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TION

(57) Abstract: In one embodiment, the invention is to a process for producing an acrylate product. The process comprises the step of reacting an alkanolic acid and an alkylating agent over a catalyst to produce a crude acrylate product stream, and to product a used catalyst. The used catalyst may then be contacted with a regenerating stream to form a regenerated catalyst. Alkanolic acid and alkylating agent may then be reacted over the regenerated catalyst to product additional crude acrylate product stream.



PROCESS FOR PRODUCING AN ACRYLATE PRODUCT COMPRISING A STEP OF
CATALYST REGENERATION

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. App. No. 13/664,934, filed October 31, 2012, the entire contents and disclosures of which are incorporated herein.

FIELD OF THE INVENTION

[0002] The present invention relates generally to the production of acrylic acid. More specifically, the present invention relates to the production of crude acrylic acid via the aldol condensation of acetic acid and formaldehyde in the presence of a catalyst. The catalyst may be regenerated via contact with a regenerating stream.

BACKGROUND OF THE INVENTION

[0003] α,β -unsaturated acids, particularly acrylic acid and methacrylic acid, and the ester derivatives thereof are useful organic compounds in the chemical industry. These acids and esters are known to readily polymerize or co-polymerize to form homopolymers or copolymers. Often the polymerized acids are useful in applications such as superabsorbents, dispersants, flocculants, and thickeners. The polymerized ester derivatives are used in coatings (including latex paints), textiles, adhesives, plastics, fibers, and synthetic resins.

[0004] Because acrylic acid and its esters have long been valued commercially, many methods of production have been developed. One exemplary acrylic acid ester production process utilizes: (1) the reaction of acetylene with water and carbon monoxide; and/or (2) the reaction of an alcohol and carbon monoxide, in the presence of an acid, e.g., hydrochloric acid, and nickel tetracarbonyl, to yield a crude product comprising the acrylate ester as well as hydrogen and nickel chloride. Another conventional process involves the reaction of ketene (often obtained by the pyrolysis of acetone or acetic acid) with formaldehyde, which yields a crude product comprising acrylic acid and either water (when acetic acid is used as a pyrolysis reactant) or methane (when acetone is used as a pyrolysis reactant). These processes have become obsolete for economic, environmental, or other reasons.

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[0005] More recent acrylic acid production processes have relied on the gas phase oxidation of propylene, via acrolein, to form acrylic acid. The reaction can be carried out in single- or two-step processes but the latter is favored because of higher yields. The oxidation of propylene produces acrolein, acrylic acid, acetaldehyde and carbon oxides. Acrylic acid from the primary oxidation can be recovered while the acrolein is fed to a second step to yield the crude acrylic acid product, which comprises acrylic acid, water, small amounts of acetic acid, as well as impurities such as furfural, acrolein, and propionic acid. Purification of the crude product may be carried out by azeotropic distillation. Although this process may show some improvement over earlier processes, this process suffers from production and/or separation inefficiencies. In addition, this oxidation reaction is highly exothermic and, as such, creates an explosion risk. As a result, more expensive reactor design and metallurgy are required. Also, the cost of propylene is often prohibitive.

[0006] The aldol condensation reaction of formaldehyde and acetic acid and/or carboxylic acid esters has been disclosed in literature. This reaction forms acrylic acid and is often conducted over a catalyst. For example, condensation catalysts consisting of mixed oxides of vanadium and phosphorus were investigated and described in M. Ai, *J. Catal.*, 107, 201 (1987); M. Ai, *J. Catal.*, 124, 293 (1990); M. Ai, *Appl. Catal.*, 36, 221 (1988); and M. Ai, *Shokubai*, 29, 522 (1987). The acetic acid conversions in these reactions, however, may leave room for improvement. Although this reaction is disclosed, there has been little if any disclosure relating to: 1) the reaction parameters and the effects thereof; or 2) separation schemes that may be employed to effectively provide purified acrylic acid from the aldol condensation crude product.

[0007] Thus, the need exists for a process for producing purified acrylic acid, which provides improvements in reaction yield, catalyst performance, and overall reaction efficiency.

[0008] The references mentioned above are hereby incorporated by reference.

BRIEF DESCRIPTION OF DRAWINGS

[0009] The invention is described in detail below with reference to the appended drawings, wherein like numerals designate similar parts.

[0010] FIG. 1 is a process flowsheet showing an acrylic acid reaction/separation system in accordance with an embodiment of the present invention.

[0011] FIG. 2 is a schematic diagram of an acrylic acid reaction/separation system in accordance

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with one embodiment of the present invention.

[0012] FIG. 3 is a schematic diagram of an acrylic acid reaction/separation system in accordance with one embodiment of the present invention.

[0013] FIG. 4 is a graph showing typical catalyst deactivation.

[0014] FIG. 5 is a graph showing regenerated catalyst activity.

SUMMARY OF THE INVENTION

[0015] In one embodiment, the invention is directed to a process for producing an acrylate product, the process comprising the steps of (a) contacting an alkanoic acid and an alkylating agent in a reactor over an initial catalyst under conditions effective to form: (i) a crude acrylate product stream comprising acrylate product and residual alkylating agent; and (ii) used catalyst; (b) contacting the used catalyst with a regenerating stream to form a regenerated catalyst; and (c) separating at least a portion of the crude acrylate product stream to form an alkylating agent stream comprising at least 1 wt.% alkylating agent and an intermediate product stream comprising acrylate product. The process may further comprise step (d) contacting an alkanoic acid and an alkylating agent over the regenerated catalyst under conditions effective to form additional acrylate product; and step (e) separating the intermediate acrylate product stream to form a finished acrylate product stream comprising acrylate product and a finished acetic acid stream comprising acetic acid. The catalyst may comprise vanadium, titanium, bismuth, tungsten, and combinations thereof. In some embodiments, the regenerating stream may comprise oxygen or hydrogen. In further embodiments, the regenerating stream comprises at least 1 wt.% oxygen. The initial catalyst may have a deactivation point at which step (b) is performed. For example, the deactivation point may occur when the conversion of the alkanoic acid is less than 20%, when the selectivity of the alkanoic acid to acrylate product is less than 70% and/or when the space time yield is less than 100 g/L catalyst/hr. Steps (a), (b), and (d) may be conducted in a swinging-bed reactor comprising at least two reactors. After step (b), the crude acrylate product may contain less than 10 wt.% carbon dioxide and carbon monoxide, combined.

[0016] In one embodiment, the present invention is directed to a process for producing an acrylate product, the process comprising the steps of: (a) contacting an alkanoic acid and an alkylating agent over a first active catalyst under conditions effective to form: (i) a first acrylate product stream

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comprising acrylate product and residual alkylating agent and (ii) a first used catalyst; (b) contacting the first used catalyst with a regenerating stream to form a first regenerated catalyst; (c) contacting an alkanolic acid and an alkylating agent over a second active catalyst under conditions effective to form: (i) a second acrylate product stream comprising acrylate product and alkylating agent and (ii) a second used catalyst; (d) contacting the second used catalyst with a regenerating stream to form a second regenerated catalyst; and (e) contacting an alkanolic acid and an alkylating agent over the first regenerated catalyst under conditions effective to form a third acrylate product stream comprising acrylate product. In further embodiments, the process may further comprise the step of (f) contacting an alkanolic acid and an alkylating agent over the second regenerated catalyst under conditions effective to form a fourth acrylate product stream comprising acrylate product. The first active catalyst and second active catalyst each have an independent deactivation point.

[0017] In another embodiment, the present invention is directed to a process for producing an acrylate product, the process comprising the steps of: (a) reacting in a reactor an alkanolic acid and an alkylating agent, over a catalyst under conditions effective to form a crude acrylate product stream comprising acrylate product and alkylating agent; (b) determining a catalyst deactivation point; (c) regenerating the catalyst when the catalyst reaches the catalyst deactivation point to form a regenerated catalyst; and (d) reacting an alkanolic acid and an alkylating agent over the regenerated catalyst to produce additional crude acrylate product stream. In one embodiment, the regeneration of the catalyst occurs prior to the deactivation point.

DETAILED DESCRIPTION OF THE INVENTION

Introduction

[0018] Production of unsaturated carboxylic acids such as acrylic acid and methacrylic acid and the ester derivatives thereof via most conventional processes have been limited by economic and environmental constraints. In the interest of finding a new reaction path, the aldol condensation reaction of acetic acid and an alkylating agent, e.g., formaldehyde, has been investigated. This reaction may yield a unique crude product that comprises, *inter alia*, a higher amount of (residual) formaldehyde, which is generally known to add unpredictability and problems to separation schemes. Although the aldol condensation reaction of acetic acid and formaldehyde may be disclosed, there has been little if any disclosure relating to the regeneration of catalysts that may be

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used in this reaction. In particular, the use of a pre-determined deactivation point for determining when the catalyst requires regeneration has not been explored in much detail at all.

[0019] Similarly, there has been little if any disclosure relating to separation schemes that may be employed to effectively purify the unique crude product that is produced. Other conventional reactions, e.g., propylene oxidation or ketene/formaldehyde, do not yield crude products that comprises higher amounts of formaldehyde. The primary reactions and the side reactions in propylene oxidation do not create formaldehyde. In the reaction of ketene and formaldehyde, a two-step reaction is employed and the formaldehyde is confined to the first stage. Also, the ketene is highly reactive and converts substantially all of the reactant formaldehyde. As a result of these features, very little, if any, formaldehyde remains in the crude product exiting the reaction zone. Because no formaldehyde is present in crude products formed by these conventional reactions, the separation schemes associated therewith have not addressed the problems and unpredictability that accompany crude products that have higher formaldehyde content.

[0020] In one embodiment, the present invention relates to a process for producing an acrylate product. The process may comprise the step of contacting an alkanolic acid and an alkylating agent over an initial catalyst to form a crude acrylate product stream and a used catalyst. The crude acrylate product comprises acrylate product and residual, e.g., unreacted, alkylating agent. In some embodiments, this step is conducted in a swinging-bed reactor. The swinging-bed reactor comprises at least two reactors, e.g., at least 3 reactors, at least 4 reactors or at least 5 reactors.

[0021] The used catalyst may then be contacted with a regenerating stream to form a regenerated catalyst. In one embodiment, the regenerating stream comprises a regenerating agent. In some embodiments, the regenerating agent may be an oxidant, e.g., oxygen, ozone, nitrous oxides, and combinations thereof. In other embodiments, the regenerating agent may be a reductant, e.g., hydrogen. Steam may also be used as an air-diluting agent to aid in catalyst regeneration. In some embodiments, the regenerating stream comprises at least 0.5 wt.% regenerating agent, e.g., at least 1 wt.%, at least 2 wt.%, at least 3 wt.% or at least 5 wt.%. In terms of ranges, the regenerating stream may comprise from 0.5 wt.% to 100 wt.% regenerating agent, e.g., from 1 wt.% to 99 wt.%, from 2 wt.% to 95 wt.%, from 3 wt.% to 90 wt.% or from 5 wt.% to 85 wt.%. In preferred embodiments, the regenerating agent comprises oxygen. By treating the used catalyst with the regenerating stream in accordance with the present invention, the activity of the catalyst is surprisingly improved and the

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useful lifetime of the catalyst is extended. As a result, the catalyst remains more effective for longer periods of time, which provides process efficiencies. In some embodiments, the regenerating stream may be combined with the alkanolic acid and/or alkylating agent feed described herein.

[0022] In one embodiment, the contacting of the regenerating stream with the used catalyst is triggered before the catalyst reaches a (pre-determined) deactivation point. The catalyst deactivation point may, for example, be based on conversion, selectivity and/or space time yield. In some embodiments, for example, the deactivation point is reached when the overall alkanolic acid conversion is less than 40%, e.g., less than 30%, less than 20%, less than 15% or less than 10%. In terms of ranges, the deactivation point is reached when the overall alkanolic acid conversion is from 0.01 to 40%, e.g., from 0.01 to 30%, from 0.01 to 20%, from 0.01 to 15% or from 0.01 to 10%. In one embodiment, the deactivation point is reached when the selectivity to acrylate product is less than 90%, e.g., less than 80 %, less than 70%, less than 60% or less than 50%. In terms of ranges, the deactivation point is reached when the selectivity to acrylate product is from 0.01 to 90%, e.g., from 0.01 to 80%, from 0.01 to 70%, from 0.01 to 60% or from 0.01 to 50%. In another embodiment, the deactivation point is reached when the STY is less than 300 grams/liter catalyst/hour (g/L/hr), e.g., less than 200 g/L/hr, less than 100 g/L/hr, or less than 50 g/L/hr. In terms of ranges, the deactivation point is reached when the STY is from 0.01 to 300 g/L/hr, e.g., from 0.01 to 200 g/L/hr, from 0.01 to 100 g/L/hr, or from 0.01 to 50 g/L/hr. By regenerating the catalyst before the deactivation point is reached, the reaction continues to be conducted over a catalyst having a high degree of activity. As a result, the reaction achieves higher conversions and yields for longer periods of time.

[0023] The regeneration of the catalyst, e.g., step (b), may be conducted until the effectiveness of the catalyst is improved. In one embodiment, the effectiveness of the catalyst may be determined based on the total combined carbon monoxide and carbon dioxide level produced in the reactor. Carbon monoxide and/or carbon dioxide are undesired reaction by-products. Without being bound by theory, the carbon monoxide and/or carbon dioxide may be produced from the oxidation of coke on the catalyst. Further, without being bound by theory, the formation of high amounts of these compounds may indicate that the catalyst is not effectively catalyzing the desired reaction. As the amount of these compounds decrease, coke buildup on the catalyst has decreased. In one embodiment, the contacting of the regeneration stream with the used catalyst may be conducted until

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the total combined carbon monoxide and carbon dioxide level is below 10 wt.%, e.g., below 5 wt.%, below 3wt.% or below 1 wt.%. In terms of ranges, the regeneration of the catalyst using an oxidant regenerating agent may occur until the total combined carbon monoxide and carbon dioxide level falls within the range of from 0.01 wt.% to 10 wt.%, e.g., from 0.05 wt.% to 5 wt.%, from 0.1 wt.% to 3 wt.% or from 0.5 to 1 wt.%. In other embodiments, a reductant regenerating agent is used and the off-gas products may include methane, ethane, other hydrocarbons, and oxygenates including alcohols.

[0024] Once the used catalyst is regenerated, alkanoic acid and alkylating agent may then be passed over the regenerated catalyst under conditions effective to form additional acrylate product. In some embodiments, the initial contacting step over the initial catalyst and the additional contacting step over the regenerated catalyst are conducted in a swinging-bed reactor optionally comprising a first reactor and a second reactor. The first reactor may be used to produce crude acrylate product while the second reactor may be used to regenerate the catalyst. At or before the point at which the first catalyst reaches its deactivation point, the used catalyst is contacted with the regenerating stream. The second reactor may then be used to produce additional crude acrylate product while the catalyst in the first reactor is regenerated.

[0025] In another embodiment, the process may comprise the step of contacting an alkanoic acid and an alkylating agent over a first active catalyst to form a first acrylate product stream comprising acrylate product and residual, e.g., unreacted, alkylating agent, and a first used catalyst. In some embodiments, the first used catalyst may be contacted with a regenerating stream, e.g., a first regenerating stream, to form a first regenerated catalyst. This contacting may be conducted in a manner similar to that discussed above.

[0026] In one embodiment, an alkanoic acid and an alkylating agent may be passed over a second active catalyst under conditions effective to form a second acrylate product stream comprising (i) acrylate product comprising acrylate product and alkylating agent and (ii) a second used catalyst. The second used catalyst may be contacted with a regenerating stream, e.g., a second regenerating stream, to form a second regenerated catalyst. This contacting may be conducted in a manner similar to that discussed above. In one embodiment, the second regenerating stream may be the same as the first regenerating stream used to regenerate the first active catalyst. In other embodiments, the second regenerating stream may be different than the first regenerating stream.

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[0027] In one embodiment, the process further comprises the step of contacting an alkanolic acid and an alkylating agent over the first regenerated catalyst under conditions effective to form a third acrylate product stream comprising acrylate product. The process may further comprise the step of contacting an alkanolic acid and an alkylating agent over the second regenerated catalyst under conditions effective to form a fourth acrylate product stream comprising acrylate product.

[0028] In some embodiments, this process is conducted in a swinging-bed reactor. In this case, the first catalyst is utilized until it reaches (or approaches) the respective deactivation point. When this point is reached, the first catalyst is regenerated. While the first catalyst is being regenerated, the second active catalyst may be used to conduct the reaction. The second active catalyst is then utilized until it reaches the respective deactivation point. When this point is reached, the second catalyst is regenerated. While the second catalyst is being regenerated, the first regenerated catalyst may be used to conduct the reaction. This configuration results in an essentially continuous process. The regenerating time required for the catalyst may determine the number of reactors used in the swinging-bed set-up.

[0029] In another embodiment, the present invention is to a process comprising the step of reacting in a reactor an alkanolic acid and an alkylating agent, over a catalyst under conditions effective to form a crude acrylate product stream comprising acrylate product and residual alkylating agent. The process further comprising the step of determining a catalyst deactivation point. When the catalyst reaches the deactivation point, the catalyst is regenerated to form a regenerated catalyst. An alkanolic acid and alkylating agent may then be reacted over the regenerated catalyst to produce additional crude acrylate product stream. The deactivation point is determined as explained herein. In some embodiments, a gas analyzer may be used to monitor the crude acrylate product, prior to the removal of any non-condensable gases, to determine the deactivation point.

[0030] Returning to the crude acrylate product, the crude acrylate product, as formed may then be separated to form an alkylating agent stream comprising at least 1 wt.% alkylating agent and an intermediate acrylate product stream comprising acrylate product. The intermediate acrylate product stream is then separated to form a finished acrylate product stream comprising acrylate products and a finished acetic acid stream comprising acetic acid.

[0031] As used herein, acrylic acid, methacrylic acid, and/or the salts and esters thereof, collectively or individually, may be referred to as "acrylate products." The use of the terms acrylic

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acid, methacrylic acid, or the salts and esters thereof, individually, does not exclude the other acrylate products, and the use of the term acrylate product does not require the presence of acrylic acid, methacrylic acid, and the salts and esters thereof.

[0032] The crude product stream of the present invention, unlike most conventional acrylic acid-containing crude products, further comprises a significant portion of at least one alkylating agent. Preferably, the at least one alkylating agent is formaldehyde. For example, the crude product stream may comprise at least 0.5 wt% alkylating agent(s), e.g., at least 1 wt%, at least 5 wt%, at least 7 wt%, at least 10 wt%, or at least 25 wt%. In terms of ranges, the crude product stream may comprise from 0.5 wt% to 50 wt% alkylating agent(s), e.g., from 1 wt% to 45 wt%, from 1 wt% to 25 wt%, from 1 wt% to 10 wt%, or from 5 wt% to 10 wt%. In terms of upper limits, the crude product stream may comprise less than 50 wt% alkylating agent(s), e.g., less than 45 wt%, less than 25 wt%, or less than 10 wt%.

[0033] In another embodiment, the crude product stream of the present invention further comprises water. For example, the crude product stream may comprise less than 60 wt% water, e.g., less than 50 wt%, less than 40 wt%, or less than 30 wt%. In terms of ranges, the crude product stream may comprise from 1 wt% to 60 wt% water, e.g., from 5 wt% to 50 wt%, from 10 wt% to 40 wt%, or from 15 wt% to 40 wt%. In terms of upper limits, the crude product stream may comprise at least 1 wt% water, e.g., at least 5 wt%, at least 10 wt%, or at least 15 wt%.

[0034] In one embodiment, the crude product stream of the present invention comprises very little, if any, of the impurities found in most conventional acrylic acid crude product streams. For example, the crude product stream of the present invention may comprise less than 1000 wppm of such impurities (either as individual components or collectively), e.g., less than 500 wppm, less than 100 wppm, less than 50 wppm, or less than 10 wppm. Exemplary impurities include acetylene, ketene, beta-propiolactone, higher alcohols, e.g., C₂₊, C₃₊, or C₄₊, and combinations thereof. Importantly, the crude product stream of the present invention comprises very little, if any, furfural and/or acrolein. In one embodiment, the crude product stream comprises substantially no furfural and/or acrolein, e.g., no furfural and/or acrolein. In one embodiment, the crude product stream comprises less than less than 500 wppm acrolein, e.g., less than 100 wppm, less than 50 wppm, or less than 10 wppm. In one embodiment, the crude product stream comprises less than less than 500 wppm furfural, e.g., less than 100 wppm, less than 50 wppm, or less than 10 wppm. Furfural and

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acrolein are known to act as detrimental chain terminators in acrylic acid polymerization reactions. Also, furfural and/or acrolein are known to have adverse effects on the color of purified product and/or to subsequent polymerized products.

[0035] In addition to the acrylic acid and the alkylating agent, the crude product stream may further comprise acetic acid, water, propionic acid, and light ends such as oxygen, nitrogen, carbon monoxide, carbon dioxide, methanol, methyl acetate, methyl acrylate, acetaldehyde, hydrogen, and acetone. Exemplary compositional data for the crude product stream are shown in Table 1. The compositional data in Table 1 reflects the composition of the crude product stream that is fed to the separation zone if 1) nitrogen dilution conditions are not employed; 2) nitrogen dilution conditions are employed and at least a major portion, preferably substantially all, of the nitrogen used in the nitrogen dilution is removed from the crude product stream before being fed to the separation zone; or 3) at least a major portion, preferably substantially all, of non-condensable gases are removed from the crude product stream before being fed to the separation zone. Components other than those listed in Table 1 may also be present in the crude product stream.

TABLE 1				
CRUDE ACRYLATE PRODUCT STREAM COMPOSITIONS				
Component	Conc. (wt%)	Conc. (wt%)	Conc. (wt%)	Conc. (wt%)
Acrylic Acid	1 to 75	1 to 50	5 to 50	10 to 40
Alkylating Agent(s)	0.5 to 50	1 to 45	1 to 25	1 to 10
Acetic Acid	1 to 90	1 to 70	5 to 50	10 to 50
Water	1 to 60	5 to 50	10 to 40	15 to 40
Propionic Acid	0.01 to 10	0.1 to 10	0.1 to 5	0.1 to 1
Oxygen	0.01 to 10	0.1 to 10	0.1 to 5	0.1 to 1
Nitrogen	0.1 to 20	0.1 to 10	0.5 to 5	0.5 to 4
Carbon Monoxide	0.01 to 10	0.1 to 10	0.1 to 5	0.5 to 3
Carbon Dioxide	0.01 to 10	0.1 to 10	0.1 to 5	0.5 to 3
Other Light Ends	0.01 to 10	0.1 to 10	0.1 to 5	0.5 to 3

Production of Acrylate Products

[0036] Any suitable reaction and/or separation scheme may be employed to form the crude product stream as long as the reaction provides the crude product stream components that are discussed above. For example, in some embodiments, the acrylate product stream is formed by contacting an alkanolic acid, e.g., acetic acid, or an ester thereof with an alkylating agent, e.g., a methylenating

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agent, for example formaldehyde, under conditions effective to form the crude acrylate product stream. Preferably, the contacting is performed over a suitable catalyst. The crude product stream may be the reaction product of the alkanolic acid-alkylenating agent reaction. In a preferred embodiment, the crude product stream is the reaction product of the aldol condensation reaction of acetic acid and formaldehyde, which is conducted over a catalyst comprising vanadium and titanium. In one embodiment, the crude product stream is the product of a reaction in wherein methanol with acetic acid are combined to generate formaldehyde *in situ*. The aldol condensation then follows. In one embodiment, a methanol-formaldehyde solution is reacted with acetic acid to form the crude product stream.

[0037] The alkanolic acid, or an ester of the alkanolic acid, may be of the formula $R'-CH_2-COOR$, where R and R' are each, independently, hydrogen or a saturated or unsaturated alkyl or aryl group. As an example, R and R' may be a lower alkyl group containing for example 1-4 carbon atoms. In one embodiment, an alkanolic acid anhydride may be used as the source of the alkanolic acid. In one embodiment, the reaction is conducted in the presence of an alcohol, preferably the alcohol that corresponds to the desired ester, e.g., methanol. In addition to reactions used in the production of acrylic acid, the inventive catalyst, in other embodiments, may be employed to catalyze other reactions.

[0038] The alkanolic acid, e.g., acetic acid, may be derived from any suitable source including natural gas, petroleum, coal, biomass, and so forth. As examples, acetic acid may be produced via methanol carbonylation, acetaldehyde oxidation, ethylene oxidation, oxidative fermentation, and anaerobic fermentation. As petroleum and natural gas prices fluctuate, becoming either more or less expensive, methods for producing acetic acid and intermediates such as methanol and carbon monoxide from alternate carbon sources have drawn increasing interest. In particular, when petroleum is relatively expensive compared to natural gas, it may become advantageous to produce acetic acid from synthesis gas ("syngas") that is derived from any available carbon source. US Patent No. 6,232,352, which is hereby incorporated by reference, for example, teaches a method of retrofitting a methanol plant for the manufacture of acetic acid. By retrofitting a methanol plant, the large capital costs associated with carbon monoxide generation for a new acetic acid plant are significantly reduced or largely eliminated. All or part of the syngas is diverted from the methanol

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synthesis loop and supplied to a separator unit to recover carbon monoxide and hydrogen, which are then used to produce acetic acid.

[0039] In some embodiments, at least some of the raw materials for the above-described aldol condensation process may be derived partially or entirely from syngas. For example, the acetic acid may be formed from methanol and carbon monoxide, both of which may be derived from syngas. For example, the methanol may be formed by steam reforming syngas, and the carbon monoxide may be separated from syngas. In other embodiments, the methanol may be formed in a carbon monoxide unit, e.g., as described in EP2076480; EP1923380; EP2072490; EP1914219; EP1904426; EP2072487; EP2072492; EP2072486; EP2060553; EP1741692; EP1907344; EP2060555; EP2186787; EP2072488; and US7842844, which are hereby incorporated by reference. Of course, this listing of methanol sources is merely exemplary and is not meant to be limiting. In addition, the above-identified methanol sources, *inter alia*, may be used to form the formaldehyde, e.g., *in situ*, which, in turn may be reacted with the acetic acid to form the acrylic acid. The syngas, in turn, may be derived from variety of carbon sources. The carbon source, for example, may be selected from the group consisting of natural gas, oil, petroleum, coal, biomass, and combinations thereof.

[0040] Methanol carbonylation processes suitable for production of acetic acid are described in US Patent Nos. 7,208,624, 7,115,772, 7,005,541, 6,657,078, 6,627,770, 6,143,930, 5,599,976, 5,144,068, 5,026,908, 5,001,259, and 4,994,608, all of which are hereby incorporated by reference.

[0041] US Patent No. RE 35,377, which is hereby incorporated by reference, provides a method for the production of methanol by conversion of carbonaceous materials such as oil, coal, natural gas and biomass materials. The process includes hydrogasification of solid and/or liquid carbonaceous materials to obtain a process gas which is steam pyrolyzed with additional natural gas to form syn gas. The syn gas is converted to methanol which may be carbonylated to acetic acid. US Patent No. 5,821,111, which discloses a process for converting waste biomass through gasification into syn gas, as well as US Patent No. 6,685,754 are hereby incorporated by reference.

[0042] In one optional embodiment, the acetic acid that is utilized in the condensation reaction comprises acetic acid and may also comprise other carboxylic acids, e.g., propionic acid, esters, and anhydrides, as well as acetaldehyde and acetone. In one embodiment, the acetic acid fed to the condensation reaction comprises propionic acid. For example, the acetic acid fed to the reaction may comprise from 0.001 wt% to 15 wt% propionic acid, e.g., from 0.001 wt% to 13 wt%, from

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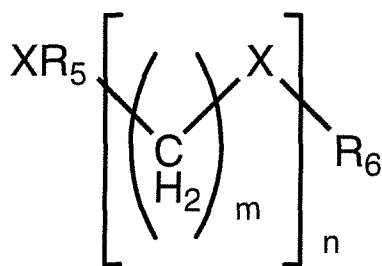
0.125 wt% to 12.5 wt%, from 1.25 wt% to 11.25 wt%, or from 3.75 wt% to 8.75 wt%. Thus, the acetic acid feed stream may be a cruder acetic acid feed stream, e.g., a less-refined acetic acid feed stream.

[0043] As used herein, “alkylenating agent” means an aldehyde or precursor to an aldehyde suitable for reacting with the alkanoic acid, e.g., acetic acid, to form an unsaturated acid, e.g., acrylic acid, or an alkyl acrylate. In preferred embodiments, the alkylenating agent comprises a methylenating agent such as formaldehyde, which preferably is capable of adding a methylene group ($=CH_2$) to the organic acid. Other alkylenating agents may include, for example, acetaldehyde, propanal, butanal, aryl aldehydes, benzyl aldehydes, alcohols, and combinations thereof. This listing is not exclusive and is not meant to limit the scope of the invention. In one embodiment, an alcohol may serve as a source of the alkylenating agent. For example, the alcohol may be reacted *in situ* to form the alkylenating agent, e.g., the aldehyde.

[0044] The alkylenating agent, e.g., formaldehyde, may be derived from any suitable source. Exemplary sources may include, for example, aqueous formaldehyde solutions, anhydrous formaldehyde derived from a formaldehyde drying procedure, trioxane, diether of methylene glycol, and paraformaldehyde. In a preferred embodiment, the formaldehyde is produced via a methanol oxidation process, which reacts methanol and oxygen to yield the formaldehyde.

[0045] In other embodiments, the alkylenating agent is a compound that is a source of formaldehyde. Where forms of formaldehyde that are not as freely or weakly complexed are used, the formaldehyde will form *in situ* in the condensation reactor or in a separate reactor prior to the condensation reactor. Thus for example, trioxane may be decomposed over an inert material or in an empty tube at temperatures over 350 °C or over an acid catalyst at over 100 °C to form the formaldehyde.

[0046] In one embodiment, the alkylenating agent corresponds to Formula I.



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[0047] In this formula, R_5 and R_6 may be independently selected from C_1 - C_{12} hydrocarbons, preferably, C_1 - C_{12} alkyl, alkenyl or aryl, or hydrogen. Preferably, R_5 and R_6 are independently C_1 - C_6 alkyl or hydrogen, with methyl and/or hydrogen being most preferred. X may be either oxygen or sulfur, preferably oxygen; and n is an integer from 1 to 10, preferably 1 to 3. In some embodiments, m is 1 or 2, preferably 1.

[0048] In one embodiment, the compound of formula I may be the product of an equilibrium reaction between formaldehyde and methanol in the presence of water. In such a case, the compound of formula I may be a suitable formaldehyde source. In one embodiment, the formaldehyde source includes any equilibrium composition. Examples of formaldehyde sources include but are not restricted to methylal (1,1 dimethoxymethane); polyoxymethylenes $-(CH_2-O)_i-$ wherein i is from 1 to 100; formalin; and other equilibrium compositions such as a mixture of formaldehyde, methanol, and methyl propionate. In one embodiment, the source of formaldehyde is selected from the group consisting of 1, 1 dimethoxymethane; higher formaldehydes of formaldehyde and methanol; and $CH_3-O-(CH_2-O)_i-CH_3$ where i is 2.

[0049] The alkylating agent may be used with or without an organic or inorganic solvent.

[0050] The term "formalin," refers to a mixture of formaldehyde, methanol, and water. In one embodiment, formalin comprises from 25 wt% to 85% formaldehyde; from 0.01 wt% to 25 wt% methanol; and from 25 wt% to 70 wt% water. In cases where a mixture of formaldehyde, methanol, and methyl propionate is used, the mixture comprises less than 10 wt% water, e.g., less than 5 wt% or less than 1 wt%.

[0051] In some embodiments, the condensation reaction may achieve favorable conversion of acetic acid and favorable selectivity and productivity to acrylates. For purposes of the present invention, the term "conversion" refers to the amount of acetic acid in the feed that is converted to a compound other than acetic acid. Conversion is expressed as a percentage based on acetic acid in the feed. The conversion of acetic acid may be at least 10%, e.g., at least 20%, at least 40%, or at least 50%.

[0052] Selectivity, as it refers to the formation of acrylate product, is expressed as the ratio of the amount of carbon in the desired product(s) and the amount of carbon in the total products. This ratio may be multiplied by 100 to arrive at the selectivity. Preferably, the catalyst selectivity to acrylate products, e.g., acrylic acid and methyl acrylate, is at least 40 mol%, e.g., at least 50 mol%, at least 60

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mol%, or at least 70 mol%. In some embodiments, the selectivity to acrylic acid is at least 30 mol %, e.g., at least 40 mol%, or at least 50 mol%; and/or the selectivity to methyl acrylate is at least 10 mol%, e.g., at least 15 mol%, or at least 20 mol%.

[0053] The terms “productivity” or “space time yield” as used herein, refers to the grams of a specified product, e.g., acrylate products, formed per hour during the condensation based on the liters of catalyst used . A productivity of at least 20 grams of acrylate product per liter catalyst per hour, e.g., at least 40 grams of acrylates per liter catalyst per hour or at least 100 grams of acrylates per liter catalyst per hour, is preferred. In terms of ranges, the productivity preferably is from 20 to 500 grams of acrylates per liter catalyst per hour, e.g., from 20 to 200 per kilogram catalyst per hour or from 40 to 140 per kilogram catalyst per hour.

[0054] In one embodiment, the inventive process yields at least 1,800 kg/hr of finished acrylic acid, e.g., at least 3,500 kg/hr, at least 18,000 kg/hr, or at least 37,000 kg/hr.

[0055] Preferred embodiments of the inventive process demonstrate a low selectivity to undesirable products, such as carbon monoxide and carbon dioxide. The selectivity to these undesirable products preferably is less than 29 %, e.g., less than 25 % or less than 15 %. More preferably, these undesirable products are not detectable. Formation of alkanes, e.g., ethane, may be low, and ideally less than 2%, less than 1%, or less than 0.5% of the acetic acid passed over the catalyst is converted to alkanes, which have little value other than as fuel.

[0056] The alkanoic acid or ester thereof and alkylating agent may be fed independently or after prior mixing to a reactor containing the catalyst. The reactor may be any suitable reactor or combination of reactors. Preferably, the reactor comprises a fixed bed reactor or a series of fixed bed reactors. In one embodiment, the reactor is a packed bed reactor or a series of packed bed reactors. In one embodiment, the reactor is a fixed bed reactor. Of course, other reactors such as a continuous stirred tank reactor or a fluidized bed reactor, may be employed.

[0057] In some embodiments, the alkanoic acid, e.g., acetic acid, and the alkylating agent, e.g., formaldehyde, are fed to the reactor at a molar ratio of at least 0.10:1, e.g., at least 0.75:1 or at least 1:1. In terms of ranges the molar ratio of alkanoic acid to alkylating agent may range from 0.10:1 to 10:1 or from 0.75:1 to 5:1. In some embodiments, the reaction of the alkanoic acid and the alkylating agent is conducted with a stoichiometric excess of alkanoic acid. In these instances, acrylate selectivity may be improved. As an example the acrylate selectivity may be at least 10%

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higher than a selectivity achieved when the reaction is conducted with an excess of alkylating agent, e.g., at least 20% higher or at least 30% higher. In other embodiments, the reaction of the alkanolic acid and the alkylating agent is conducted with a stoichiometric excess of alkylating agent.

[0058] The condensation reaction may be conducted at a temperature of at least 250 °C, e.g., at least 300 °C, or at least 350 °C. In terms of ranges, the reaction temperature may range from 200 °C to 500 °C, e.g., from 250 °C to 400 °C, or from 250 °C to 350 °C. Residence time in the reactor may range from 1 second to 200 seconds, e.g., from 1 second to 100 seconds. Reaction pressure is not particularly limited, and the reaction is typically performed near atmospheric pressure. In one embodiment, the reaction may be conducted at a pressure ranging from 0 KPa to 4100 KPa, e.g., from 3 KPa to 345 KPa, or from 6 to 103 KPa. The acetic acid conversion, in some embodiments, may vary depending upon the reaction temperature.

[0059] In one embodiment, the reaction is conducted at a gas hourly space velocity ("GHSV") greater than 600 hr⁻¹, e.g., greater than 1000 hr⁻¹ or greater than 2000 hr⁻¹. In one embodiment, the GHSV ranges from 600 hr⁻¹ to 10000 hr⁻¹, e.g., from 1000 hr⁻¹ to 8000 hr⁻¹ or from 1500 hr⁻¹ to 7500 hr⁻¹. As one particular example, when GHSV is at least 2000 hr⁻¹, the acrylate product STY may be at least 150 g/hr/liter.

[0060] Water may be present in the reactor in amounts up to 60 wt%, by weight of the reaction mixture, e.g., up to 50 wt% or up to 40 wt%. Water, however, is preferably reduced due to its negative effect on process rates and separation costs.

[0061] In one embodiment, an inert or reactive gas is supplied to the reactant stream. Examples of inert gases include, but are not limited to, nitrogen, helium, argon, and methane. Examples of reactive gases or vapors include, but are not limited to, oxygen, carbon oxides, sulfur oxides, and alkyl halides. When reactive gases such as oxygen are added to the reactor, these gases, in some embodiments, may be added in stages throughout the catalyst bed at desired levels as well as feeding with the other feed components at the beginning of the reactors. The addition of these additional components may improve reaction efficiencies.

[0062] In one embodiment, the unreacted components such as the alkanolic acid and formaldehyde as well as the inert or reactive gases that remain are recycled to the reactor after sufficient separation from the desired product.

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[0063] When the desired product is an unsaturated ester made by reacting an ester of an alkanolic acid ester with formaldehyde, the alcohol corresponding to the ester may also be fed to the reactor either with or separately to the other components. For example, when methyl acrylate is desired, methanol may be fed to the reactor. The alcohol, amongst other effects, reduces the quantity of acids leaving the reactor. It is not necessary that the alcohol is added at the beginning of the reactor and it may for instance be added in the middle or near the back, in order to effect the conversion of acids such as propionic acid, methacrylic acid to their respective esters without depressing catalyst activity. In one embodiment, the alcohol may be added downstream of the reactor.

Catalyst Composition

[0064] The catalyst may be any suitable catalyst composition. As one example, condensation catalyst consisting of mixed oxides of vanadium and phosphorus have been investigated and described in M. Ai, *J. Catal.*, 107, 201 (1987); M. Ai, *J. Catal.*, 124, 293 (1990); M. Ai, *Appl. Catal.*, 36, 221 (1988); and M. Ai, *Shokubai*, 29, 522 (1987). Other examples include binary vanadium-titanium phosphates, vanadium-silica-phosphates, and alkali metal-promoted silicas, e.g., cesium- or potassium-promoted silicas.

[0065] In one embodiment, the inventive process employs a catalyst composition comprising vanadium, titanium, and optionally at least one oxide additive. The oxide additive(s), if present, are preferably present in the active phase of the catalyst. In one embodiment, the oxide additive(s) are selected from the group consisting of silica, alumina, zirconia, and mixtures thereof or any other metal oxide other than metal oxides of titanium or vanadium. Preferably, the molar ratio of oxide additive to titanium in the active phase of the catalyst composition is greater than 0.05:1, e.g., greater than 0.1:1, greater than 0.5:1, or greater than 1:1. In terms of ranges, the molar ratio of oxide additive to titanium in the inventive catalyst may range from 0.05:1 to 20:1, e.g., from 0.1:1 to 10:1, or from 1:1 to 10:1. In these embodiments, the catalyst comprises titanium, vanadium, and one or more oxide additives and have relatively high molar ratios of oxide additive to titanium.

[0066] In another embodiment, the inventive process employs a catalyst comprising vanadium, titanium, bismuth, tungsten, or mixtures thereof. Exemplary catalyst compositions include vanadium/titanium/bismuth, vanadium/titanium/tungsten, bismuth/tungsten, and vanadium/bismuth/tungsten.

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[0067] In other embodiments, the catalyst may further comprise other compounds or elements (metals and/or non-metals). For example, the catalyst may further comprise phosphorus and/or oxygen. In these cases, the catalyst may comprise from 15 wt% to 45 wt% phosphorus, e.g., from 20 wt% to 35 wt% or from 23 wt% to 27 wt%; and/or from 30 wt% to 75 wt% oxygen, e.g., from 35 wt% to 65 wt% or from 48 wt% to 51 wt%.

[0068] In some embodiments, the catalyst further comprises additional metals and/or oxide additives. These additional metals and/or oxide additives may function as promoters. If present, the additional metals and/or oxide additives may be selected from the group consisting of copper, molybdenum, tungsten, nickel, niobium, and combinations thereof. Other exemplary promoters that may be included in the catalyst of the invention include lithium, sodium, magnesium, aluminum, chromium, manganese, iron, cobalt, calcium, yttrium, ruthenium, silver, tin, barium, lanthanum, the rare earth metals, hafnium, tantalum, rhenium, thorium, bismuth, antimony, germanium, zirconium, uranium, cesium, zinc, and silicon and mixtures thereof. Other modifiers include boron, gallium, arsenic, sulfur, halides, Lewis acids such as BF_3 , ZnBr_2 , and SnCl_4 . Exemplary processes for incorporating promoters into catalyst are described in US Pat. No. 5,364,824, the entirety of which is incorporated herein by reference.

[0069] If the catalyst comprises additional metal(s) and/or metal oxides(s), the catalyst optionally may comprise additional metals and/or metal oxides in an amount from 0.001 wt% to 30 wt%, e.g., from 0.01 wt% to 5 wt% or from 0.1 wt% to 5 wt%. If present, the promoters may enable the catalyst to have a weight/weight space time yield of at least 25 grams of acrylic acid/gram catalyst-h, e.g., least 50 grams of acrylic acid/gram catalyst-h, or at least 100 grams of acrylic acid/gram catalyst-h.

[0070] In some embodiments, the catalyst is unsupported. In these cases, the catalyst may comprise a homogeneous mixture or a heterogeneous mixture as described above. In one embodiment, the homogeneous mixture is the product of an intimate mixture of vanadium and titanium oxides, hydroxides, and phosphates resulting from preparative methods such as controlled hydrolysis of metal alkoxides or metal complexes. In other embodiments, the heterogeneous mixture is the product of a physical mixture of the vanadium and titanium phosphates. These mixtures may include formulations prepared from phosphorylating a physical mixture of preformed

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hydrous metal oxides. In other cases, the mixture(s) may include a mixture of preformed vanadium pyrophosphate and titanium pyrophosphate powders.

[0071] In another embodiment, the catalyst is a supported catalyst comprising a catalyst support in addition to the vanadium, titanium, oxide additive, and optionally phosphorous and oxygen, in the amounts indicated above (wherein the molar ranges indicated are without regard to the moles of catalyst support, including any vanadium, titanium, oxide additive, phosphorous or oxygen contained in the catalyst support). The total weight of the support (or modified support), based on the total weight of the catalyst, preferably is from 75 wt.% to 99.9 wt.%, e.g., from 78 wt.% to 97 wt.% or from 80 wt.% to 95 wt.%. The support may vary widely. In one embodiment, the support material is selected from the group consisting of silica, alumina, zirconia, titania, aluminosilicates, zeolitic materials, mixed metal oxides (including but not limited to binary oxides such as SiO_2 - Al_2O_3 , SiO_2 - TiO_2 , SiO_2 - ZnO , SiO_2 - MgO , SiO_2 - ZrO_2 , Al_2O_3 - MgO , Al_2O_3 - TiO_2 , Al_2O_3 - ZnO , TiO_2 - MgO , TiO_2 - ZrO_2 , TiO_2 - ZnO , TiO_2 - SnO_2) and mixtures thereof, with silica being one preferred support. In embodiments where the catalyst comprises a titania support, the titania support may comprise a major or minor amount of rutile and/or anatase titanium dioxide. Other suitable support materials may include, for example, stable metal oxide-based supports or ceramic-based supports. Preferred supports include siliceous supports, such as silica, silica/alumina, a Group IIA silicate such as calcium metasilicate, pyrogenic silica, high purity silica, silicon carbide, sheet silicates or clay minerals such as montmorillonite, beidellite, saponite, pillared clays, other microporous and mesoporous materials, and mixtures thereof. Other supports may include, but are not limited to, iron oxide, magnesia, steatite, magnesium oxide, carbon, graphite, high surface area graphitized carbon, activated carbons, and mixtures thereof. These listings of supports are merely exemplary and are not meant to limit the scope of the present invention.

[0072] In some embodiments, a zeolitic support is employed. For example, the zeolitic support may be selected from the group consisting of montmorillonite, NH_4 ferrierite, H-mordenite-PVOx, vermiculite-1, H-ZSM5, NaY, H-SDUSY, Y zeolite with high SAR, activated bentonite, H-USY, MONT-2, HY, mordenite SAR 20, SAPO-34, Aluminosilicate (X), VUSY, Aluminosilicate (CaX), Re-Y, and mixtures thereof. H-SDUSY, VUSY, and H-USY are modified Y zeolites belonging to the faujasite family. In one embodiment, the support is a zeolite that does not contain any metal oxide modifier(s). In some embodiments, the catalyst composition comprises a zeolitic support and

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the active phase comprises a metal selected from the group consisting of vanadium, aluminum, nickel, molybdenum, cobalt, iron, tungsten, zinc, copper, titanium cesium bismuth, sodium, calcium, chromium, cadmium, zirconium, and mixtures thereof. In some of these embodiments, the active phase may also comprise hydrogen, oxygen, and/or phosphorus.

[0073] In other embodiments, in addition to the active phase and a support, the inventive catalyst may further comprise a support modifier. A modified support, in one embodiment, relates to a support that includes a support material and a support modifier, which, for example, may adjust the chemical or physical properties of the support material such as the acidity or basicity of the support material. In embodiments that use a modified support, the support modifier is present in an amount from 0.1 wt.% to 50 wt.%, e.g., from 0.2 wt.% to 25 wt.%, from 0.5 wt.% to 15 wt.%, or from 1 wt.% to 8 wt.%, based on the total weight of the catalyst composition.

[0074] In one embodiment, the support modifier is an acidic support modifier. In some embodiments, the catalyst support is modified with an acidic support modifier. The support modifier similarly may be an acidic modifier that has a low volatility or little volatility. The acidic modifiers may be selected from the group consisting of oxides of Group IVB metals, oxides of Group VB metals, oxides of Group VIB metals, iron oxides, aluminum oxides, and mixtures thereof. In one embodiment, the acidic modifier may be selected from the group consisting of WO_3 , MoO_3 , Fe_2O_3 , Cr_2O_3 , V_2O_5 , MnO_2 , CuO , Co_2O_3 , Bi_2O_3 , TiO_2 , ZrO_2 , Nb_2O_5 , Ta_2O_5 , Al_2O_3 , B_2O_3 , P_2O_5 , and Sb_2O_3 .

[0075] In another embodiment, the support modifier is a basic support modifier. The presence of chemical species such as alkali and alkaline earth metals, are normally considered basic and may conventionally be considered detrimental to catalyst performance. The presence of these species, however, surprisingly and unexpectedly, may be beneficial to the catalyst performance. In some embodiments, these species may act as catalyst promoters or a necessary part of the acidic catalyst structure such in layered or sheet silicates such as montmorillonite. Without being bound by theory, it is postulated that these cations create a strong dipole with species that create acidity.

[0076] Additional modifiers that may be included in the catalyst include, for example, boron, aluminum, magnesium, zirconium, and hafnium.

[0077] As will be appreciated by those of ordinary skill in the art, the support materials, if included in the catalyst of the present invention, preferably are selected such that the catalyst system is suitably active, selective and robust under the process conditions employed for the formation of the

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desired product, e.g., acrylic acid or alkyl acrylate. Also, the active metals and/or pyrophosphates that are included in the catalyst of the invention may be dispersed throughout the support, coated on the outer surface of the support (egg shell) or decorated on the surface of the support. In some embodiments, in the case of macro- and meso-porous materials, the active sites may be anchored or applied to the surfaces of the pores that are distributed throughout the particle and hence are surface sites available to the reactants but are distributed throughout the support particle.

[0078] The inventive catalyst may further comprise other additives, examples of which may include: molding assistants for enhancing moldability; reinforcements for enhancing the strength of the catalyst; pore-forming or pore modification agents for formation of appropriate pores in the catalyst, and binders. Examples of these other additives include stearic acid, graphite, starch, cellulose, silica, alumina, glass fibers, silicon carbide, and silicon nitride. Preferably, these additives do not have detrimental effects on the catalytic performances, e.g., conversion and/or activity. These various additives may be added in such an amount that the physical strength of the catalyst does not readily deteriorate to such an extent that it becomes impossible to use the catalyst practically as an industrial catalyst.

Separation

[0079] The unique crude product of the present invention may be separated in a separation zone to form a final product, e.g., a (purified) final acrylic acid product. The inventive process comprises the step of separating at least a portion of the crude product to form at least one alkylenating agent stream and at least one purified acrylate product stream.

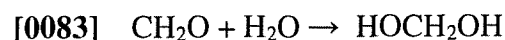
[0080] There has been little if any disclosure relating to separation schemes that may be employed to effectively purify the unique crude product that is produced. Other conventional reactions, e.g., propylene oxidation or ketene/formaldehyde, do not yield crude products that comprises higher amounts of formaldehyde. The primary reactions and the side reactions in propylene oxidation do not create formaldehyde. In the reaction of ketene and formaldehyde, a two-step reaction is employed and the formaldehyde is confined to the first stage. Also, the ketene is highly reactive and converts substantially all of the reactant formaldehyde. As a result of these features, very little, if any, formaldehyde remains in the crude product exiting the reaction zone. Because no formaldehyde is present in crude products formed by these conventional reactions, the separation schemes

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associated therewith have not addressed the problems and unpredictability that accompany crude products that have higher formaldehyde content.

[0081] In one embodiment, the separation comprises the step of separating at least a portion of the crude product stream to form an alkylating agent stream and an intermediate product stream. This separating step may be referred to as an “alkylating agent split.” In one embodiment, the alkylating agent stream comprises significant amounts of alkylating agent(s). For example, the alkylating agent stream may comprise at least 1 wt% alkylating agent(s), e.g., at least 5 wt%, at least 10 wt%, at least 15 wt%, or at least 25 wt%. In terms of ranges, the alkylating stream may comprise from 1 wt% to 75 wt% alkylating agent(s), e.g., from 3 wt% to 50 wt%, from 3 wt% to 25 wt%, or from 10 wt% to 20 wt%. In terms of upper limits, the alkylating stream may comprise less than 75 wt% alkylating agent(s), e.g. less than 50 wt% or less than 40 wt%. In preferred embodiments, the alkylating agent is formaldehyde.

[0082] As noted above, the presence of alkylating agent in the crude product stream adds unpredictability and problems to separation schemes. Without being bound by theory, it is believed that formaldehyde reacts in many side reactions with water to form by-products. The following side reactions are exemplary.



[0085] Without being bound by theory, it is believed that, in some embodiments, as a result of these reactions, the alkylating agent, e.g., formaldehyde, acts as a “light” component at higher temperatures and as a “heavy” component at lower temperatures. The reaction(s) are exothermic. Accordingly, the equilibrium constant increases as temperature decreases and decreases as temperature increases. At lower temperatures, the larger equilibrium constant favors methylene glycol and oligomer production and formaldehyde becomes limited, and, as such, behaves as a heavy component. At higher temperatures, the smaller equilibrium constant favors formaldehyde production and methylene glycol becomes limited. As such, formaldehyde behaves as a light component. In view of these difficulties, as well as others, the separation of streams that comprise water and formaldehyde cannot be expected to behave as a typical two-component system. These features contribute to the unpredictability and difficulty of the separation of the unique crude product stream of the present invention.

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[0086] The present invention, surprisingly and unexpectedly, achieves effective separation of alkylenating agent(s) from the inventive crude product stream to yield a purified product comprising acrylate product and very low amounts of other impurities.

[0087] In one embodiment, the alkylenating split is performed such that a lower amount of acetic acid is present in the resulting alkylenating stream. Preferably, the alkylenating agent stream comprises little or no acetic acid. As an example, the alkylenating agent stream, in some embodiments, comprises less than 50 wt% acetic acid, e.g., less than 45 wt%, less than 25 wt%, less than 10 wt%, less than 5 wt%, less than 3 wt%, or less than 1 wt%. Surprisingly and unexpectedly, the present invention provides for the lower amounts of acetic acid in the alkylenating agent stream, which, beneficially reduces or eliminates the need for further treatment of the alkylenating agent stream to remove acetic acid. In some embodiments, the alkylenating agent stream may be treated to remove water therefrom, e.g., to purge water.

[0088] In some embodiments, the alkylenating agent split is performed in at least one column, e.g., at least two columns or at least three columns. Preferably, the alkylenating agent is performed in a two column system. In other embodiments, the alkylenating agent split is performed via contact with an extraction agent. In other embodiments, the alkylenating agent split is performed via precipitation methods, e.g., crystallization, and/or azeotropic distillation. Of course, other suitable separation methods may be employed either alone or in combination with the methods mentioned herein.

[0089] The intermediate product stream comprises acrylate products. In one embodiment, the intermediate product stream comprises a significant portion of acrylate products, e.g., acrylic acid. For example, the intermediate product stream may comprise at least 5 wt% acrylate products, e.g., at least 25 wt%, at least 40 wt%, at least 50 wt%, or at least 60 wt%. In terms of ranges, the intermediate product stream may comprise from 5 wt% to 99 wt% acrylate products, e.g. from 10 wt% to 90 wt%, from 25 wt% to 75 wt%, or from 35 wt% to 65 wt%. The intermediate product stream, in one embodiment, comprises little if any alkylenating agent. For example, the intermediate product stream may comprise less than 1 wt% alkylenating agent, e.g., less than 0.1 wt%, less than 0.05 wt%, or less than 0.01 wt%. In addition to the acrylate products, the intermediate product stream optionally comprises acetic acid, water, propionic acid and other components.

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[0090] In some cases, the intermediate acrylate product stream comprises higher amounts of alkylating agent. For example, in one embodiment, the intermediate acrylate product stream comprises from 1 wt% to 50 wt% alkylating agent, e.g., from 1 wt% to 10 wt% or from 5 wt% to 50 wt%. In terms of limits, the intermediate acrylate product stream may comprise at least 1 wt% alkylating agent, e.g., at least 5 wt% or at least 10 wt%.

[0091] In one embodiment, the crude product stream is optionally treated, e.g. separated, prior to the separation of alkylating agent therefrom. In such cases, the treatment(s) occur before the alkylating agent split is performed. In other embodiments, at least a portion of the intermediate acrylate product stream may be further treated after the alkylating agent split. As one example, the crude product stream may be treated to remove light ends therefrom. This treatment may occur either before or after the alkylating agent split, preferably before the alkylating agent split. In some of these cases, the further treatment of the intermediate acrylate product stream may result in derivative streams that may be considered to be additional purified acrylate product streams. In other embodiments, the further treatment of the intermediate acrylate product stream results in at least one finished acrylate product stream.

[0092] In one embodiment, the inventive process operates at a high process efficiency. For example, the process efficiency may be at least 10%, e.g., at least 20% or at least 35%. In one embodiment, the process efficiency is calculated based on the flows of reactants into the reaction zone. The process efficiency may be calculated by the following formula.

$$\text{Process Efficiency} = 2N_{\text{HAcA}}/[N_{\text{HOAc}} + N_{\text{HCHO}} + N_{\text{H}_2\text{O}}]$$

[0093] where:

[0094] N_{HAcA} is the molar production rate of acrylate products; and

[0095] N_{HOAc} , N_{HCHO} , and $N_{\text{H}_2\text{O}}$ are the molar feed rates of acetic acid, formaldehyde, and water.

[0096] As discussed above, the crude product stream is separated to yield an intermediate acrylate product stream. FIG. 1 is a flow diagram depicting the formation of the crude product stream and the separation thereof to obtain an intermediate acrylate product stream. Acrylate product system 100 comprises reaction zone 102 and alkylating agent split zone 132. Reaction zone 102 comprises reactor 106, alkanoic acid feed, e.g., acetic acid feed, 108, alkylating agent feed, e.g., formaldehyde feed 110, vaporizer 112, and regenerating stream 113.

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[0097] Acetic acid and formaldehyde are fed to vaporizer 112 via lines 108 and 110, respectively, to create a vapor feed stream, which exits vaporizer 112 via line 114 and is directed to reactor 106. In one embodiment, lines 108 and 110 may be combined and jointly fed to the vaporizer 112. The temperature of the vapor feed stream in line 114 is preferably from 200°C to 600°C, e.g., from 250°C to 500°C or from 340°C to 425°C. Alternatively, a vaporizer may not be employed and the reactants may be fed directly to reactor 106. Once the catalyst has reached its deactivation point, regenerating stream 113 may be fed to the reactor.

[0098] Any feed that is not vaporized may be removed from vaporizer 112 and may be recycled or discarded. In addition, although line 114 is shown as being directed to the upper half of reactor 106, line 114 may be directed to the middle or bottom of first reactor 106. Further modifications and additional components to reaction zone 102 and alkylenating agent split zone 132 are described below.

[0099] Reactor 106 contains the catalyst that is used in the reaction to form crude product stream, which is withdrawn, preferably continuously, from reactor 106 via line 116. Although FIG. 1 shows the crude product stream being withdrawn from the bottom of reactor 106, the crude product stream may be withdrawn from any portion of reactor 106. Exemplary composition ranges for the crude product stream are shown in Table 1 above.

[0100] In one embodiment, one or more guard beds (not shown) may be used upstream of the reactor to protect the catalyst from poisons or undesirable impurities contained in the feed or return/recycle streams. Such guard beds may be employed in the vapor or liquid streams. Suitable guard bed materials may include, for example, carbon, silica, alumina, ceramic, or resins. In one aspect, the guard bed media is functionalized, e.g., silver functionalized, to trap particular species such as sulfur or halogens.

[0101] The crude product stream in line 116 is fed to alkylenating agent split unit 132. Alkylenating agent split unit 132 may comprise one or more separation units, e.g., two or more or three or more. In one example, the alkylenating agent split unit contains multiple columns, as shown in FIG. 2. Alkylenating agent split unit 132 separates the crude product stream into at least one intermediate acrylate product stream, which exits via line 118 and at least one alkylenating agent stream, which exits via line 120. Exemplary compositional ranges for the intermediate acrylate product stream are shown in Table 2. Components other than those listed in Table 2 may also be

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present in the intermediate acrylate product stream. Examples include methanol, methyl acetate, methyl acrylate, dimethyl ketone, carbon dioxide, carbon monoxide, oxygen, nitrogen, and acetone.

TABLE 2
INTERMEDIATE ACRYLATE PRODUCT STREAM COMPOSITION

	Conc. (wt%)	Conc. (wt%)	Conc. (wt%)
Acrylic Acid	at least 5	5 to 99	35 to 65
Acetic Acid	less than 95	5 to 90	20 to 60
Water	less than 25	0.1 to 10	0.5 to 7
Alkylenating Agent	< 1	< 0.5	< 0.1
Propionic Acid	< 10	0.01 to 5	0.01 to 1

[0102] In other embodiments, the intermediate acrylate product stream comprises higher amounts of alkylenating agent. For example, the intermediate acrylate product stream may comprise from 1 wt% to 10 wt% alkylenating agent, e.g., from 1 wt% to 8 wt% or from 2 wt% to 5 wt%. In one embodiment, the intermediate acrylate product stream comprises greater than 1 wt% alkylenating agent, e.g., greater than 5 wt% or greater than 10 wt%.

[0103] Exemplary compositional ranges for the alkylenating agent stream are shown in Table 3. Components other than those listed in Table 3 may also be present in the purified alkylate product stream. Examples include methanol, methyl acetate, methyl acrylate, dimethyl ketone, carbon dioxide, carbon monoxide, oxygen, nitrogen, and acetone.

TABLE 3
ALKYLENATING AGENT STREAM COMPOSITION

	Conc. (wt%)	Conc. (wt%)	Conc. (wt%)
Acrylic Acid	less than 15	0.01 to 10	0.1 to 5
Acetic Acid	10 to 65	20 to 65	25 to 55
Water	15 to 75	25 to 65	30 to 60
Alkylenating Agent	at least 1	1 to 75	10 to 20
Propionic Acid	< 10	0.001 to 5	0.01 1

[0104] In other embodiments, the alkylenating stream comprises lower amounts of acetic acid. For example, the alkylenating agent stream may comprise less than 10 wt% acetic acid, e.g., less than 5 wt% or less than 1 wt%.

[0105] As mentioned above, the crude product stream of the present invention comprises little, if any, furfural and/or acrolein. As such the derivative stream(s) of the crude product streams will comprise little, if any, furfural and/or acrolein. In one embodiment, the derivative stream(s), e.g., the streams of the separation zone, comprises less than less than 500 wppm acrolein, e.g., less than

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100 wppm, less than 50 wppm, or less than 10 wppm. In one embodiment, the derivative stream(s) comprises less than less than 500 wppm furfural, e.g., less than 100 wppm, less than 50 wppm, or less than 10 wppm.

[0106] FIG. 2 shows an overview of a reaction/separation scheme in accordance with the present invention. Acrylate product system 200 comprises reaction zone 202 and separation zone 204. Reaction zone 202 comprises reactor 206, alkanolic acid feed, e.g., acetic acid feed, 208, alkylating agent feed, e.g., formaldehyde feed, 210, vaporizer 212, line 213 and line 214. Reaction zone 202 and the components thereof function in a manner similar to reaction zone 102 of FIG. 1.

[0107] Reaction zone 202 yields a crude product stream, which exits reaction zone 202 via line 216 and is directed to separation zone 204. The components of the crude product stream are discussed above. Separation zone 204 comprises alkylating agent split unit 232, acrylate product split unit 234, acetic acid split unit 236, and drying unit 238. Separation zone 204 may also comprise an optional light ends removal unit (not shown). For example, the light ends removal unit may comprise a condenser and/or a flasher. The light ends removal unit may be configured either upstream or downstream of the alkylating agent split unit. Depending on the configuration, the light ends removal unit removes light ends from the crude product stream, the alkylating stream, and/or the intermediate acrylate product stream. In one embodiment, when the light ends are removed, the remaining liquid phase comprises the acrylic acid, acetic acid, alkylating agent, and/or water.

[0108] Alkylating agent split unit 232 may comprise any suitable separation device or combination of separation devices. For example, alkylating agent split unit 232 may comprise a column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In other embodiments, alkylating agent split unit 232 comprises a precipitation unit, e.g., a crystallizer and/or a chiller. Preferably, alkylating agent split unit 232 comprises two standard distillation columns. In another embodiment, the alkylating agent split is performed by contacting the crude product stream with a solvent that is immiscible with water. For example alkylating agent split unit 232 may comprise at least one liquid-liquid extraction columns. In another embodiment, the alkylating agent split is performed via azeotropic distillation, which employs an azeotropic agent. In these cases, the azeotropic agent may be selected from the group consisting of methyl isobutylketene, o-xylene, toluene, benzene, n-hexane,

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cyclohexane, p-xylene, and mixtures thereof. This listing is not exclusive and is not meant to limit the scope of the invention. In another embodiment, the alkylenating agent split is performed via a combination of distillation, e.g., standard distillation, and crystallization. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

[0109] In FIG. 2, alkylenating agent split unit 232 comprises first column 244 and second column 246. Alkylenating agent split unit 232 receives crude acrylic product stream in line 216 and separates same into at least one alkylenating agent stream, e.g., stream 248, and at least one purified product stream, e.g., stream 242. Alkylenating agent split unit 232 performs an alkylenating agent split, as discussed above.

[0110] In operation, as shown in FIG. 2, the crude product stream in line 216 is directed to first column 244. First column 244 separates the crude product stream a distillate in line 240 and a residue in line 242. The distillate may be refluxed and the residue may be boiled up as shown. Stream 240 comprises at least 1 wt% alkylenating agent. As such, stream 240 may be considered an alkylenating agent stream. The first column residue exits first column 244 in line 242 and comprises a significant portion of acrylate product. As such, stream 242 is an intermediate product stream. Exemplary compositional ranges for the distillate and residue of first column 244 are shown in Table 4. Components other than those listed in Table 4 may also be present in the residue and distillate.

TABLE 4
FIRST COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	0.1 to 20	1 to 10	1 to 5
Acetic Acid	25 to 65	35 to 55	40 to 50
Water	15 to 55	25 to 45	30 to 40
Alkylenating Agent	at least 1	1 to 75	10 to 20
Propionic Acid	< 10	0.001 to 5	0.001 to 1
<u>Residue</u>			
Acrylic Acid	at least 5	5 to 99	35 to 65
Acetic Acid	less than 95	5 to 90	20 to 60
Water	less than 25	0.1 to 10	0.5 to 7
Alkylenating Agent	< 1	< 0.5	< 0.1
Propionic Acid	< 10	0.01 to 5	0.01 to 1

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[0111] In one embodiment, the first distillate comprises smaller amounts of acetic acid, e.g., less than 25 wt%, less than 10 wt% , e.g., less than 5 wt% or less than 1 wt%. In one embodiment, the first residue comprises larger amounts of alkylating agent, e.g.,

[0112] In other embodiments, the intermediate acrylate product stream comprises higher amounts of alkylating agent, e.g., greater than 1 wt% greater than 5 wt% or greater than 10 wt%.

[0113] For convenience, the distillate and residue of the first column may also be referred to as the “first distillate” or “first residue.” The distillates or residues of the other columns may also be referred to with similar numeric modifiers (second, third, etc.) in order to distinguish them from one another, but such modifiers should not be construed as requiring any particular separation order.

[0114] In one embodiment, polymerization inhibitors and/or anti-foam agents may be employed in the separation zone, e.g., in the units of the separation zone. The inhibitors may be used to reduce the potential for fouling caused by polymerization of acrylates. The anti-foam agents may be used to reduce potential for foaming in the various streams of the separation zone. The polymerization inhibitors and/or the anti-foam agents may be used at one or more locations in the separation zone.

[0115] Returning to FIG. 2, at least a portion of stream 240 is directed to second column 246. Second column 246 separates the at least a portion of stream 240 into a distillate in line 248 and a residue in line 250. The distillate may be refluxed and the residue may be boiled up as shown. The distillate comprises at least 1 wt% alkylating agent. Stream 248, like stream 240, may be considered an alkylating agent stream. The second column residue exits second column 246 in line 250 and comprises a significant portion of acetic acid. At least a portion of line 250 may be returned to first column 244 for further separation. In one embodiment, at least a portion of line 250 is returned, either directly or indirectly, to reactor 206. Exemplary compositional ranges for the distillate and residue of second column 246 are shown in Table 5. Components other than those listed in Table 5 may also be present in the residue and distillate.

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TABLE 5
SECOND COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	0.01 to 10	0.05 to 5	0.1 to 0.5
Acetic Acid	10 to 50	20 to 40	25 to 35
Water	35 to 75	45 to 65	50 to 60
Alkylenating Agent	at least 1	1 to 75	10 to 20
Propionic Acid	0.01 to 10	0.01 to 5	0.01 to 0.05
<u>Residue</u>			
Acrylic Acid	0.1 to 25	0.05 to 15	1 to 10
Acetic Acid	40 to 80	50 to 70	55 to 65
Water	1 to 40	5 to 35	10 to 30
Alkylenating Agent	at least 1	1 to 75	10 to 20
Propionic Acid	< 10	0.001 to 5	0.001 to 1

[0116] In cases where any of the alkylenating agent split unit comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are operated may range from 1 kPa to 300 kPa, e.g., from 10 kPa to 100 kPa or from 40 kPa to 80 kPa. In preferred embodiments, the pressure at which the column(s) are operated is kept at a low level e.g., less than 100 kPa, less than 80 kPa, or less than 60 kPa. In terms of lower limits, the column(s) may be operated at a pressures of at least 1 kPa, e.g., at least 20 kPa or at least 40 kPa. Without being bound by theory, it is believed that alkylenating agents, e.g., formaldehyde, may not be sufficiently volatile at lower pressures. Thus, maintenance of the column pressures at these levels surprisingly and unexpectedly provides for efficient separation operations. In addition, it has surprisingly and unexpectedly been found that be maintaining a low pressure in the columns of alkylenating agent split unit 232 may inhibit and/or eliminate polymerization of the acrylate products, e.g., acrylic acid, which may contribute to fouling of the column(s).

[0117] In one embodiment, the alkylenating agent split is achieved via one or more liquid-liquid extraction units. Preferably, the one or more liquid-liquid extraction units employ one or more extraction agents. Multiple liquid-liquid extraction units may be employed to achieve the alkylenating agent split. Any suitable liquid-liquid extraction devices used for multiple equilibrium

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stage separations may be used. Also, other separation devices, e.g., traditional columns, may be employed in conjunction with the liquid-liquid extraction unit(s).

[0118] In one embodiment (not shown), the crude product stream is fed to a liquid-liquid extraction column where the crude product stream is contacted with an extraction agent, e.g., an organic solvent. The liquid-liquid extraction column extracts the acids, e.g., acrylic acid and acetic acid, from the crude product stream. An aqueous stage comprising water, alkylating agent, and some acetic acid exits the liquid-liquid extraction unit. Small amounts of acrylic acid may also be present in the aqueous stream. The aqueous phase may be further treated and/or recycled. An organic phase comprising acrylic acid, acetic acid, and the extraction agent also exits the liquid-liquid extraction unit. The organic phase may also comprise water and formaldehyde. The acrylic acid may be separated from the organic phase and collected as product. The acetic acid may be separated then recycled and/or used elsewhere. The solvent may be recovered and recycled to the liquid-liquid extraction unit.

[0119] The inventive process further comprises the step of separating the intermediate acrylate product stream to form a finished acrylate product stream and a first finished acetic acid stream. The finished acrylate product stream comprises acrylate product(s) and the first finished acetic acid stream comprises acetic acid. The separation of the acrylate products from the intermediate product stream to form the finished acrylate product may be referred to as the “acrylate product split.”

[0120] Returning to FIG. 2, purified product stream 242 exits alkylating agent split unit 232 and is directed to acrylate product split unit 234 for further separation, e.g., to further separate the acrylate products therefrom. Acrylate product split unit 234 may comprise any suitable separation device or combination of separation devices. For example, acrylate product split unit 234 may comprise at least one column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In other embodiments, acrylate product split unit 234 comprises a precipitation unit, e.g., a crystallizer and/or a chiller. Preferably, acrylate product split unit 234 comprises two standard distillation columns as shown in FIG. 2. In another embodiment, acrylate product split unit 234 comprises a liquid-liquid extraction unit. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

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[0121] In FIG. 2, acrylate product split unit 234 comprises third column 252 and fourth column 254. Acrylate product split unit 234 receives at least a portion of purified acrylic product stream in line 242 and separates same into finished acrylate product stream 256 and at least one acetic acid-containing stream. As such, acrylate product split unit 234 may yield the finished acrylate product.

[0122] As shown in FIG. 2, at least a portion of purified acrylic product stream in line 242 is directed to third column 252. Third column 252 separates the purified acrylic product stream to form third distillate, e.g., line 258, and third residue, which is the finished acrylate product stream, e.g., line 256. The distillate may be refluxed and the residue may be boiled up as shown.

[0123] Stream 258 comprises acetic acid and some acrylic acid. The third column residue exits third column 252 in line 256 and comprises a significant portion of acrylate product. As such, stream 256 is a finished product stream. Exemplary compositional ranges for the distillate and residue of third column 252 are shown in Table 6. Components other than those listed in Table 6 may also be present in the residue and distillate.

TABLE 6
THIRD COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	0.1 to 40	1 to 30	5 to 30
Acetic Acid	60 to 99	70 to 90	75 to 85
Water	0.1 to 25	0.1 to 10	1 to 5
Alkylating Agent	less than 1	0.001 to 1	0.1 to 1
Propionic Acid	< 10	0.001 to 5	0.001 to 1
<u>Residue</u>			
Acrylic Acid	at least 85	85 to 99.9	95 to 99.5
Acetic Acid	less than 15	0.1 to 10	0.1 to 5
Water	less than 1	less than 0.1	less than 0.01
Alkylating Agent	less than 1	0.001 to 1	0.1 to 1
Propionic Acid	0.1 to 10	0.1 to 5	0.5 to 3

[0124] Returning to FIG. 2, at least a portion of stream 258 is directed to fourth column 254. Fourth column 254 separates the at least a portion of stream 258 into a distillate in line 260 and a residue in line 262. The distillate may be refluxed and the residue may be boiled up as shown. The distillate comprises a major portion of acetic acid. In one embodiment, at least a portion of line 260 is returned, either directly or indirectly, to reactor 206. The fourth column residue exits fourth column 254 in line 262 and comprises acetic acid and some acrylic acid. At least a portion of line

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262 may be returned to third column 252 for further separation. In one embodiment, at least a portion of line 262 is returned, either directly or indirectly, to reactor 206. In another embodiment, at least a portion of the acetic acid-containing stream in either or both of lines 260 and 262 may be directed to an ethanol production system that utilizes the hydrogenation of acetic acid form the ethanol. In another embodiment, at least a portion of the acetic acid-containing stream in either or both of lines 260 and 262 may be directed to a vinyl acetate system that utilizes the reaction of ethylene, acetic acid, and oxygen form the vinyl acetate. Exemplary compositional ranges for the distillate and residue of fourth column 254 are shown in Table 7. Components other than those listed in Table 7 may also be present in the residue and distillate.

TABLE 7
FOURTH COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	0.01 to 10	0.05 to 5	0.1 to 1
Acetic Acid	50 to 99.9	70 to 99.5	80 to 99
Water	0.1 to 25	0.1 to 15	1 to 10
Alkylating Agent	less than 10	0.001 to 5	0.01 to 5
Propionic Acid	0.0001 to 10	0.001 to 5	0.001 to 0.05
<u>Residue</u>			
Acrylic Acid	5 to 50	15 to 40	20 to 35
Acetic Acid	50 to 95	60 to 80	65 to 75
Water	0.01 to 10	0.01 to 5	0.1 to 1
Alkylating Agent	less than 1	0.001 to 1	0.1 to 1
Propionic Acid	< 10	0.001 to 5	0.001 to 1

[0125] In cases where the acrylate product split unit comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are operated may range from 1 kPa to 300 kPa, e.g., from 10 kPa to 100 kPa or from 40 kPa to 80 kPa. In preferred embodiments, the pressure at which the column(s) are operated is kept at a low level e.g., less than 50 kPa, less than 27 kPa, or less than 20 kPa. In terms of lower limits, the column(s) may be operated at a pressures of at least 1 kPa, e.g., at least 3 kPa or at least 5 kPa. Without being bound by theory, it has surprisingly and unexpectedly been found that be maintaining a low pressure in the columns of acrylate product split unit 234 may inhibit and/or eliminate

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polymerization of the acrylate products, e.g., acrylic acid, which may contribute to fouling of the column(s).

[0126] It has also been found that, surprisingly and unexpectedly, maintaining the temperature of acrylic acid-containing streams fed to acrylate product split unit 234 at temperatures below 140°C, e.g., below 130°C or below 115°C, may inhibit and/or eliminate polymerization of acrylate products. In one embodiment, to maintain the liquid temperature at these temperatures, the pressure of the column(s) is maintained at or below the pressures mentioned above. In these cases, due to the lower pressures, the number of theoretical column trays is kept at a low level, e.g., less than 10, less than 8, less than 7, or less than 5. As such, it has surprisingly and unexpectedly been found that multiple columns having fewer trays inhibit and/or eliminate acrylate product polymerization. In contrast, a column having a higher amount of trays, e.g., more than 10 trays or more than 15 trays, would suffer from fouling due to the polymerization of the acrylate products. Thus, in a preferred embodiment, the acrylic acid split is performed in at least two, e.g., at least three, columns, each of which have less than 10 trays, e.g. less than 7 trays. These columns each may operate at the lower pressures discussed above.

[0127] The inventive process further comprises the step of separating an alkylenating agent stream to form a purified alkylenating stream and a purified acetic acid stream. The purified alkylenating agent stream comprises a significant portion of alkylenating agent, and the purified acetic acid stream comprises acetic acid and water. The separation of the alkylenating agent from the acetic acid may be referred to as the “acetic acid split.”

[0128] Returning to FIG. 2, alkylenating agent stream 248 exits alkylenating agent split unit 232 and is directed to acetic acid split unit 236 for further separation, e.g., to further separate the alkylenating agent and the acetic acid therefrom. Acetic acid split unit 236 may comprise any suitable separation device or combination of separation devices. For example, acetic acid split unit 236 may comprise at least one column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In other embodiments, acetic acid split unit 236 comprises a precipitation unit, e.g., a crystallizer and/or a chiller. Preferably, acetic acid split unit 236 comprises a standard distillation column as shown in FIG. 2. In another embodiment, acetic acid split unit 236 comprises a liquid-liquid extraction unit. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

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[0129] In FIG. 2, acetic acid split unit 236 comprises fifth column 264. Acetic acid split unit 236 receives at least a portion of alkylenating agent stream in line 248 and separates same into a fifth distillate comprising alkylenating agent in line 266, e.g., a purified alkylenating stream, and a fifth residue comprising acetic acid in line 268, e.g., a purified acetic acid stream. The distillate may be refluxed and the residue may be boiled up as shown. In one embodiment, at least a portion of line 266 and/or line 268 are returned, either directly or indirectly, to reactor 206. At least a portion of stream in line 268 may be further separated. In another embodiment, at least a portion of the acetic acid-containing stream in line 268 may be directed to an ethanol production system that utilizes the hydrogenation of acetic acid form the ethanol. In another embodiment, at least a portion of the acetic acid-containing stream in either or both of lines 260 and 262 may be directed to a vinyl acetate system that utilizes the reaction of ethylene, acetic acid, and oxygen form the vinyl acetate.

[0130] The stream in line 266 comprises alkylenating agent and water. The stream in line 268 comprises acetic acid and water. Exemplary compositional ranges for the distillate and residue of fifth column 264 are shown in Table 8. Components other than those listed in Table 8 may also be present in the residue and distillate.

TABLE 8
FIFTH COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	less than 1	0.001 to 5	0.001 to 1
Acetic Acid	less than 1	0.001 to 5	0.001 to 1
Water	40 to 80	50 to 70	55 to 65
Alkylenating Agent	20 to 60	30 to 50	35 to 45
Propionic Acid	less than 1	0.001 to 5	0.001 to 1
<u>Residue</u>			
Acrylic Acid	less than 1	0.01 to 5	0.1 to 1
Acetic Acid	25 to 65	35 to 55	40 to 50
Water	35 to 75	45 to 65	50 to 60
Alkylenating Agent	less than 1	0.01 to 5	0.1 to 1
Propionic Acid	less than 1	0.001 to 5	0.01 1

[0131] In cases where the acetic acid split unit comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are

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operated may range from 1 kPa to 500 kPa, e.g., from 25 kPa to 400 kPa or from 100 kPa to 300 kPa.

[0132] The inventive process further comprises the step of separating the purified acetic acid stream to form a second finished acetic acid stream and a water stream. The second finished acetic acid stream comprises a major portion of acetic acid, and the water stream comprises mostly water. The separation of the acetic from the water may be referred to as dehydration.

[0133] Returning to FIG. 2, fifth residue 268 exits acetic acid split unit 236 and is directed to drying unit 238 for further separation, e.g., to remove water from the acetic acid. Drying unit 238 may comprise any suitable separation device or combination of separation devices. For example, drying unit 238 may comprise at least one column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In other embodiments, drying unit 238 comprises a dryer and/or a molecular sieve unit. In a preferred embodiment, drying unit 238 comprises a liquid-liquid extraction unit. In one embodiment, drying unit 238 comprises a standard distillation column as shown in FIG. 2. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

[0134] In FIG. 2, drying unit 238 comprises sixth column 270. Drying unit 238 receives at least a portion of second finished acetic acid stream in line 268 and separates same into a sixth distillate comprising a major portion of water in line 272 and a sixth residue comprising acetic acid and small amounts of water in line 274. The distillate may be refluxed and the residue may be boiled up as shown. In one embodiment, at least a portion of line 274 is returned, either directly or indirectly, to reactor 206. In another embodiment, at least a portion of the acetic acid-containing stream in line 274 may be directed to an ethanol production system that utilizes the hydrogenation of acetic acid form the ethanol. In another embodiment, at least a portion of the acetic acid-containing stream in either or both of lines 260 and 262 may be directed to a vinyl acetate system that utilizes the reaction of ethylene, acetic acid, and oxygen form the vinyl acetate.

[0135] Exemplary compositional ranges for the distillate and residue of sixth column 270 are shown in Table 9. Components other than those listed in Table 9 may also be present in the residue and distillate.

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TABLE 9
SIXTH COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	less than 1	0.001 to 5	0.001 to 1
Acetic Acid	less than 1	0.01 to 5	0.01 to 1
Water	90 to 99.9	95 to 99.9	95 to 99.5
Alkylating Agent	less than 1	0.01 to 5	0.01 to 1
Propionic Acid	less than 1	0.001 to 5	0.001 to 1
<u>Residue</u>			
Acrylic Acid	less than 1	0.01 to 5	0.01 to 1
Acetic Acid	75 to 99.9	85 to 99.5	90 to 99.5
Water	25 to 65	35 to 55	40 to 50
Alkylating Agent	less than 1	less than 0.001	less than 0.0001
Propionic Acid	less than 1	0.01 5	0.02 1

[0136] In cases where the drying unit comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are operated may range from 1 kPa to 500 kPa, e.g., from 25 kPa to 400 kPa or from 100 kPa to 300 kPa. FIG. 2 also shows tank 276, which, collects at least one of the process streams prior to recycling same to reactor 206. Tank 276 is an optional feature. The various recycle streams that may, alternatively, be recycled directly to reactor 206 without being collected in tank 276.

[0137] FIG. 3 shows an overview of an alternative reaction/separation scheme in accordance with the present invention. Acrylate product system 300 comprises reaction zone 302 and separation zone 304. Reaction zone 302 comprises reactor 306, alkanoic acid feed, e.g., acetic acid feed, 308, alkylating agent feed, e.g., formaldehyde feed, 310, vaporizer 312, line 313 and line 314. Reaction zone 302 and the components thereof function in a manner similar to reaction zone 102 of FIG. 1.

[0138] Reaction zone 302 yields a crude acrylate product, which exits reaction zone 302 via line 316 and is directed to separation zone 304. Separation zone 304 comprises alkylating agent split unit 332, acrylate product split unit 334, drying unit 336, and methanol removal unit 338. Separation zone 304 may optionally comprise a light ends removal unit 322. For example, the light ends removal unit may comprise a condenser and/or a flasher. The light ends removal unit may be

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configured either upstream or downstream of alkylenating agent split unit 332. Depending on the configuration, the light ends removal unit removes light ends from the crude acrylate product, the alkylenating stream, and/or the intermediate acrylate product stream. In one embodiment, when the light ends are removed, the remaining liquid phase comprises the acrylic acid, acetic acid, alkylenating agent, and/or water.

[0139] Alkylenating agent split unit 332 may comprise any suitable separation device or combination of separation devices. For example, alkylenating agent split unit 332 may comprise a column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In other embodiments, alkylenating agent split unit 332 comprises a precipitation unit, e.g., a crystallizer and/or a chiller. Preferably, alkylenating agent split unit 332 comprises a single distillation column.

[0140] In another embodiment, the alkylenating agent split is performed by contacting the crude product stream with a solvent that is immiscible with water. For example, alkylenating agent split unit 332 may comprise at least one liquid-liquid extraction column. In another embodiment, the alkylenating agent split is performed via azeotropic distillation, which employs an azeotropic agent. In these cases, the azeotropic agent may be selected from the group consisting of methyl isobutylketene, o-xylene, toluene, benzene, n-hexane, cyclohexane, p-xylene, and mixtures thereof. This listing is not exclusive and is not meant to limit the scope of the invention. In another embodiment, the alkylenating agent split is performed via a combination of distillations, e.g., standard distillation, and crystallization. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

[0141] In FIG. 3, alkylenating agent split unit 332 comprises first column 344. The crude product stream in line 316 is directed to first column 344. First column 344 separates the crude product stream to form a distillate in line 340 and a residue in line 342. The distillate may be refluxed and the residue may be boiled up as shown. Stream 340 comprises at least 1 wt.% alkylenating agent. As such, stream 340 may be considered an alkylenating agent stream. The first column residue exits first column 344 in line 342 and comprises a significant portion of acrylate product. As such, stream 342 is an intermediate product stream. In some embodiments, at least a portion of stream 342 may be recycled to line 315. In one embodiment, at least a portion of stream 340 is directed to drying column 336.

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[0142] Exemplary compositional ranges for the distillate and residue of first column 344 are shown in Table 10. Components other than those listed in Table 10 may also be present in the residue and distillate.

TABLE 10
FIRST COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	less than 5	less than 3	0.05 to 1
Acetic Acid	less than 10	less than 5	0.5 to 3
Water	40 to 90	45 to 85	50 to 80
Alkylating Agent	at least 1	1 to 75	10 to 40
Propionic Acid	less than 10	less than 5	less than 1
Methanol	less than 5	less than 1	less than 0.5
<u>Residue</u>			
Acrylic Acid	10 to 80	15 to 65	20 to 50
Acetic Acid	40 to 80	45 to 70	50 to 65
Water	1 to 40	1 to 20	1 to 10
Alkylating Agent	less than 50	0.1 to 50	0.1 to 10
Propionic Acid	less than 10	less than 5	less than 1

[0143] In one embodiment, the first distillate comprises smaller amounts of acetic acid, e.g., 25 wt.%, less than 10 wt.%, less than 5 wt.% or less than 1 wt.%. In one embodiment, the first residue comprises larger amounts of alkylating agent.

[0144] In some embodiments, the intermediate acrylate product stream comprises higher amounts of alkylating agent, e.g., greater than 1 wt.% greater than 5 wt.% or greater than 10 wt.%.

[0145] In one embodiment, polymerization inhibitors and/or anti-foam agents may be employed in the separation zone, e.g., in the units of the separation zone. The inhibitors may be used to reduce the potential for fouling caused by polymerization of acrylates. The anti-foam agents may be used to reduce potential for foaming in the various streams of the separation zone. The polymerization inhibitors and/or the anti-foam agents may be used at one or more locations in the separation zone.

[0146] In cases where any of alkylating agent split unit 332 comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are operated may range from 1 kPa to 300 kPa, e.g., from 10 kPa to 100 kPa or from 40

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kPa to 80 kPa. In preferred embodiments, the pressure at which the column(s) are operated is kept at a low level e.g., less than 100 kPa, less than 80 kPa, or less than 60 kPa. In terms of lower limits, the column(s) may be operated at a pressures of at least 1 kPa, e.g., at least 20 kPa or at least 40 kPa. Without being bound by theory, it is believed that alkylating agents, e.g., formaldehyde, may not be sufficiently volatile at lower pressures. Thus, maintenance of the column pressures at these levels surprisingly and unexpectedly provides for efficient separation operations. In addition, it has surprisingly and unexpectedly been found that by maintaining a low pressure in the columns of alkylating agent split unit 332 may inhibit and/or eliminate polymerization of the acrylate products, e.g., acrylic acid, which may contribute to fouling of the column(s).

[0147] In one embodiment, the alkylating agent split is achieved via one or more liquid-liquid extraction units. Preferably, the one or more liquid-liquid extraction units employ one or more extraction agents. Multiple liquid-liquid extraction units may be employed to achieve the alkylating agent split. Any suitable liquid-liquid extraction devices used for multiple equilibrium stage separations may be used. Also, other separation devices, e.g., traditional columns, may be employed in conjunction with the liquid-liquid extraction unit(s).

[0148] In one embodiment (not shown), the crude product stream is fed to a liquid-liquid extraction column where the crude product stream is contacted with an extraction agent, e.g., an organic solvent. The liquid-liquid extraction column extracts the acids, e.g., acrylic acid and acetic acid, from the crude product stream. An aqueous phase comprising water, alkylating agent, and some acetic acid exits the liquid-liquid extraction unit. Small amounts of acrylic acid may also be present in the aqueous stream. The aqueous phase may be further treated and/or recycled. An organic phase comprising acrylic acid, acetic acid, and the extraction agent also exits the liquid-liquid extraction unit. The organic phase may also comprise water and formaldehyde. The acrylic acid may be separated from the organic phase and collected as product. The acetic acid may be separated then recycled and/or used elsewhere. The solvent may be recovered and recycled to the liquid-liquid extraction unit.

[0149] The inventive process further comprises the step of separating the intermediate acrylate product stream to form a finished acrylate product stream and a first finished acetic acid stream. The finished acrylate product stream comprises acrylate product(s) and the first finished acetic acid

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stream comprises acetic acid. The separation of the acrylate products from the intermediate product stream to form the finished acrylate product may be referred to as the “acrylate product split.”

[0150] Returning to FIG. 3, purified product stream 342 exits alkylating agent split unit 332 and is directed to acrylate product split unit 334 for further separation, e.g., to further separate the acrylate products therefrom. Acrylate product split unit 334 may comprise any suitable separation device or combination of separation devices. For example, acrylate product split unit 334 may comprise at least one column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In other embodiments, acrylate product split unit 334 comprises a precipitation unit, e.g., a crystallizer and/or a chiller. Preferably, acrylate product split unit 334 comprises two standard distillation columns as shown in FIG. 3. In another embodiment, acrylate product split unit 334 comprises a liquid-liquid extraction unit. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

[0151] In FIG. 3, acrylate product split unit 334 comprises second column 352 and third column 354. Acrylate product split unit 334 receives at least a portion of purified acrylic product stream in line 342 and separates same into finished acrylate product stream 356 and at least one acetic acid-containing stream. As such, acrylate product split unit 334 may yield the finished acrylate product.

[0152] As shown in FIG. 3, at least a portion of purified acrylic product stream in line 342 is directed to second column 352. Second column 352 separates the purified acrylic product stream to form second distillate, e.g., line 358, and second residue, which is the finished acrylate product stream, e.g., line 356. The distillate may be refluxed and the residue may be boiled up as shown. In some embodiments, at least a portion of residue 356 and/or distillate 358 may be recycled to line 315.

[0153] Stream 358 comprises acetic acid and some acrylic acid. The second column residue exits second column 352 in line 356 and comprises a significant portion of acrylate product. As such, stream 356 is a finished product stream. Exemplary compositional ranges for the distillate and residue of second column 352 are shown in Table 11. Components other than those listed in Table 11 may also be present in the residue and distillate.

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TABLE 11
SECOND COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	0.1 to 40	1 to 30	5 to 30
Acetic Acid	60 to 99	70 to 90	75 to 85
Water	0.1 to 25	0.1 to 10	1 to 5
Alkylenating Agent	0.1 to 10	0.5 to 15	1 to 5
Propionic Acid	less than 10	0.001 to 5	0.001 to 1
<u>Residue</u>			
Acrylic Acid	at least 85	85 to 99.9	95 to 99.5
Acetic Acid	less than 15	0.1 to 10	0.1 to 5
Water	less than 1	less than 0.1	less than 0.01
Alkylenating Agent	less than 1	less than 0.1	less than 0.01
Propionic Acid	less than 1	less than 0.1	less than 0.01

[0154] Returning to FIG. 3, at least a portion of stream 358 is directed to third column 354.

Third column 354 separates the at least a portion of stream 358 into a distillate in line 360 and a residue in line 362. The distillate may be refluxed and the residue may be boiled up as shown. The distillate comprises a major portion of acetic acid. In one embodiment, at least a portion of line 360 is returned, either directly or indirectly, to reactor 306. The third column residue exits third column 354 in line 362 and comprises acetic acid and some acrylic acid. At least a portion of line 362 may be returned to second column 352 for further separation. In one embodiment, at least a portion of line 362 is returned, either directly or indirectly, to reactor 306. In another embodiment, at least a portion of the acetic acid-containing stream in either or both of lines 360 and 362 may be directed to an ethanol production system that utilizes the hydrogenation of acetic acid to form the ethanol. In another embodiment, at least a portion of the acetic acid-containing stream in either or both of lines 360 and 362 may be directed to a vinyl acetate system that utilizes the reaction of ethylene, acetic acid, and oxygen form the vinyl acetate. In some embodiments, at least a portion of the acetic acid-containing stream in either or both of lines 360 and 362 may be recycled to line 315. In a preferred embodiment, at least a portion of line 360 is recycled to line 315. Exemplary compositional ranges for the distillate and residue of third column 354 are shown in Table 12. Components other than those listed in Table 12 may also be present in the residue and distillate.

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TABLE 12
THIRD COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	0.01 to 10	0.05 to 5	0.1 to 1
Acetic Acid	50 to 99.9	70 to 99.5	80 to 99
Water	0.1 to 25	0.1 to 15	1 to 10
Alkylenating Agent	0.1 to 25	0.1 to 15	1 to 10
Propionic Acid	less than 1	less than 0.1	less than 0.01
<u>Residue</u>			
Acrylic Acid	5 to 50	15 to 40	20 to 35
Acetic Acid	50 to 95	60 to 80	65 to 75
Water	0.01 to 10	0.01 to 5	0.1 to 1
Alkylenating Agent	less than 1	0.001 to 1	0.01 to 1
Propionic Acid	less than 1	less than 0.1	less than 0.01

[0155] In cases where the acrylate product split unit comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are operated may range from 1 kPa to 300 kPa, e.g., from 10 kPa to 100 kPa or from 40 kPa to 80 kPa. In preferred embodiments, the pressure at which the column(s) are operated is kept at a low level e.g., less than 50 kPa, less than 27 kPa, or less than 20 kPa. In terms of lower limits, the column(s) may be operated at a pressures of at least 1 kPa, e.g., at least 3 kPa or at least 5 kPa. Without being bound by theory, it has surprisingly and unexpectedly been found that be maintaining a low pressure in the columns of acrylate product split unit 334 may inhibit and/or eliminate polymerization of the acrylate products, e.g., acrylic acid, which may contribute to fouling of the column(s).

[0156] It has also been found that, surprisingly and unexpectedly, maintaining the temperature of acrylic acid-containing streams fed to acrylate product split unit 334 at temperatures below 140°C, e.g., below 130°C or below 115°C, may inhibit and/or eliminate polymerization of acrylate products. In one embodiment, to maintain the liquid temperature at these temperatures, the pressure of the column(s) is maintained at or below the pressures mentioned above. In these cases, due to the lower pressures, the number of theoretical column trays is kept at a low level, e.g., less than 10, less than 8, less than 7, or less than 5. As such, it has surprisingly and unexpectedly been found that multiple

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columns having fewer trays inhibit and/or eliminate acrylate product polymerization. In contrast, a column having a higher amount of trays, e.g., more than 10 trays or more than 15 trays, would suffer from fouling due to the polymerization of the acrylate products. Thus, in a preferred embodiment, the acrylic acid split is performed in at least two, e.g., at least three, columns, each of which have less than 10 trays, e.g. less than 7 trays. These columns each may operate at the lower pressures discussed above.

[0157] Returning to FIG. 3, alkylating agent stream 340 exits alkylating agent split unit 332 and is directed to drying unit 336 for further separation, e.g., to further separate the water therefrom. The separation of the formaldehyde from the water may be referred to as dehydration. Drying unit 336 may comprise any suitable separation device or combination of separation devices. For example, drying unit 338 may comprise at least one column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In other embodiments, drying unit 336 comprises a dryer and/or a molecular sieve unit. In a preferred embodiment, drying unit 336 comprises a liquid-liquid extraction unit. In one embodiment, drying unit 336 comprises a standard distillation column as shown in FIG. 3. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

[0158] In FIG. 3, drying unit 336 comprises fourth column 370. Drying unit 336 receives at least a portion of alkylating agent stream in line 340 and separates same into a fourth distillate comprising water, formaldehyde, and methanol in line 372 and a fourth residue comprising mostly water in line 374. The distillate may be refluxed and the residue may be boiled up as shown. In some preferred embodiments, at least a portion of fourth residue 374 is recycled to line 315. In one embodiment, at least a portion of line 372 is returned, either directly or indirectly, to reactor 306. Fourth column 370 may also receive water from the vaporizer in line 313. Line 313 may also comprise formaldehyde and methanol.

[0159] Exemplary compositional ranges for the distillate and residue of fourth column 370 are shown in Table 13. Components other than those listed in Table 13 may also be present in the residue and distillate.

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TABLE 13
FOURTH COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	less than 1	less than 0.1	less than 0.01
Acetic Acid	less than 2	0.01 to 1	0.01 to 1
Water	20 to 90	30 to 80	40 to 70
Alkylenating Agent	10 to 70	20 to 60	30 to 50
Methanol	0.01 to 15	0.1 to 10	1 to 5
<u>Residue</u>			
Acrylic Acid	less than 1	0.001 to 1	0.01 to 1
Acetic Acid	less than 15	0.1 to 10	0.1 to 5
Water	at least 85	85 to 99.9	95 to 99.5
Alkylenating Agent	less than 1	0.001 to 1	0.1 to 1
Propionic Acid	less than 1	less than 0.1	less than 0.01

[0160] In cases where the drying unit comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are operated may range from 1 kPa to 500 kPa, e.g., from 25 kPa to 400 kPa or from 100 kPa to 300 kPa.

[0161] Returning to FIG. 3, alkylenating agent stream 372 exits drying unit 336 and is directed to methanol removal unit 338 for further separation, e.g., to further separate the methanol therefrom. Methanol removal unit 338 may comprise any suitable separation device or combination of separation devices. For example, methanol removal unit 338 may comprise at least one column, e.g., a standard distillation column, an extractive distillation column and/or an azeotropic distillation column. In one embodiment, methanol removal unit 338 comprises a liquid-liquid extraction unit. In a preferred embodiment, methanol removal unit 338 comprises a standard distillation column as shown in FIG. 3. Of course, other suitable separation devices may be employed either alone or in combination with the devices mentioned herein.

[0162] In FIG. 3, methanol removal unit 338 comprises fifth column 380. Methanol removal unit 338 receives at least a portion of line 372 and separates same into a fifth distillate comprising methanol and water in line 384 and a fifth residue comprising water and formaldehyde in line 382. The distillate may be refluxed and the residue may be boiled up (not shown). In one embodiment, at

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least a portion of line 382 is returned, either directly or indirectly, to reactor 306. Fifth distillate 384 may be used to form formaldehyde.

[0163] Exemplary compositional ranges for the distillate and residue of fifth column 380 are shown in Table 14. Components other than those listed in Table 14 may also be present in the residue and distillate.

TABLE 14			
FIFTH COLUMN			
	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Acrylic Acid	less than 1	less than 0.1	less than 0.01
Acetic Acid	less than 1	less than 0.1	less than 0.01
Water	20 to 60	30 to 50	35 to 45
Alkylenating Agent	0.1 to 25	0.5 to 20	1 to 15
Methanol	20 to 70	30 to 60	40 to 50
<u>Residue</u>			
Acrylic Acid	less than 1	less than 0.1	less than 0.01
Acetic Acid	less than 15	0.1 to 10	0.1 to 5
Water	40 to 80	50 to 70	55 to 65
Alkylenating Agent	20 to 60	30 to 50	35 to 45
Methanol	less than 15	0.1 to 10	0.1 to 5

[0164] In cases where the methanol removal unit comprises at least one column, the column(s) may be operated at suitable temperatures and pressures. In one embodiment, the temperature of the residue exiting the column(s) ranges from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting the column(s) preferably ranges from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. The pressure at which the column(s) are operated may range from 1 kPa to 500 kPa, e.g., from 25 kPa to 400 kPa or from 100 kPa to 300 kPa.

EXAMPLES

Example 1

[0165] A liquid feed comprising 52.6 wt.% acetic acid, 29.9 wt.% water and 17.5 wt.% formaldehyde was fed to a reactor at 643.1 hr⁻¹ GHSV. The reactor was loaded with 13 mL of a V₂Ti₄ catalyst. FIG. 4 shows the amount of acetic acid and the amount of acrylate product leaving the reactor as a function of time on stream (TOS) before catalyst regeneration.

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Example 2

[0166] The same conditions were used as in Example 1, except that at approximately 12 hours TOS, a regenerating stream comprising 3 wt.% oxygen was fed to the reactor to regenerate the catalyst. The regeneration continued for 36 hours. At 48 hours TOS, the liquid feed was restored to the reactor. FIG. 5 shows the amount of acetic acid and the amount of acrylate product leaving the reactor as a function of time on stream (TOS) after catalyst regeneration. As shown by the difference in catalyst activity from FIG. 1 to FIG. 2, the regenerated catalyst regains activity to the level of the fresh catalyst.

[0167] While the invention has been described in detail, modifications within the spirit and scope of the invention will be readily apparent to those of skill in the art. In view of the foregoing discussion, relevant knowledge in the art and references discussed above in connection with the Background and Detailed Description, the disclosures of which are all incorporated herein by reference. In addition, it should be understood that aspects of the invention and portions of various embodiments and various features recited below and/or in the appended claims may be combined or interchanged either in whole or in part. In the foregoing descriptions of the various embodiments, those embodiments which refer to another embodiment may be appropriately combined with other embodiments as will be appreciated by one of skill in the art. Furthermore, those of ordinary skill in the art will appreciate that the foregoing description is by way of example only, and is not intended to limit the invention.

We claim:

1. A process for producing an acrylate product, the process comprising the steps of:
 - (a) contacting an alkanoic acid and an alkylenating agent in a reactor over an initial catalyst under conditions effective to form:
 - i) a crude acrylate product stream comprising acrylate product and residual alkylenating agent and
 - ii) used catalyst;
 - (b) contacting the used catalyst with a regenerating stream to form a regenerated catalyst;
 - (c) separating at least a portion of the crude acrylate product stream to form an alkylenating agent stream comprising at least 1 wt% alkylenating agent and an intermediate product stream comprising acrylate product.
2. The process of claim 1, wherein the regenerating stream comprises oxygen or hydrogen
3. The process of claim 2, wherein the regenerating stream comprises at least 1 wt% oxygen.
4. The process of any of the preceding claims, wherein the initial catalyst has a deactivation point and wherein step (b) is performed at the deactivation point.
5. The process of claim 4, wherein the deactivation point is a point wherein the conversion of alkanoic acid is less than 30%, the selectivity of alkanoic acid to acrylate product is less than 85%, and the space time yield is less than 300 g/L/hr.
6. The process of any of the preceding claims, further comprising the step of:
 - (d) contacting an alkanoic acid and an alkylenating agent over the regenerated catalyst under conditions effective to form additional acrylate product.
7. The process of claim 6, wherein steps (a), (b), and (d) are conducted in a swinging-bed reactor, preferably comprising at least two reactors.

8. The process of any of the preceding claims, wherein overall acetic acid conversion is at least 30%.
9. The process of any of the preceding claims, wherein the crude product stream comprises at least 0.5 wt% alkylating agent.
10. The process of any of the preceding claims, wherein the alkylating agent stream comprises at least 5 wt% alkylating agent.
11. The process of any of the preceding claims, wherein the intermediate acrylate product stream comprises at least 5% wt% acrylate product.
12. The process of any of the preceding claims, wherein the intermediate acrylate product stream further comprises less than 25 wt% water and less than 95 wt% acetic acid.
13. The process of any of the preceding claims, further comprising the step of:
(e) separating the intermediate acrylate product stream to form a finished acrylate product stream comprising acrylate product and a finished acetic acid stream comprising acetic acid.
14. The process of any of the preceding claims, wherein the catalyst comprises vanadium, titanium, bismuth, tungsten, and mixtures thereof.
15. The process of any of the preceding claims, wherein the reactor contains less than 10 wt.% carbon monoxide and carbon dioxide after step (b).

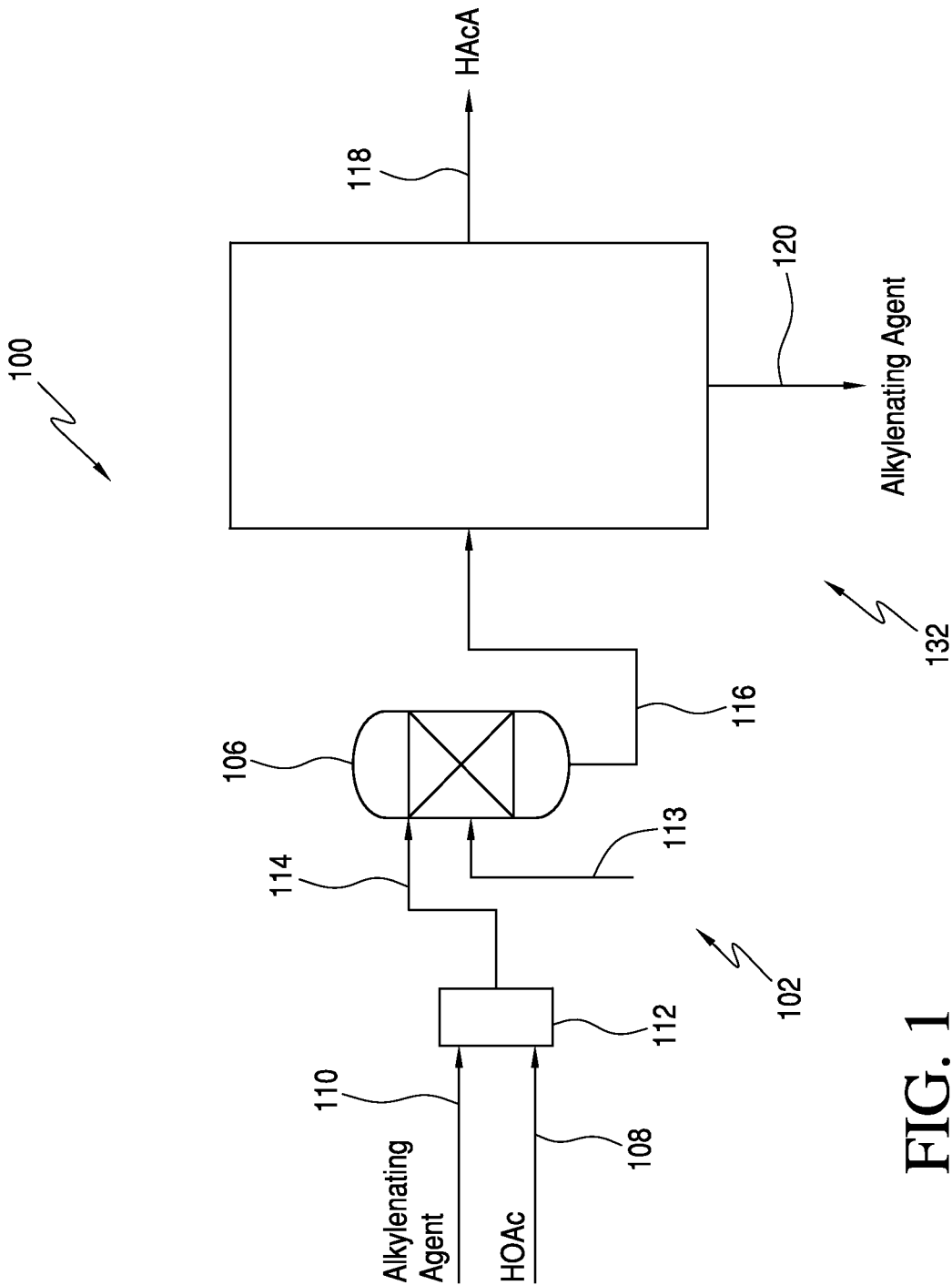


FIG. 1

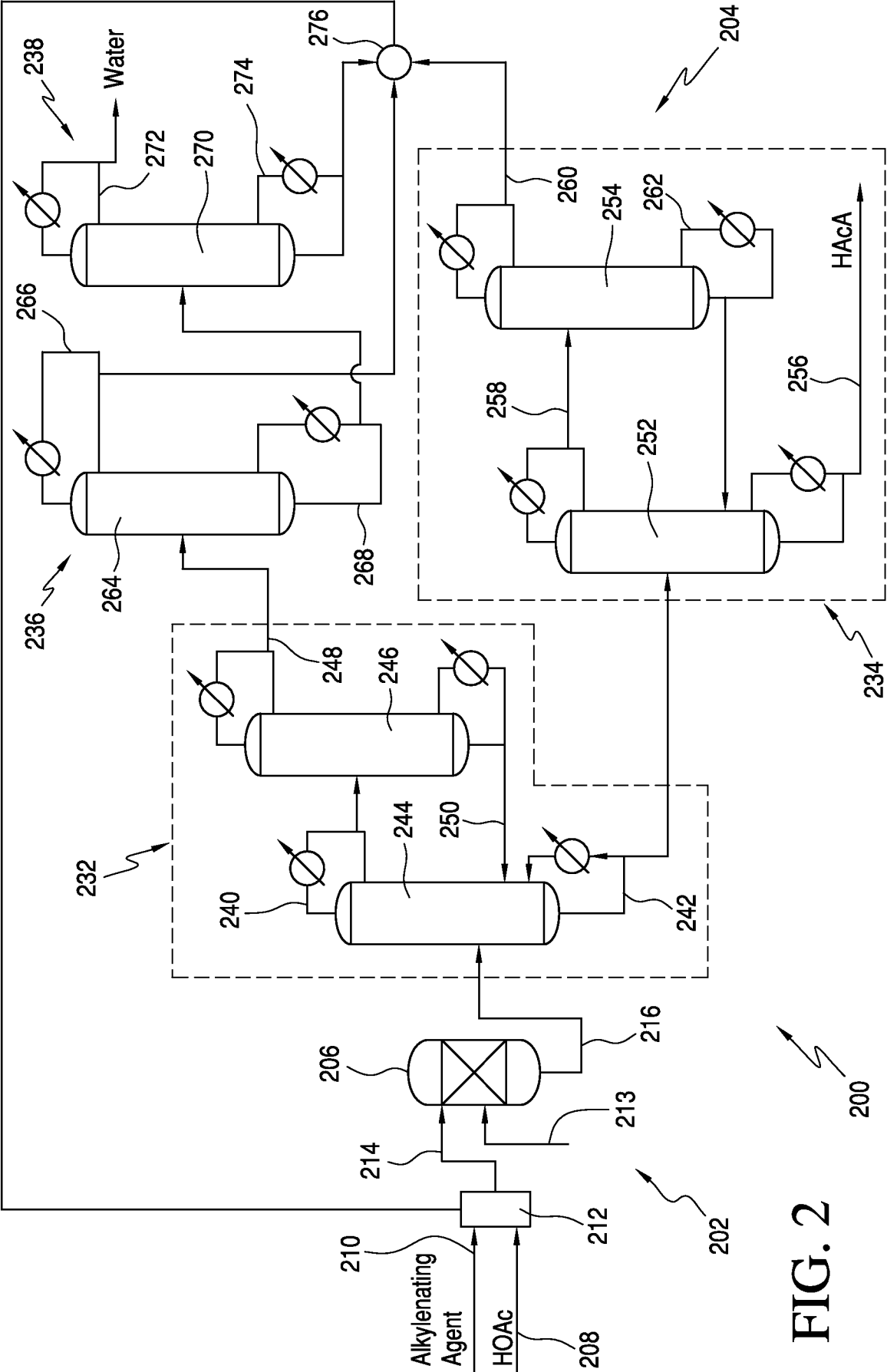


FIG. 2

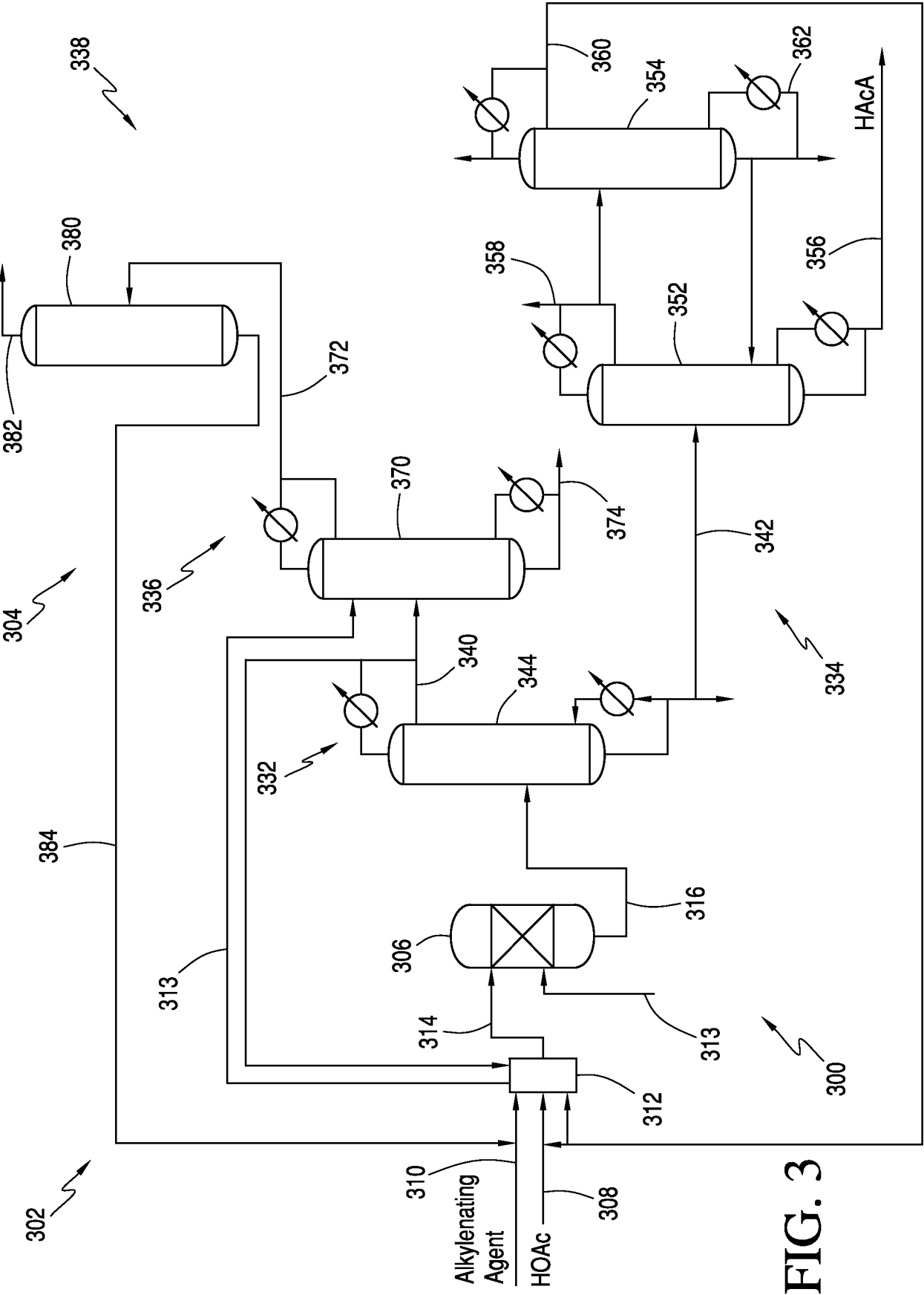


FIG. 3

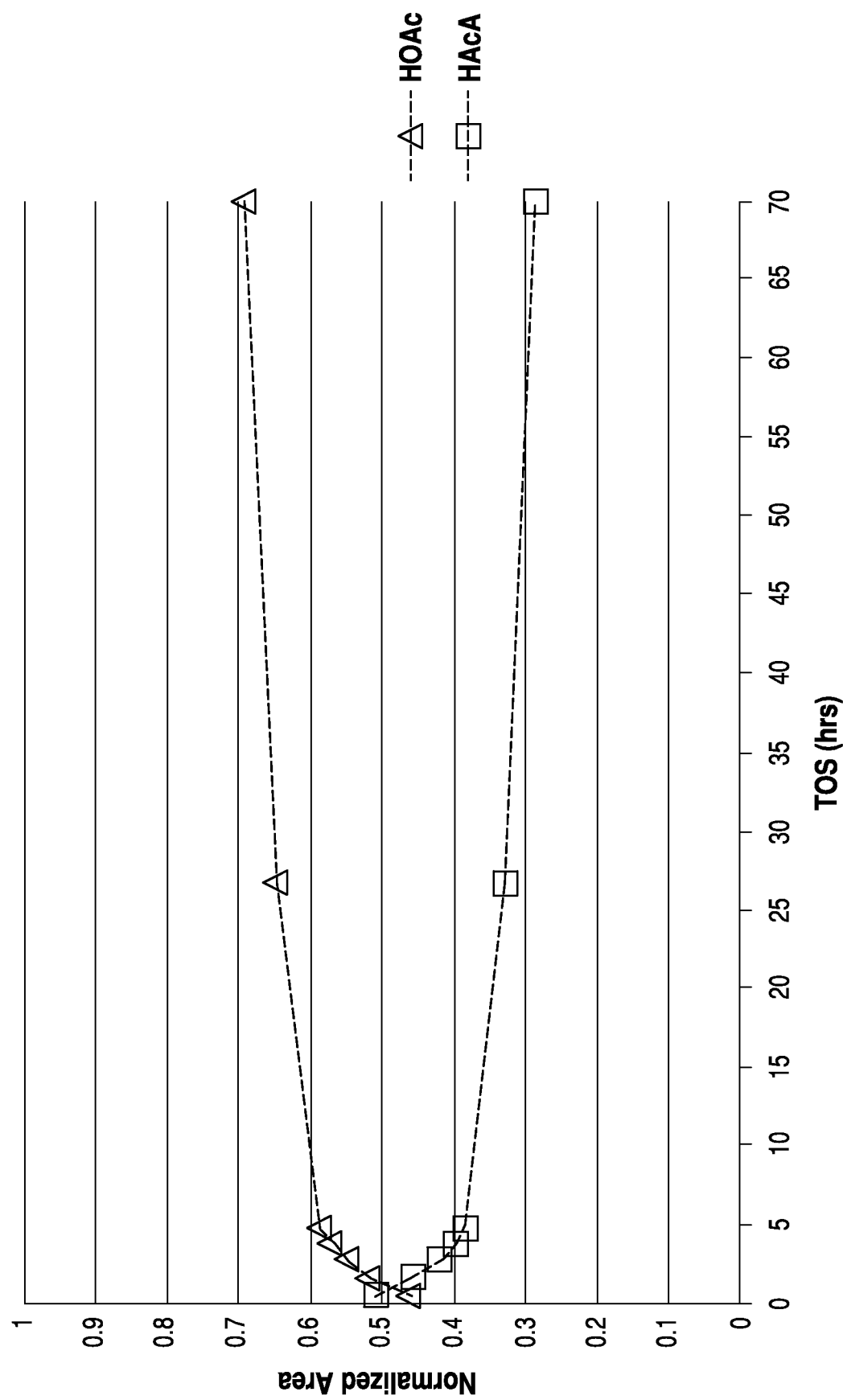


FIG. 4
Typical catalyst deactivation

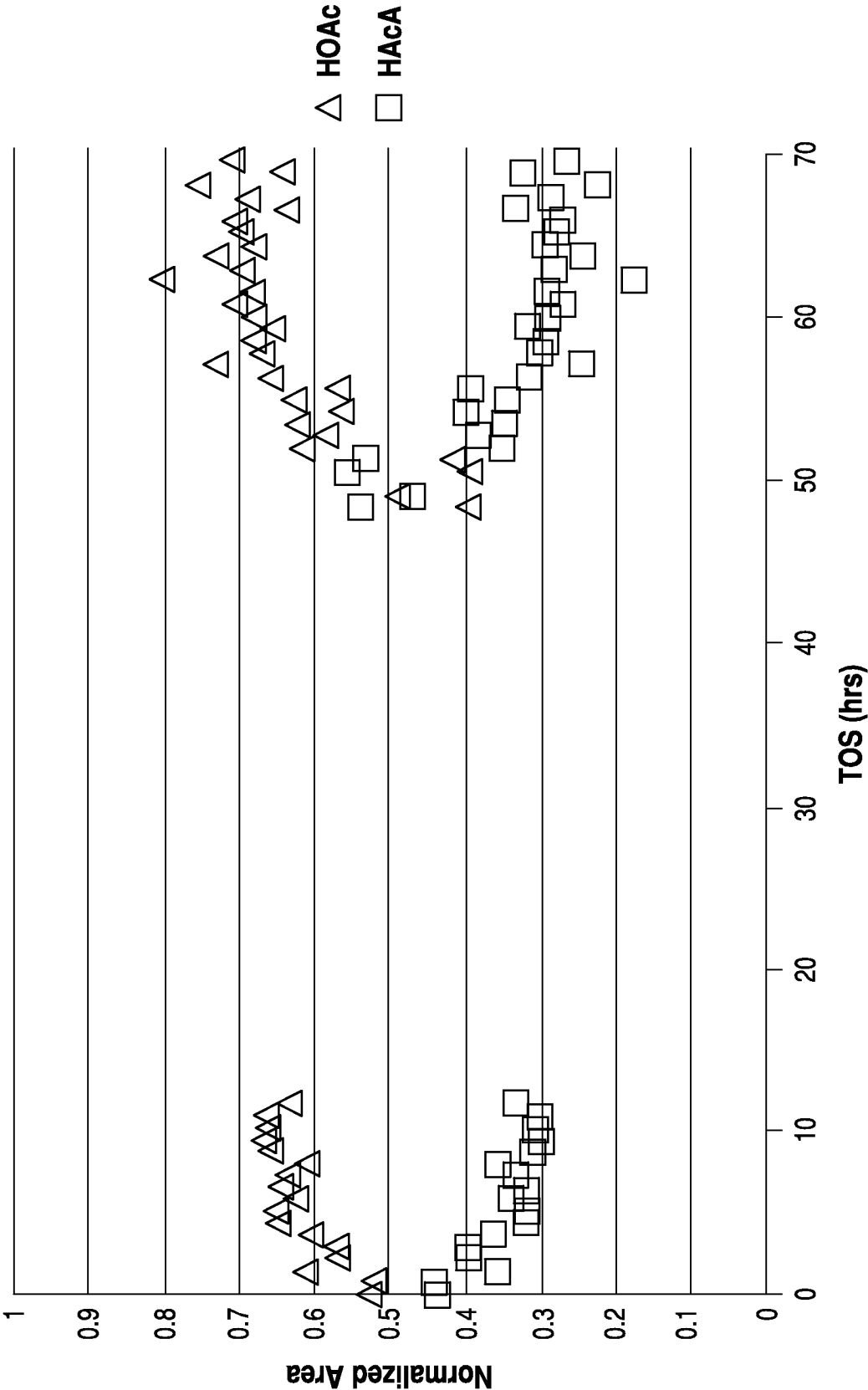


FIG. 5
Regaining of catalyst activity after O2 regeneration

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2013/067491

A. CLASSIFICATION OF SUBJECT MATTER
 INV. C07C51/353
 ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 C07C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 942 258 A (SMITH THOMAS G [US]) 17 July 1990 (1990-07-17) column 1, line 10 - line 35; claims column 5, line 30 - line 45 column 7, line 3 - line 43 -----	1-15
X	US 4 599 144 A (BALEIKO MARC O [US] ET AL) 8 July 1986 (1986-07-08) column 9, line 21 - line 59; claims; examples -----	1



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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