq \text{Cchb(HRP)} \leq b32 \text{ wt}\%$, b31 and b32 can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, as long as $b31 < b32$;
- bicyclohexane at a concentration of Cbch(HRP), where $b41 \text{ wt}\% \leq \text{Cbch(HRP)} \leq b42 \text{ wt}\%$, b41 and b42 can be, independently: 0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, as long as $b41 < b42$; and

- cyclohexanol at a concentration of $C_{xnol}(HRP)$, where $b51 \text{ wt\%} \leq C_{xnol}(HRP) \leq b52 \text{ wt\%}$, $b51$ and $b52$ can be, independently: 0.01, 0.02, 0.04, 0.05, 0.06, 0.08, 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, 1, 2, 4, 5, 6, 8, 10, as long as $b51 < b52$.

[0092] Preferably, at least one of the following criteria is met in the hydrogenation reaction product stream 115:

- $Ra31 \leq C_{chb}(ME1)/C_{chb}(HRP) \leq Ra32$, where $Ra31$ and $Ra32$ can be, independently: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.75, 0.80, 0.85, 0.90, 0.92, 0.94, 0.95, 0.96, 0.98, 1.00, 1.02, 1.04, 1.05, 1.06, 1.08, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35, 1.40, 1.50, 1.60, 1.70, 1.80, 1.90, 2.00, 3.00, 4.00, 5.00, 6.00, 7.00, 8.00, 9.00, or 10.0, as long as $Ra31 < Ra32$; more preferably, $0.80 \leq C_{chb}(ME1)/C_{chb}(HRP) \leq 1.00$, meaning that cyclohexylbenzene concentration does not decrease significantly in the hydrogenation reaction zone;
- $Ra41 \leq C_{bch}(HRP)/C_{bch}(ME1) \leq Ra42$, where $Ra41$ and $Ra42$ can be, independently: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.75, 0.80, 0.85, 0.90, 0.92, 0.94, 0.95, 0.96, 0.98, 1.00, 1.02, 1.04, 1.05, 1.06, 1.08, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35, 1.40, 1.50, 1.60, 1.70, 1.80, 1.90, 2.00, 3.00, 4.00, 5.00, 6.00, 7.00, 8.00, 9.00, or 10.0, as long as $Ra41 < Ra42$; preferably, $1.0 \leq C_{bch}(HRP)/C_{bch}(ME1) \leq 1.5$, meaning that bicyclohexane concentration does not increase significantly in the hydrogenation reaction zone; and
- $Ra51 \leq C_{xnol}(HRP)/C_{xnol}(ME1) \leq Ra52$, where $Ra51$ and $Ra52$ can be, independently: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.75, 0.80, 0.85, 0.90, 0.92, 0.94, 0.95, 0.96, 0.98, 1.00, 1.02, 1.04, 1.05, 1.06, 1.08, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35, 1.40, 1.50, 1.60, 1.70, 1.80, 1.90, 2.00, 3.00, 4.00, 5.00, 6.00, 7.00, 8.00, 9.00, or 10.0, as long as $Ra51 < Ra52$; preferably, $1.0 \leq C_{xnol}(HRP)/C_{xnol}(ME1) \leq 1.5$, meaning that cyclohexanol concentration does not increase significantly in the hydrogenation reaction zone.

[0093] Stream 115 is then delivered to a separation drum D1, where a vapor phase comprising a majority of the surplus hydrogen and a liquid phase is obtained. The vapor phase can be recycled as stream 117 to reactor R1 as part of the hydrogen supply, and the liquid phase 119 is recycled to the first distillation column T1 at one or more side locations on column T1, at least one of which is above the location where the first middle effluent 107 is taken, but below the location where the first upper effluent 105 is taken.

[0094] The first bottom effluent 109 obtained from the first distillation column T1 comprises primarily heavy components such as cyclohexylbenzene, bicyclohexane, amine salts mentioned above, C18+, C12 oxygenates, and C18+ oxygenates. This fraction is delivered to a heavies distillation column T3 (the third distillation column), from which a fourth upper effluent 127 desirably comprising cyclohexylbenzene at a concentration higher than C31 wt% and a lower

effluent 129 are produced, where C31 can be 80, 82, 84, 85, 86, 88, 90, 92, 94, 95, 96, 98, or 99. Effluent 127 may be delivered to storage S11 and effluent 129 to storage S13. Effluent 127 may further comprise olefins, primarily phenylcyclohexene isomers, at a non-negligible amount. It may be desirable to subject effluent 127 to hydrogenation to reduce olefin concentrations, and subsequently recycle the hydrogenated effluent 127 to an earlier step such as cyclohexylbenzene oxidation to convert at least a portion of it to cyclohexylbenzene hydroperoxide, such that the overall yield of the process is improved.

[0095] FIG. 2 is a schematic diagram showing a portion of a process/system similar to the process/system shown in FIG. 1, but comprising modified fluid communications between and/or within the first distillation column T1 and the hydrogenation reactor R1. In this figure, the hydrogenation reaction product 115 comprises residual hydrogen, as in the example shown in FIG. 1. Effluent 115 is first delivered into separation drum D1, where a hydrogen-rich vapor stream 117a is obtained, compressed by a compressor 118, and then delivered to reactor R1 as a stream 117b together with fresh, make-up hydrogen stream 111 into reactor R1. A liquid stream 119 is obtained from separation drum D1, then divided into multiple streams (two recycle streams 119a and 119b shown in FIG. 2), recycled to two different locations on the side of column T1, one below the location where the first middle effluent 107 is taken (shown at approximately the same level as feed 103), and the other above the location where the first middle effluent 107 is drawn. This modified recycle fluid communication between the hydrogenation reactor R1 and the first distillation column T1 compared to FIG. 1 has surprising advantages. It was found that where the recycle liquid stream 119 is fed to one location only, such as at a location above the first middle effluent 107, bicyclohexane is continuously produced in reactor R1 from the cyclohexylbenzene in stream 107, and then steadily accumulates in column T1 to such high concentration that a separate phase can form, interfering with effective product separation in column T1. On the other hand, where the recycle stream 119 is recycled back to column T1 at multiple locations on T1 (as shown in FIG. 2), the probability of forming a separate bicyclohexane phase inside T1 is drastically reduced or eliminated.

[0096] FIG. 3 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 and 2 comprising modified fluid communications and/or heat transfer arrangement between and/or within the first distillation column T1 and the cyclohexanone purification column T2. In this figure, the hydrogenation reactor R1 and its peripheral equipment are not shown. In this figure, the first middle effluent 107 drawn from column T1 is divided into multiple streams (two streams 107a and 107b shown), one of which (107a) is delivered to the hydrogenation reactor R1 (not shown) as hydrogenation feed, and the other (107b) to a heat

exchanger 131 in fluid and thermal communication with the cyclohexanone purification column T2. In this figure, the bottom stream 125 (e.g., comprising a mixture of cyclohexanone and cyclohexanol) from column T2 is divided into three streams: stream 135 which passes through heat exchanger 131 and is heated by stream 107b; stream 139 which is heated by a heat exchanger 141 and then recycled to column T2; and stream 145, which is delivered to storage S9 via pump 147. Stream 107b becomes a cooler stream 133 after passing through heat exchanger 131, and is then subsequently recycled to first distillation column T1 at one or more locations, at least one of which is located above the location where the first middle effluent 107 is drawn. A heat management scheme as illustrated in FIG. 3 can significantly improve the energy efficiency of the overall process and system.

[0097] FIG. 4 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 – 3, but comprising a tubular heat exchanger-type hydrogenation reactor. This figure illustrates an example where the hydrogenation reactor R1 operates under hydrogenation conditions such that a majority of the phenol and/or cyclohexylbenzene present in the reaction media inside the reactor R1 are in vapor phase. In this figure, the first middle effluent 107 taken from the first distillation column T1 is first combined with hydrogen feeds (including fresh make-up hydrogen stream 111 and recycle hydrogen stream 117b), heated by a heat exchanger 153 and then delivered to a tubular heat-exchanger type hydrogenation reaction R1 having hydrogenation catalyst installed inside the tubes 157. A stream of cooling media 159 such as cold water supplied from storage S11 passes through the shell of the exchanger/reactor R1 and exits the reactor R1 as a warm stream 161 and is then delivered to storage S13, thereby a significant amount of heat released from phenol hydrogenation reaction is carried away, maintaining the temperature inside the reactor R1 in a range from $T1^{\circ}\text{C}$ to $T2^{\circ}\text{C}$, and an absolute pressure inside the reactor R1 in a range from P1 kPa to P2 kPa, where T1 and T2 can be, independently: 140, 145, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195, 200, 205, 210, 215, 220, 225, 230, 235, 240, 250, 260, 270, 280, 290, 300, as long as $T1 < T2$, and P1 and P2 can be, independently: 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 250, 300, 350, or 400, as long as $P1 < P2$. Preferably $T2 = 240$ and $P2 = 200$. Alternatively, the cooling medium may comprise at least a portion of the hydrogenation feed in liquid phase, such that at least a portion of the feed is vaporized, and at least a portion of the vapor feed is then fed to the hydrogenation reactor R1.

[0098] Because heat transfer of a vapor phase is not as efficient as a liquid phase, and the phenol hydrogenation reaction is highly exothermic, it is highly desired that heat transfer is carefully managed in such vapor phase hydrogenation reactor. Other types of reactors suitable for a liquid phase reaction can be used as well. For example, fixed-bed reactors configured to have

intercooling capability and/or quenching options, so that the heat generated in the reaction can be taken away sufficiently quickly to maintain the reaction media in a desirable temperature range.

[0099] FIG. 5 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 – 4, but comprising three fixed bed hydrogenation reactors R3, R5, and R7 connected in series. This figure illustrates an example where the hydrogenation reactors operate under hydrogenation conditions such that a majority of the phenol and/or cyclohexylbenzene present in the reaction media inside the reactors R3, R5, and R7 are in liquid phase. In this figure, the first middle effluent 107 taken from the first distillation column T1 is first combined with hydrogen feeds (including fresh make-up hydrogen stream 111 and recycle hydrogen stream 117b) to form a feed stream 151, then heated by a heat exchanger 153, and then delivered as stream 155 to a first hydrogenation reactor R3 having a catalyst bed 167 inside. A portion of the phenol is converted to cyclohexanone in reactor R3, releasing a moderate amount of heat raising the temperature of the reaction media. Effluent 169 exiting reactor R3 is then cooled down by heat exchanger 171, and then delivered into a second fixed bed reactor R5 having a catalyst bed 175 inside. A portion of the phenol contained in the reaction media is converted to cyclohexanone in reactor R5, releasing a moderate amount of heat raising the temperature inside the reactor R5. Effluent 177 exiting reactor R5 is then cooled down by heat exchanger 179, and then delivered to a third fixed bed hydrogenation reactor R7 having a catalyst bed 183 inside. A portion of the phenol contained in the reaction media is converted to cyclohexanone in reactor R7, releasing a moderate amount of heat raising the temperature inside the reactor R7. Effluent 185 exiting reactor R7 is then cooled down by heat exchanger 187, and delivered to drum D1, where a vapor phase 117a and a liquid phase 119 are obtained. By using multiple reactors in the hydrogenation reaction zone, and the use of heat exchangers between adjacent reactors and after each reactor, temperatures inside the reactors R3, R5, and R7 are each independently maintained in a range from T3°C to T4°C, and the absolute pressures inside reactors R3, R5, and R7 are each independently maintained in a range from P3 kPa to P4 kPa, where T3 and T4 can be, independently: 140, 145, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195, 200, 205, 210, 215, 220, 225, 230, 235, 240, 250, 260, 270, 280, 290, 300, as long as T3 < T4, and P3 and P4 can be, independently: 375, 400, 425, 450, 475, 500, 525, 550, 575, 600, 625, 650, 675, 700, 725, 750, 775, 800, 825, 850, 875, 900, 925, 950, 975, 1000, 1025, 1050, 1075, 1100, 1125, 1134, 1150, 1175, 1200, as long as P3 < P4. Preferably, T4 = 240 and P4 = 1134. In general, higher temperature favors the production of cyclohexanol over cyclohexanone. Thus, it is highly desirable that the hydrogenation is conducted at a temperature no higher than 220°C.

[00100] FIG. 6 is a schematic diagram showing a portion of a process/system similar to the process/system shown in FIGs. 1-5, but comprising modified fluid communications between and/or within the first distillation column T1 and the hydrogenation reactor R1. In this figure, two middle effluents, including a first middle effluent 107a and a second middle effluent 107b, are drawn from the side of the first distillation column T1. The two effluents 107a and 107b have differing compositions, and are combined to form a feed 107, which is then combined with hydrogen feed streams 111 and 117b and delivered to the hydrogenation reactor(s). Drawing two middle effluents with different compositions at different locations have unexpected technical advantages. It was found that if only one middle effluent is drawn from a single location on column T1, certain undesirable components, such as hydroxycyclohexanone(s), can accumulate in column T1. It is believed that hydroxycyclohexanone(s) can undergo dehydration to form cyclohexenone, which can cause fouling inside column T1. By drawing middle effluents at different height locations on the column, one can effectively reduce the accumulation of such undesirable components and the probability of fouling inside the column.

[00101] FIG. 7 is a schematic diagram showing a portion of an exemplary process/system of the present disclosure similar to those shown in FIGs. 1 – 6, but comprising an anterior sorbent bed SBa before the first distillation column T1 configured for removing at least a portion of the S-containing components and/or the light components from a crude feed (crude mixture) to reduce or prevent catalyst poisoning in the hydrogenation reactor. A crude mixture feed stream 102 is first passed through the sorbent bed SBa, in which a basic solid-phase sorbent material described above is installed. Alternatively, where the total concentration of the S-containing components and other light components capable of poisoning the hydrogenation catalyst in the crude mixture stream 102 is exceedingly high, an anterior stripper distillation column (not shown) may be used before the anterior sorbent bed SBa, so as to remove a portion of the light components and S-containing component from the first mixture fed into the first distillation column. Desirably, upon treatment by the anterior sorbent bed SBa, concentrations of S-containing components capable of poisoning the hydrogenation catalyst is reduced significantly in effluent 107 compared to in feed 102. Thus, in the embodiment shown in FIG. 7, assuming the total concentration of S-containing components in feed 102 is $Clc(cm)$, and the total concentration of S-containing components in effluent 107 is $Clc(ME1)$, $r1 \leq Clc(ME1)/Clc(cm) \leq r2$, where $r1$ and $r2$ can be, independently: 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.02, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, as long as $r1 < r2$. Specifically, assuming the concentration of sulfuric acid in feed 102 is $Cba(cm)$, and the total concentration of sulfuric acid in effluent 107 is $Cba(ME1)$, $r1 \leq Cba(ME1)/Cba(cm) \leq r2$, where $r1$ and $r2$ can be, independently: 0.001, 0.002,

0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.02, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, as long as $r_1 < r_2$.

[00102] FIG. 8 shows an alternative to the configuration of FIG. 7. In this figure, instead of placing an anterior sorbent bed SBa before the first distillation column T1, a posterior sorbent bed SBp is placed behind column T1, which receives the first middle effluent 107 as a feed, produces a treated stream 195 depleted or low in such S-containing components, which is delivered to the hydrogenation reactor as a portion or all of the hydrogenation feed 151 together with hydrogen feeds 111 and 117b. Alternatively, where the total concentration of the S-containing components in the first middle effluent 107 is exceedingly high, a posterior stripper distillation column (not shown) may be installed before the sorbent bed SBp, and effluent 107 may be treated by both the posterior stripper distillation column and the SBp before being fed to the hydrogenation reactor R1 as at least a portion of the hydrogenation feed. Desirably, upon treatment, concentrations of S-containing components capable of poisoning the hydrogenation catalyst is reduced significantly in the hydrogenation feed compared to in effluent 107. Thus, in the embodiment shown in FIG. 8, assuming the total concentration of S-containing components in the hydrogenation feed is $Clc(hf)$, and the total concentration of S-containing components in effluent 107 is $Clc(ME1)$, $r_1 \leq Clc(hf)/Clc(ME1) \leq r_2$, where r_1 and r_2 can be, independently: 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.02, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, as long as $r_1 < r_2$. Specifically, assuming the concentration of sulfuric acid in the hydrogenation feed is $Cba(hf)$, and the total concentration of sulfuric acid in effluent 107 is $Cba(ME1)$, $r_1 \leq Cba(hf)/Cba(ME1) \leq r_2$, where r_1 and r_2 can be, independently: 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.02, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, as long as $r_1 < r_2$.

[00103] If necessary, both of the anterior S-containing component removing mechanism described in connection with FIG. 7 (one or both of the anterior stripper distillation column and the anterior sorbent) and the posterior S-containing component removing mechanism described in connection with FIG. 8 (one or both of the posterior stripper distillation column and the posterior sorbent) may be used to prevent the S-containing components from entering into the hydrogenation reactor(s) at an unacceptably high concentration. The anterior and posterior sorbents can be the same or different, and may be selected from: massive nickel; activated carbon, ion exchange resins (such as strong and weak anion resins which are usually amine based), clay, kaolin, silica sorbents, alumina sorbents, molecular sieves, (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v)

complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more of (i), (ii), (iii), (iv), (v), (vi), and (vii). The sorbents may remove the S-containing components by physical absorption or adsorption, extraction, and/or chemical reactions. Massive nickel is particularly useful for removing S-containing and N-containing poison components. However, a basic, solid-phase sorbent material such as those described above is preferable for removing sulfuric acid. A basic ion exchange resin is particularly preferable for removing acid species and/or S-containing species.

[00104] Preferably, the hydrogenation feed thus treated by the anterior and/or posterior treatment(s) described in connection with FIG. 7 and/or FIG. 8 may comprise the S-containing components at a total concentration in a range from Clc(hf)1 ppm to Clc(hf)2 ppm by weight based on the total weight of the hydrogenation feed, where Clc(hf)1 and Clc(hf)2 can be, independently, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, or 100, as long as Clc(hf)1 < Clc(hf)2. Preferably, the hydrogenation feed thus treated by the anterior and/or posterior treatment(s) described in connection with FIG. 7 and/or FIG. 8 may comprise the benzoic acid at a concentration in a range from Cba(hf)1 ppm to Cba(hf)2 ppm by weight based on the total weight of the hydrogenation feed, where Cba(hf)1 and Cba(hf)2 can be, independently, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, or 100, as long as Clc(hf)1 < Clc(hf)2.

[00105] FIG. 9 is a schematic diagram showing a portion of a process/system similar to those shown in FIGs. 1 – 8 comprising a side stripper column T6 after the cyclohexanone purification column T2, configured to reduce amounts of light components from the final cyclohexanone product. In this figure, the first upper effluent 105 comprising primarily cyclohexanone and light components obtained from the first distillation column T1 and from the upper anterior stripper effluent, if any, is delivered to cyclohexanone purification column T2, where three effluents are obtained: a second upper effluent 121 rich in light components such as water and methylcyclopentanone and depleted in cyclohexanone and cyclohexanol, a second middle effluent 123 rich in cyclohexanone and depleted in light components and cyclohexanol, and a second lower effluent 125 rich in cyclohexanol. Effluent 121 is first cooled down by a heat exchanger 197, then delivered to a separation drum D2 to obtain a liquid phase 199, which is recycled to column T2, and a vapor phase 201, which is cooled again by a heat exchanger 203, and delivered to another separation drum D3 to obtain a liquid phase which is partly recycled as stream 205 to drum D2, and partly delivered to storage S5, and a vapor phase 206 which can be purged. Effluent 123 is delivered to a side stripper T6 where the following streams are produced: a substantially pure

cyclohexanone stream 211 in the vicinity of the bottom thereof, which is delivered to a storage S7; and a light component stream 209, which is recycled to the column T2 at a location above 123.

[00106] In all of the above drawings, the phenol/cyclohexanone/cyclohexylbenzene hydrogenation feed delivered to the hydrogenation reactor is wholly obtained from one or more middle effluents from first distillation column T1. However, it is contemplated that, additionally, a second phenol feed stream comprising phenol at a concentration not lower than the feed obtained from column T1 can be fed to the hydrogenation reactor, either independently and separately or after being combined with the feed obtained from column T1 and/or hydrogen feed. For example, the second phenol stream may comprise substantially pure phenol having a phenol concentration, based on its total weight, of at least C_{phol}(f2) wt%, where C_{phol}(f2) can be, e.g., 80, 82, 84, 85, 86, 88, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 99.5, 99.8, or even 99.9.

Uses of Cyclohexanone and Phenol

[00107] The cyclohexanone produced through the processes disclosed herein may be used, for example, as an industrial solvent, as an activator in oxidation reactions and in the production of adipic acid, cyclohexanone resins, cyclohexanone oxime, caprolactam, and nylons, such as nylon-6 and nylon-6,6.

[00108] The phenol produced through the processes disclosed herein may be used, for example, to produce phenolic resins, bisphenol A, ε-caprolactam, adipic acid, and/or plasticizers.

[00109] While the present invention has been described and illustrated by reference to particular embodiments, those of ordinary skill in the art will appreciate that the invention lends itself to variations not necessarily illustrated herein. For this reason, then, reference should be made solely to the appended claims for purposes of determining the true scope of the present invention.

[00110] The contents of all references cited herein are incorporated by reference in their entirety.

[00111] The present invention includes one or more of the following non-limiting aspects and/or embodiments.

 EI-1. A process for making cyclohexanone, the process comprising:

 (Ia) providing a crude mixture comprising cyclohexanone, phenol, cyclohexylbenzene, and an S-containing component;

 (Ib) contacting the crude mixture with an anterior sorbent capable of removing at least a portion of the S-containing component to obtain a first mixture comprising cyclohexanone, phenol, and cyclohexylbenzene;

 (Ic) feeding the first mixture into a first distillation column;

(II) obtaining from the first distillation column:

a first upper effluent comprising cyclohexanone at a concentration higher than the first mixture;

a first middle effluent comprising phenol at a concentration higher than the first mixture, cyclohexanone, cyclohexylbenzene, and bicyclohexane; and

a first lower effluent comprising cyclohexylbenzene at a concentration higher than the first mixture;

(III) providing hydrogen and at least a portion of the first middle effluent as at least a portion of a hydrogenation feed to a hydrogenation reaction zone;

(IV) contacting the hydrogenation feed with hydrogen in the hydrogenation reaction zone where phenol reacts with hydrogen in the presence of a hydrogenation catalyst under hydrogenation reaction conditions to obtain a hydrogenation reaction product comprising cyclohexanone at a concentration higher than the hydrogenation feed, phenol at a concentration lower than the hydrogenation feed, cyclohexylbenzene, and bicyclohexane; and

(V) feeding at least a portion of the hydrogenation reaction product into the first distillation column.

EI-2. The process of EI-1, wherein the anterior sorbent in step (Ib) comprises a solid-phase basic material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v) complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more of (i), (ii), (iii), (iv), (v), (vi), and (vii).

EI-3. The process of EI-1 or EI-2, wherein the S-containing component comprises SO_3 , HSO_4^- , R-HSO_4 and/or sulfuric acid.

EI-4. The process of any of EI-1 to EI-3, wherein the concentration of the S-containing component in the crude mixture is in a range from 10 ppm to 10,000 ppm by weight based on the total weight of the crude mixture.

EI-5. The process of any of EI-1 to EI-4, wherein the concentration of the S-containing component in the first middle effluent is in a range from 1 ppm to 1,000 ppm by weight based on the total weight of the first middle effluent.

EI-6. The process of any of EI-1 to EI-5, wherein the concentration of the S-containing component in the hydrogenation feed is at most 100 ppm by weight based on the total weight of the hydrogenation feed.

EI-7. The process of any of EI-1 to EI-6, wherein the concentration of the S-containing component in the hydrogenation feed based on the total weight of the hydrogenation feed is at most 10% of the concentration of the S-containing component in the crude mixture based on the total weight of the crude mixture.

5 EI-8. The process of any of EI-1 to EI-7, wherein the hydrogenation feed comprises:

cyclohexanone at a concentration in a range from 1 wt% to 50 wt%;

phenol at a concentration in a range from 10 wt% to 80 wt%;

cyclohexylbenzene at a concentration in a range from 0.001 wt% to 30 wt%; and

bicyclohexane at a concentration in a range from 0.001 wt% to 30 wt%,

10 the percentages being based on the total weight of the hydrogenation feed.

EI-9. The process of any of EI-1 to EI-8, wherein the crude mixture comprises:

cyclohexanone at a concentration in a range from 10 wt% to 90 wt%;

phenol at a concentration in a range from 10 wt% to 80 wt%; and

cyclohexylbenzene at a concentration in a range from 0.001 wt% to 75 wt%;

15 the percentages being based on the total weight of the crude mixture.

EI-10. The process of any of EI-1 to EI-9, wherein in step (IV), the hydrogenation catalyst comprises (i) a hydrogenation metal selected from Fe, Co, Ni, Ru, Rh, Pd, Ag, Re, Os, Ir, and Pt at a concentration in a range from 0.001 wt% to 5.0 wt%, based on the total weight of the catalyst; and (ii) an inorganic support material selected from activated carbon, Al₂O₃, Ga₂O₃, SiO₂, GeO₂,
20 SnO, SnO₂, TiO₂, ZrO₂, Sc₂O₃, Y₂O₃, alkali metal oxides, alkaline earth metal oxides, and mixtures, combinations, complexes and compounds thereof.

EI-11. The process of any of EI-1 to EI-10, wherein the first upper effluent comprises the sulfur-containing component at a concentration of no greater than 50 ppm by weight, based on the total weight of the first upper effluent.

25 EI-12. The process of any of EI-1 to EI-11, wherein the first upper effluent comprises the sulfur-containing component at a concentration based on the total weight of the first upper effluent no greater than 10% than the concentration of the sulfur-containing component in the first mixture based on the total weight of the first mixture.

EI-13. The process of any of EI-1 to EI-12, wherein the first upper effluent further
30 comprises cyclohexanol, and the process further comprises:

(VI) feeding at least a portion of the first upper effluent into a second distillation column;

and

(VII) obtaining the following from the second distillation column:

a second upper effluent comprising cyclohexanone at a concentration higher than the first upper effluent;

a third upper effluent at a location above the second upper effluent, the third upper effluent comprising components having normal boiling points lower than that of cyclohexanone; and

5 a second lower effluent comprising cyclohexanone at a concentration lower than the first upper effluent, and cyclohexanol at a concentration higher than the first upper effluent.

EI-14. The process of any of EI-1 to EI-13, wherein step (III) comprises:

(IIIa) contacting at least a portion of the first middle effluent with a posterior sorbent capable of removing at least a portion of the S-containing component to obtain the hydrogenation
10 feed.

EI-15. The process of EI-14, wherein the posterior sorbent comprises a solid-phase basic material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v) complexes of two or
15 more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more of (i), (ii), (iii), (iv), (v), (vi), and (vii).

EI-16. The process of any of EI-1 to EI-15, wherein the crude mixture comprises sulfuric acid at a concentration in a range from 1 ppm to 2,000 ppm by weight based on the total weight of the crude mixture.

20 EI-17. The process of any of EI-1 to EI-16, wherein the concentration of the sulfuric acid in the hydrogenation feed is at most 100 ppm by weight based on the total weight of the hydrogenation feed.

EI-18. The process of any of EI-1 to EI-17, wherein the first distillation column operates at a temperature of at least 120°C.

25 EI-19. The process of any of EI-1 to EI-18, wherein the first distillation column operates at a temperature higher than the disassociation temperature of at least one of the following: (i) 1,5-pentane diamine sulfuric acid complex; (ii) 1-methyl-1,5-pentane diamine sulfuric acid complex; and (iii) 1,6-hexane diamine sulfuric acid complex.

EI-20. The process of EI-14 or EI-15, wherein the concentration of the S-containing
30 component in the hydrogenation feed based on the total weight of the hydrogenation feed is at most 10% of the concentration of the S-containing component in the first middle effluent based on the total weight of the first middle effluent.

EI-21. The process of any of EI-1 to EI-20, wherein in step (IV), hydrogen and phenol are fed into the hydrogenation reaction zone at a hydrogen to phenol molar ratio in a range from 1.0 to 10.

5 EI-22. The process of any of EI-1 to EI-21, wherein the crude mixture in step (Ia) is obtained by a cleavage process comprising a step of contacting a cleavage feed mixture comprising 1-phenyl-1-cyclohexane-hydroperoxide and cyclohexylbenzene with an acid catalyst in a cleavage reactor to obtain a cleavage reaction product.

EI-23. The process of EI-22, wherein the acid catalyst comprises sulfuric acid.

EI-24. The process of EI-23, wherein the cleavage feed mixture is obtained by:

10 (Ia-1) contacting benzene with hydrogen in the presence of a hydroalkylation catalyst under hydroalkylation conditions to produce a hydroalkylation product mixture comprising cyclohexylbenzene;

(Ia-2) contacting the cyclohexylbenzene with oxygen in the presence of a catalyst to produce an oxidation reaction product mixture comprising 1-phenyl-1-cyclohexane-hydroperoxide;
15 and

(Ia-3) providing the cleavage feed mixture from the oxidation reaction product mixture.

EII-1. A process for making cyclohexanone, the process comprising:

(I) feeding a first mixture comprising cyclohexanone, phenol, cyclohexylbenzene, and an S-containing component into a first distillation column;

20 (II) obtaining from the first distillation column:
a first upper effluent comprising cyclohexanone at a concentration higher than the first mixture;

a first middle effluent comprising phenol at a concentration higher than the first mixture, cyclohexanone, cyclohexylbenzene, bicyclohexane, and a portion of the S-containing component;
25 and

a first lower effluent comprising cyclohexylbenzene at a concentration higher than the first mixture;

(III) removing at least a portion of the S-containing component from the first middle effluent to obtain a hydrogenation feed;

30 (IV) feeding at least a portion of the hydrogenation feed and hydrogen into a hydrogenation reaction zone where phenol reacts with hydrogen in the presence of a hydrogenation catalyst under hydrogenation reaction conditions to obtain a hydrogenation reaction product comprising cyclohexanone at a concentration higher than the hydrogenation feed, phenol at a concentration lower than the hydrogenation feed, cyclohexylbenzene, and bicyclohexane; and

(V) feeding at least a portion of the hydrogenation reaction product into the first distillation column.

EII-2. The process of EII-1, wherein the S-containing component comprises SO_3 , HSO_4^- , R-HSO_4 and/or sulfuric acid.

5 EII-3. The process of EII-1 or EII-2, wherein step (III) comprises:

(IIIa) contacting at least a portion of the first middle effluent with a posterior sorbent capable of removing at least a portion of the S-containing component to obtain the hydrogenation feed.

10 EII-4. The process of EII-3, wherein the posterior sorbent comprises a solid-phase basic material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v) complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more of (i), (ii), (iii), (iv), (v), (vi), and (vii).

15 EII-5. The process of any of EII-1 to EII-4, wherein the hydrogenation feed comprises:

cyclohexanone at a concentration in a range from 1 wt% to 50 wt%;

phenol at a concentration in a range from 10 wt% to 80 wt%;

cyclohexylbenzene at a concentration in a range from 0.001 wt% to 30 wt%; and

bicyclohexane at a concentration in a range from 0.001 wt% to 30 wt%,

20 the percentages being based on the total weight of the hydrogenation feed.

EII-6. The process of any of EII-1 to EII-5, wherein the first mixture comprises:

cyclohexanone at a concentration in a range from 10 wt% to 90 wt%;

phenol at a concentration in a range from 10 wt% to 80 wt%; and

cyclohexylbenzene at a concentration in a range from 0.001 wt% to 75 wt%;

25 the percentages being based on the total weight of the first mixture.

EII-7. The process of any of EII-1 to EII-6, wherein in step (IV), the hydrogenation catalyst comprises (i) a hydrogenation metal selected from Fe, Co, Ni, Ru, Rh, Pd, Ag, Re, Os, Ir, and Pt at a concentration in a range from 0.001 wt% to 5.0 wt%, based on the total weight of the catalyst; and (ii) an inorganic support material selected from activated carbon, Al_2O_3 , Ga_2O_3 , SiO_2 , GeO_2 ,
30 SnO , SnO_2 , TiO_2 , ZrO_2 , Sc_2O_3 , Y_2O_3 , alkali metal oxides, alkaline earth metal oxides, and mixtures, combinations, complexes and compounds thereof.

EII-8. The process of any of EII-1 to EII-7, wherein the first upper effluent further comprises cyclohexanol, and the process further comprises:

(VI) feeding at least a portion of the first upper effluent into a second distillation column;
and

(VII) obtaining the following from the second distillation column:

a second upper effluent comprising cyclohexanone at a concentration higher than the first
5 upper effluent;

a third upper effluent at a location above the second upper effluent, the third upper effluent
comprising components having normal boiling points lower than that of cyclohexanone; and

a second lower effluent comprising cyclohexanone at a concentration lower than the first
upper effluent, and cyclohexanol at a concentration higher than the first upper effluent.

10 EII-9. The process of any of EII-1 to EII-8, wherein the concentration of the S-containing
component in the first middle effluent is in a range from 1 ppm to 1,000 ppm by weight based on
the total weight of the first middle effluent.

EII-10. The process of any of EII-1 to EII-9, wherein step (I) comprises:

(Ia) providing a crude mixture comprising cyclohexanone, phenol, cyclohexylbenzene, and
15 the S-containing component;

(Ib) contacting the crude mixture with an anterior sorbent capable of removing at least a
portion of the S-containing component to obtain the first mixture.

EII-11. The process of EII-10, wherein the anterior sorbent in step (Ib) comprises a solid-
phase basic material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii)
20 hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals,
alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v)
complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and
(viii) mixtures and combinations of two or more of (i), (ii), (iii), (iv), (v), (vi), and (vii).

EII-12. The process of any of EII-3 to EII-11, wherein the posterior sorbent and/or the
25 anterior sorbent comprise ion-exchange resins.

EII-13. The process of any of EII-10 to EII-12, wherein the concentration of the S-
containing component in the first middle effluent is in a range from 10 ppm to 1,000 ppm by weight
based on the total weight of the first middle effluent.

EII-14. The process of any of EII-10 to EII-13, wherein the concentration of the S-
30 containing component in the first middle effluent based on the total weight of the middle effluent is
at most 10% of the concentration of the S-containing component in the crude mixture based on the
total weight of the crude mixture.

EII-15. The process of any of EII-10, EII-11, and EII-14, wherein the crude mixture comprises sulfuric acid at a concentration in a range from 1 ppm to 2,000 ppm by weight based on the total weight of the crude mixture.

5 EII-16. The process of any of EII-1 to EII-15, wherein the concentration of the S-containing component in the hydrogenation feed is at most 100 ppm by weight based on the total weight of the hydrogenation feed.

EII-17. The process of any of EII-1 to EII-16, wherein the first distillation column operates at a temperature of at least 120°C.

10 EII-18. The process of any of EII-1 to EII-17, wherein the first distillation column operates at a temperature higher than the disassociation temperature of at least one of the following: (i) 1,5-pentane diamine sulfuric acid complex; (ii) 1-methyl-1,5-pentane diamine sulfuric acid complex; and (iii) 1,6-hexane diamine sulfuric acid complex.

EII-19. The process of any of EII-1 to EII-18, wherein the concentration of the S-containing component in the hydrogenation feed based on the total weight of the hydrogenation feed is at most
15 10% of the concentration of the S-containing component in the first middle effluent.

EII-20. The process of any of EII-1 to EII-19, wherein in step (IV), hydrogen and phenol are fed into the hydrogenation reaction zone at a hydrogen to phenol molar ratio in a range from 1.0 to 10.

20 EII-21. The process of any of EII-1 to EII-20, wherein the first mixture in step (I) is obtained by a cleavage process comprising a step of contacting a cleavage feed mixture comprising 1-phenyl-1-cyclohexane-hydroperoxide and cyclohexylbenzene with an acid catalyst in a cleavage reactor to obtain a cleavage reaction product.

EII-22. The process of EII-21, wherein the cleavage feed mixture is obtained by:

25 (Ia-1) contacting benzene with hydrogen in the presence of a hydroalkylation catalyst under hydroalkylation conditions to produce a hydroalkylation product mixture comprising cyclohexylbenzene;

(Ia-2) contacting the cyclohexylbenzene with oxygen in the presence of a catalyst to produce an oxidation reaction product mixture comprising 1-phenyl-1-cyclohexane-hydroperoxide; and

30 (Ia-3) providing the cleavage feed mixture from the oxidation reaction product mixture.

CLAIMS

1. A process for making cyclohexanone, the process comprising:

(Ia) providing a crude mixture comprising cyclohexanone, phenol, cyclohexylbenzene,
5 and an S-containing component;

(Ib) contacting the crude mixture with an anterior sorbent capable of removing at least a
portion of the S-containing component to obtain a first mixture comprising cyclohexanone, phenol,
and cyclohexylbenzene;

(Ic) feeding the first mixture into a first distillation column;

10 (II) obtaining from the first distillation column:

a first upper effluent comprising cyclohexanone at a concentration higher than the first
mixture;

a first middle effluent comprising phenol at a concentration higher than the first mixture,
cyclohexanone, cyclohexylbenzene, and bicyclohexane; and

15 a first lower effluent comprising cyclohexylbenzene at a concentration higher than the first
mixture;

(III) providing hydrogen and at least a portion of the first middle effluent as at least a
portion of a hydrogenation feed to a hydrogenation reaction zone;

(IV) contacting the hydrogenation feed with hydrogen in the hydrogenation reaction zone
20 where phenol reacts with hydrogen in the presence of a hydrogenation catalyst under hydrogenation
reaction conditions to obtain a hydrogenation reaction product comprising cyclohexanone at a
concentration higher than the hydrogenation feed, phenol at a concentration lower than the
hydrogenation feed, cyclohexylbenzene, and bicyclohexane; and

(V) feeding at least a portion of the hydrogenation reaction product into the first
25 distillation column.

2. The process of claim 1, wherein the anterior sorbent in step (Ib) comprises a solid-phase
basic material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii)
hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals,
alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v)
30 complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and
(viii) mixtures and combinations of two or more thereof.

3. The process of claim 1 or claim 2, wherein the S-containing component comprises SO_3 ,
 HSO_4^- , R-HSO_4 and/or sulfuric acid.

4. The process of any of claims 1 to claim 3, wherein the concentration of the S-containing component in the crude mixture is in a range from 10 ppm to 10,000 ppm by weight based on the total weight of the crude mixture.

5 5. The process of any of claims 1 to claim 4, wherein the concentration of the S-containing component in the first middle effluent is in a range from 1 ppm to 1,000 ppm by weight based on the total weight of the first middle effluent.

6. The process of any of claims 1 to claim 5, wherein the concentration of the S-containing component in the hydrogenation feed is at most 100 ppm by weight based on the total weight of the hydrogenation feed.

10 7. The process of any of claims 1 to claim 6, wherein the concentration of the S-containing component in the hydrogenation feed based on the total weight of the hydrogenation feed is at most 10% of the concentration of the S-containing component in the crude mixture based on the total weight of the crude mixture.

15 8. The process of any of claims 1 to claim 7, wherein the first upper effluent comprises the sulfur-containing component at a concentration of no greater than 50 ppm by weight, based on the total weight of the first upper effluent.

9. The process of any of claims 1 to claim 8, wherein step (III) comprises:

(IIIa) contacting at least a portion of the first middle effluent with a posterior sorbent capable of removing at least a portion of the S-containing component to obtain the hydrogenation
20 feed.

10. The process of claim 9, wherein the posterior sorbent comprises a solid-phase basic material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v) complexes of two or
25 more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more thereof.

11. The process of any of claims 1 to claim 10, wherein the first distillation column operates at a temperature of at least 120°C.

12. The process of any of claims 1 to claim 11, wherein the first distillation column operates
30 at a temperature higher than the disassociation temperature of at least one of the following: (i) 1,5-pentane diamine sulfuric acid complex; (ii) 1-methyl-1,5-pentane diamine sulfuric acid complex; and (iii) 1,6-hexane diamine sulfuric acid complex.

13. The process of any of claims 9 to claim 12, wherein the concentration of the S-containing component in the hydrogenation feed based on the total weight of the hydrogenation

feed is at most 10% of the concentration of the S-containing component in the first middle effluent based on the total weight of the first middle effluent.

14. A process for making cyclohexanone, the process comprising:

(I) feeding a first mixture comprising cyclohexanone, phenol, cyclohexylbenzene, and
5 an S-containing component into a first distillation column;

(II) obtaining from the first distillation column:

a first upper effluent comprising cyclohexanone at a concentration higher than the first mixture;

a first middle effluent comprising phenol at a concentration higher than the first mixture,
10 cyclohexanone, cyclohexylbenzene, bicyclohexane, and a portion of the S-containing component;
and

a first lower effluent comprising cyclohexylbenzene at a concentration higher than the first mixture;

(III) removing at least a portion of the S-containing component from the first middle
15 effluent to obtain a hydrogenation feed;

(IV) feeding at least a portion of the hydrogenation feed and hydrogen into a hydrogenation reaction zone where phenol reacts with hydrogen in the presence of a hydrogenation catalyst under hydrogenation reaction conditions to obtain a hydrogenation reaction product comprising cyclohexanone at a concentration higher than the hydrogenation feed, phenol at a
20 concentration lower than the hydrogenation feed, cyclohexylbenzene, and bicyclohexane; and

(V) feeding at least a portion of the hydrogenation reaction product into the first distillation column.

15. The process of claim 14, wherein the S-containing component comprises SO_3 , HSO_4^- , R-HSO_4 and/or sulfuric acid.

25 16. The process of claim 14 or claim 15, wherein step (III) comprises:

(IIIa) contacting at least a portion of the first middle effluent with a posterior sorbent capable of removing at least a portion of the S-containing component to obtain the hydrogenation feed.

17. The process of claim 16, wherein the posterior sorbent comprises a solid-phase basic
30 material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v) complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more thereof.

18. The process of any of claims 14 to claim 17, wherein the concentration of the S-containing component in the first middle effluent is in a range from 1 ppm to 1,000 ppm by weight based on the total weight of the first middle effluent.

19. The process of any of claims 14 to claim 18, wherein step (I) comprises:

5 (Ia) providing a crude mixture comprising cyclohexanone, phenol, cyclohexylbenzene, and the S-containing component;

(Ib) contacting the crude mixture with an anterior sorbent capable of removing at least a portion of the S-containing component to obtain the first mixture.

10 20. The process of claim 19, wherein the anterior sorbent in step (Ib) comprises a solid-phase basic material selected from: (i) oxides of alkali metals, alkaline earth metals, and zinc; (ii) hydroxides of alkali metals, alkaline earth metals, and zinc; (iii) carbonates of alkali metals, alkaline earth metals, and zinc; (iv) bicarbonates of alkali metals, alkaline earth metals, and zinc; (v) complexes of two or more of (i), (ii), (iii), and (iv); (vi) solid amines; (vii) ion-exchange resins; and (viii) mixtures and combinations of two or more thereof.

15 21. The process of any of claims 16 to claim 20, wherein the posterior sorbent and/or the anterior sorbent comprise ion-exchange resins.

22. The process of any of claims 19 to claim 21, wherein the concentration of the S-containing component in the first middle effluent is in a range from 10 ppm to 1,000 ppm by weight based on the total weight of the first middle effluent.

20 23. The process of claim 14 or claim 15, wherein the crude mixture comprises sulfuric acid at a concentration in a range from 1 ppm to 2,000 ppm by weight based on the total weight of the crude mixture.

24. The process of any of claims 14 to claim 23, wherein the concentration of the S-containing component in the hydrogenation feed is at most 100 ppm by weight based on the total weight of the hydrogenation feed.

25 25. The process of any of claims 14 to claim 24, wherein the first distillation column operates at a temperature of at least 120°C.