2-26-2019

Method of Increasing Mass Transfer Rate of Acid Gas Scrubbing Solvents

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Recommended Citation
Remias, Joseph E.; Lippert, Cameron A.; and Liu, Kunlei, "Method of Increasing Mass Transfer Rate of Acid Gas Scrubbing Solvents" (2019). Center for Applied Energy Research Faculty Patents. 53.
https://uknowledge.uky.edu/caer_patents/53

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A method of increasing the overall mass transfer rate of acid gas scrubbing solids is disclosed. Various catalyst compounds for that purpose are also disclosed.

12 Claims, 6 Drawing Sheets
FIG. 1
FIG. 2
FIG. 3

Removal Rate (mol/h/kg) vs. Carbon Loading (mol C/mol N)

- 30% MEA 40C
- 30% MEA C1P 40C
- 30% MEA C1I 40C
- 30% MEA C3P 40C
- 30% MEA C3I 40C
FIG. 4
FIG. 6
METHOD OF INCREASING MASS TRANSFER RATE OF ACID GAS SCRUBBING SOLVENTS

This application is a division of U.S. patent application Ser. No. 13/853,292 filed 29 Mar. 2013, now U.S. Pat. No. 9,409,125.

TECHNICAL FIELD

The present invention relates generally to various methods of increasing the overall mass transfer rate of acid gas scrubbing solvents utilizing various catalyst compounds.

BACKGROUND

The cleanup of acid gases or sour gas, such as CO₂ in particular, from natural gas and in oil refining has been an extensively practiced technology. The industrial removal of CO₂ from natural gas dates back to the 1930’s. In the 21st century, due to the potential impact of anthropogenic CO₂ emissions on the climate, post-combustion CO₂ capture has gained tremendous attention. While several technologies exist for the removal of acid gases one of the most commonly employed practices is the use of aqueous amines. Of these amines, tertiary amines are often used for natural gas applications due to their low energy of regeneration. For post-combustion CO₂ capture applications primary and secondary amines tend to be in part favored by their faster rate at the low CO₂ driving force condition. Regardless of the application, the mass transfer rate in the absorber column dictates the size of the column (capital cost) used and, consequently, has a substantial impact on the overall process cost. An overall process depicting a thermal swing process is presented in FIG. 1. An aqueous amine solution is circulated between the absorber 10 and stripper 12. The gas, containing CO₂, enters the bottom of the absorber where it contacts the aqueous amine absorbent removing it from the gas stream. The liquid solution, CO₂ rich amine solution, is then passed through a heat exchanger 14 to improve efficiency before being heated to a higher temperature in the stripper 12. The stripper 12 removes the CO₂ as a gas from the amine solution to produce a lean, or CO₂ deficient solution. The lean solution is returned to the absorber 10 by way of the heat exchanger 14 to repeat the process.

In order to minimize system capital (absorber cost) it is important to maximize the overall mass transfer rate for the scrubber system as there is a direct correlation between the two. This invention relates to methods for this purpose as well as to catalyst compounds useful in those methods.

SUMMARY

A method is provided for increasing the overall mass transfer rate of acid gas scrubbing solvents. The method comprises adding a catalyst compound to a fluid stream including an acid gas and an acid gas scrubbing solvent wherein that catalyst compound has a chemical formula:

where:
(a) M is any group VII B through XII B element;
(b) E is any combination of N, O, S having a net 2⁻ charge per individual ligand;
(c) R₁ =-H, -COOH, -[OCH₂CH₂]ₙ⁻, OR₉, CH₃, amine, amide, phosphate, -OH, -R₅OH, -[SO₃]⁻;
(d) R₃ =-H, -COOH, -[OCH₂CH₂]ₙ⁻, OR₉, amine, amide, phosphate, -OH, -R₅OH, -[SO₃]⁻, -(CH₂)ₙ Q⁺ [A⁻];
(e) R₅ =C₁-C₅ alkyl; (f) A=monovalent anion: Cl, Br, I, F, PF₆, BF₄, acetate, trifluoroacetate, ClO₄, NO₃;
(g) Q=monovalent cation: PX₃ where X=alkyl, cyclic alkyl, aryl, O-alkyl, O-aryl, N(R₆)₃ where R₆ =alkyl, cyclic alkyl, N-heterocyclic ring, imidazole;

(h)

where Y =-H, -COOH, -R₇OOH (R₇ =alkyl ranging from 2-10 carbons);
-OCH₂CH₂CH₂ₙOR₉; -OH; -SO₃; -NO₃; amine, amide, or
where $Z_1$ = H, any alkyl, -COOH, $-R_8$OOH ($R_8$=alkyl ranging from 2-10 carbons), -[OCH$_2$CH$_2$]$_n$-OR$_9$; OH; SO$_3$; NO$_2$; amine, amide; and
(i) where $n$=1 to 10; and
(j) $R_9$=H or alkyl.
In one possible embodiment the catalyst compound has a chemical formula:

In another possible embodiment the catalyst compound has a chemical formula:

where $R$=any alkyl
$M$=Co, Zn.
In another possible embodiment the catalyst compound has a chemical formula:

where $M$=Co, Zn.
In another possible embodiment the catalyst compound has a chemical formula:

where $M$=Co, Zn.
In another possible embodiment the catalyst compound has a chemical formula:

where $M$=Co, Zn.
In still another possible embodiment the catalyst compound has a chemical formula:

where $M$=Co, Zn.
In still another possible embodiment the catalyst compound has a chemical formula:
In any of the embodiments the acid gas scrubbing solvent includes an amine or a mixture of amines. In one possible embodiment the acid gas scrubbing solvent includes a mixture of (a) a promoter amine and (b) a tertiary amine.

In one possible embodiment the acid gas scrubbing solvent includes chemical compounds selected from a group including but not limited to, monoethanolamine (MEA), 1-amino-2-propanol (1A2P), 3-amino-1-propanol, 2-amino-1-propanol, 2-amino-1-butanol, 1-amino-2-butanol, 3-amino-2-butanol, 2-(methylamino)ethanol (MAE), 2-(ethylamino)ethanol, morpholine, piperazine (PZ), 1-methylpiperazine (NMP), 2-methylpiperazine, hydroxypiperidine, 2-piperidineethanol, N,N-ethylpiperazine (AEPI), aminopropylylmorpholine, 4-aminopiperidine, 2-amino-2-methyl-1-propanol (AMP), diethanolamine (DEA), diisopropanolamine (DIPA), glycine, alanine, β-alanine, sarcosine, ethylene diamine (EDA), 1,3-propanediol, 1,5-pentanediol, 1,6-hexanediol, methyl diethanolamine (MDEA), triethanolamine (TEA), dimethylethanol amine (DMEA), N,N,N′,N′-tetramethyl-1,8-naphthalenedi amine, diethylmonoethanol amine, dipropylmonoethanol amine, 1,4-dimethylpiperazine, N,N,N′,N′-tetramethyl-1,6-hexanedi amine, N,N,N′,N′,N′-pentamethylethylendiamine, N,N,N′,N′- tetramethylethylendiamine, N,N,N′,N′-tetramethylpropene-1,3-diamine, N,N,N′, N′-tetramethylethylbutane-1,4-diamine, N,N,N′,N′-tetr amethylpiperazine, alkali carbonate, and mixtures thereof.

Further the catalyst compound is provided at a concentration of between about 0.05 mM and about 100 mM. Various catalyst compounds are also claimed.

**BRIEF DESCRIPTION OF THE DRAWING**

The accompanying drawings incorporated herein and forming a part of the specification, illustrate several aspects of the present method and together with the description serve to explain certain principles thereof. In the drawings:

**FIG. 1** is a schematical illustration of a process for removing acid gas from a fluid stream utilizing solvent and thermal swing regeneration.

**FIG. 2** is a schematical illustration of a simple CO₂ bubbling apparatus used for catalyst testing.

**FIG. 3** is a graphical illustration of removal rate versus carbon loading for various catalysts used with 30 wt% MEA at 40°C.

**FIG. 4** is a graphical illustration of removal rate versus carbon loading for various catalysts in 20% 1-amino-2-propanol solvent with 13% CO₂ at 40°C.

**FIG. 5** is a schematical illustration of a wetted wall column (WWC) apparatus used in testing the catalysts.

**FIG. 6** is a graphical comparison of CO₂ overall mass transfer as measured on a wetted wall column for 30 wt% MEA at 40°C with catalyst CAER—C1P and CAER—C3I.

**DETAILED DESCRIPTION**

This document relates generally to methods of increasing overall mass transfer rate of acid gas scrubbing solvents as well as to novel transition metal monomer complexes incorporating a single transition metal atom.

The method may be broadly described as comprising adding a catalyst compound to a fluid stream including an acid gas and an acid gas scrubbing solvent. The catalyst compound has a chemical formula:
where $Z_{1-6} = \text{H, any alkyl, COOH, } R_9 \text{OOH (}$

$R_9 \text{= alkyl ranging from 2-10 carbons), } [\text{OCH}_2 \text{CH}_2]_n \text{, OR}_9; \text{ OH; SO}_3; \text{ NO}_2; \text{ amine, amide; (i) where } n = 1 \text{ to } 10; \text{ and (j) } R_9 = \text{H or alkyl.}

In one particular embodiment the catalyst compound has a chemical formula:

where $R = \text{any alkyl}$

$M = \text{Co, Zn.}

In another possible embodiment the catalyst compound has a chemical formula:

where $M = \text{Co, Zn.}

In yet another possible embodiment the catalyst compound has a chemical formula:

where $M = \text{Co, Zn.}

In another possible embodiment the catalyst compound has a chemical formula:

where $M = \text{Co, Zn.}

In another possible embodiment the catalyst compound has a chemical formula:

where $M = \text{Co, Zn.}
In yet another possible embodiment the catalyst compound has a chemical formula:

where \( M = \text{Co, Zn} \).

In still another possible embodiment the catalyst compound has a chemical formula:

where \( M = \text{Co, Zn} \).

For any embodiment of catalyst compound, the terms “alkyl” or “any alkyl”, when not otherwise stipulated, include at least \( C_2-C_{10} \) alkyl compounds.

For any of the method embodiments the acid gas scrubbing solvent may include an amine. In one possible embodiment the acid gas scrubbing solvent includes a mixture of (a) a promoter amine, selected from a group of primary and secondary amines and (b) a tertiary amine.

Such a mixture is described in detail in copending U.S. patent application Ser. No. 13/853,186, filed on Mar. 29, 2013 and entitled “Solvent and Method for Removal of an Acid Gas from a Fluid Stream”, the full disclosure of which is incorporated herein by reference. Promoter amines useful in the present method include, but are not limited to monoethanolamine (MEA), triethanolamine (TEA), N,N,-dialkyldibenzylamine, 1,4-dialkylpiperazine, N,N,N',N'-tetraalkyl-1,2-ethanediamine, N,N,N',N'-tetrakis (2-hydroxyethyl)triphenylphosphoniumchloride (5.00 g, 11.55 mmol), and CoCl₂ (5.7 mmol), and EtOH (40 mL) was added.

Preparation of \( \text{H}_2\text{LP} \): To a solution of 1-(3-formyl-4-hydroxybenzyl)triphenylphosphoniumchloride (5.00 g, 11.55 mmol) in dry ethanol (40 mL) was added ethylenediamine (0.40 mL, 6 mmol) slowly at room temperature. The resulting solution was stirred at reflux temperature for 3 h. The solution was allowed to cool to room temperature and the solvent was removed under reduced pressure. The yellow residue was dissolved in dichloromethane (50 mL) and slowly added dropwise to 150 mL of stirring ethyl acetate to give a bright yellow powder which was collected via filtration. The following examples further illustrate how to synthesize or manufacture certain representative catalysts used in the method of increasing the overall mass transfer rate of acid gas scrubbing solvents.

**EXAMPLE 1**

**Preparation of \( \text{CAER-ClP} \):** A 100-mL round-bottom flask was charged with \( \text{H}_2\text{LP} \) (4.594 g, 5.17 mmol) and \( \text{CoCl}_2 \) (5.17 mmol) and \( \text{EtOH} \) (40 mL) was added.
remove ammonium salts and then triturated with ether to
give the desired product as a brown solid (3.2295 g, 63%)

EXAMPLE 2

ZnCl₂ (1.4652 g, 10.8 mmol), and dissolved in EtOH (40 mL), 2 equiv. of Et₃N (2.1 mL, 15 mmol) was added and the mixture was heated at reflux for 3 hours. The mixture was cooled to room temperature and the solvent was removed under reduced pressure to give a thick, oily substance. The oil was washed with ether (3x10 mL) to produce a white solid which was removed via filtration. The ether was evaporated slowly over 24 hours to produce a thick, colorless viscous oil (4.8832 g, 89%) in >90% purity based on ¹H NMR spectroscopy.

EXAMPLE 3

Preparation of CAER-C₃P*: A 100-mL round-bottom flask was charged with H₂L₄ (5.028 g, 0.06980 g, 0.196 mmol) and ZnCl₂ (0.0433 g, 0.318 mmol), and EtOH was added to make a slurry. 2 equiv. of Et₃N (58 µL, 0.417 mmol) was added and the mixture was heated at reflux for 3 hours. The mixture was cooled to room temperature and a pale yellow solid was collected via filtration (66.7 g, 81%) in >95% purity based on ¹H NMR spectroscopy.

EXAMPLE 4

Preparation of H₂L₄: A 50 mL round bottom flask was charged with 2 equiv. 4-formyl-3-hydroxybenzoic acid (0.2471 g, 1.49 mmol) and dissolved in ethyl acetate (40 mL) and triethylphosphite (11.5 mL, 67 mmol) was added. The mixture was heated at reflux (80° C.) for 3 hours. The mixture was cooled to room temp. and a yellow powder was collected via filtration (247.3 mg, 93%) >95% purity based on ¹H NMR spectroscopy.

Preparation of CAER-C₅: A 100-mL round-bottom flask was charged with H₂L₄ (0.06980 g, 0.196 mmol) and ZnCl₂ (0.0433 g, 0.318 mmol), and EtOH was added to make a slurry. 2 equiv. of Et₃N (58 µL, 0.417 mmol) was added and the mixture was heated at reflux for 3 hours. The mixture was cooled to room temperature and a pale yellow solid was collected via filtration (66.7 g, 81%) in >95% purity based on ¹H NMR spectroscopy.

EXAMPLE 5
with N₂ is firstly saturated with water in the first impinger and then bubbled through 15 ml of testing solvent in the second impinger. Both the saturator and bubbler are immersed in a water bath at 40°C. The gas effluent is dried through an ice condenser and a Drierite tube before it is analyzed for CO₂ concentration using a dual-beam NDIR online CO₂ analyzer (Model 510, HORIBA, Ltd). Data of CO₂ outlet concentration with respect to time is continuously recorded through a LABVIEW® package with 1 second interval. A line that bypasses the saturator and the bubbler is set up for inlet CO₂ concentration determination.

### EXAMPLE 6

**Preparation of CAER-Cl:** A 100-mL round-bottom flask was charged with H₂L₃ (5.002 g, 5.63 mmol) and ZnCl₂ (1.3630 g, 10 mmol), and EtOH (40 mL) was added to make a slurry. 2 equiv. of Et₃N (1.75 mL, 12 mmol) was added and the mixture was heated at reflux for 3 hours. The mixture was cooled to room temperature and a pale yellow solid was collected via filtration (4.9790 g, 93%) in >95% purity based on ¹H NMR spectroscopy.

### EXAMPLE 7

**Preparation of CAER-C₃P:** A 100-mL round-bottom flask was charged with H₂L₅ (5.002 g, 5.63 mmol) and CoCl₂·6(H₂O) (1.0641 g, 4.44 mmol), and EtOH (40 mL) was added to make a slurry. 2 equiv. of Et₃N (1.2 mL, 8.63 mmol) was added and the mixture was heated at reflux for 3 hours. The mixture was cooled to room temperature and a dark brown solid was collected via filtration (3.592 g, 93%).

### Catalyst Testing in Concentrated Primary Amines: WWC Method

A schematic of the apparatus used is shown in FIG. 2. Briefly, 0.85 L/min feed gas containing ~13% CO₂ mixed with N₂ is firstly saturated with water in the first impinger and then bubbled through 15 ml of testing solvent in the second impinger. Both the saturator and bubbler are immersed in a water bath at 40°C. The gas effluent is dried through an ice condenser and a Drierite tube before it is analyzed for CO₂ concentration using a dual-beam NDIR online CO₂ analyzer (Model 510, HORIBA, Ltd). Data of CO₂ outlet concentration with respect to time is continuously recorded through a LABVIEW® package with 1 second interval. A line that bypasses the saturator and the bubbler is set up for inlet CO₂ concentration determination. Before each experiment, the alkalinity of the testing solvent is precisely determined through acid-base titration.

The difference of inlet and outlet CO₂ concentration represents the absorbed amount of CO₂ at a particular time. The integration of the concentration difference represents the CO₂ loading as expressed in Eq 1

$$\text{CO₂ Loading(mol CO₂/kg solution)} = \frac{\int (C_{in} - C_{out}(t)) dt}{mol}$$

in which $G_{in}$ is the CO₂ feed gas rate in mol/s, $C_{out}$ is the CO₂ effluent rate in mol/s, $t$ is the time in second, and mol is the mass of solution in kg. The CO₂ loading at $G_{eq}$ is the equilibrium CO₂ capacity at 13% CO₂ and 40°C. With the alkalinity (mol N/kg of solution) of the solution known, the CO₂ loading can also be written as in Eq 2

$$d = \frac{\text{CO₂ Loading(mol CO₂/kg solution)}}{\text{Alkalinity(mol N/kg solution)}} = \frac{\text{mole of CO₂}}{\text{mole of N}}$$

In addition, the absorption rate can be described by the derivate of CO₂ loading with respect to time:

$$\text{Absorption rate(mol CO₂/kg solution)} = \frac{d \text{CO₂ Loading}}{dt}$$

As illustrated in FIGS. 3 and 4, the current catalyst compounds improve the removal rate of a 30 wt % MEA acid gas scrubbing solvent.
WWC apparatus is illustrated in FIG. 5. The improved overall mass transfer resulting from the use of two catalysts is illustrated in FIG. 6.

In each test, solvent is loaded to a mol CO₂/mol N level of approximately 0.1 with CO₂ by sparging the solution reservoir with a concentrated CO₂/N₂ mixture. The initially loaded solution is then circulating through the wetted wall column and a pre-heater which heats the solution to the desired temperature. Once the solution is thermally stable, a simulated flue gas stream (CO₂ balanced with N₂) saturated with water flows into the wetted wall column. In the wetted wall column, liquid flows downwards on the outside surface on an annular tube while CO₂ gas stream flows upwards around the annular tube. CO₂ absorption from the gas phase into the liquid takes place along the tube’s wall. Gas effluent from the WWC is dried and analyzed by an infrared CO₂ analyzer for CO₂ concentration determination. CO₂ inlet concentration is analyzed by directing the gas stream to bypass the WWC. A liquid sample downstream of the WWC is collected at each solution carbon loading and tested for total liquid CO₂ loading, viscosity, density, and pH measurements. Liquid film thickness is calculated by Eq. 1. The bulk solution is then loaded with more CO₂ and the data collection cycle is repeated

\[
\delta = \sqrt{\frac{3\mu Q_{sol}}{\rho W}}
\]

Eq. 1

where \(\mu\) is the viscosity, \(Q_{sol}\) is the liquid flow rate, \(\rho\) is the density of liquid, and \(W\) is the circumference of the column.

The overall mass transfer coefficient at the operating condition can be calculated from Eq. 2.

\[
K_C = \frac{N_{CO_2}}{\Delta P_{CO_2}}
\]

Eq. 2

in which \(N_{CO_2}\) is the flux of CO₂, \(K_C\) is the overall mass transfer coefficient, \(\Delta P_{CO_2}\) is the log mean of driving force which is defined by

\[
\Delta P_{CO_2} = \frac{P_{CO_2}^{in} - P_{CO_2}^{out}}{(P_{CO_2}^{in} - P_{CO_2}^{out})}
\]

Eq. 3

in which \(P_{CO_2}^{in}\) and \(P_{CO_2}^{out}\) represent the CO₂ partial pressure at the inlet and outlet of the wetted wall column, and \(P_{CO_2}^{eq}\) is the equilibrium partial pressure of CO₂. The \(P_{CO_2}^{eq}\) is obtained by making the flux \(N_{CO_2}\) to be zero at zero driving force and solving the 2 equations simultaneously using a trial-and-error routine in MATLAB®.

The foregoing has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the embodiments to the precise form disclosed. Obvious modifications and variations are possible in light of the above teachings. All such modifications and variations are within the scope of the appended claims when interpreted in accordance with the breadth to which they are fairly, legally and equitably entitled.

What is claimed:

1. A method of increasing overall mass transfer rate of acid gas scrubbing solvents, comprising:

   adding a catalyst compound to a fluid stream including an acid gas and an acid gas scrubbing solvent, said catalyst compound having a chemical formula:

   \[
   \text{R}_1 - \text{C} - \text{R}_2
   \]

   where:

   (a) M is any group VII B through XII B element;
   (b) E is a combination of N with O and/or S having a net 2- charge per individual ligand with N positioned as set forth in (i);
   (c) \(R_1 = \text{H} - \text{COOH}, -[\text{OCH}_2\text{CH}_2]_{n}1\text{R}_2\), amine, amide, phosphate, -OH, -R_50H, -[SO_3]^-
   (d) \(R_1 = \text{H} - \text{COOH}, -[\text{OCH}_2\text{CH}_2]_{n}1\text{R}_2\), amine, amide, phosphate, -OH, -R_50H, -[SO_3]^-
   (e) \(R_5 = \text{C}_1 - \text{C}_5\) alkyl;
   (f) A monovalent anion: Cl, Br, I, F, PF_6, BF_4, acetate, trifluoroacetate, CIO_4, NO_3;
   (g) Q monovalent cation: PX_3 where X=alkyl, cyclic alkyl, alyl, O-alkyl, O-aryl, N(R_6)_3 where R_6 =alkyl, cyclic alkyl, N-heterocyclic ring, imidazole;
   (h) n=1 to 10;
   (i)
where $Z_{1-6} = \text{H; any alkyl; -COOH; -R}_8\text{OOH where}$

$R_8$ is an alkyl ranging from 2-10 carbons; $-\{OCH}_2CH}_2n\text{OR}_9; \text{OH; SO}_3; \text{NO}_2; \text{amine, amide};$

1. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $M = \text{Co, Zn}$

2. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $R = \text{any alkyl M=Co, Zn}$

3. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $R = \text{any alkyl M=Co, Zn}$

4. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $M = \text{Co, Zn}$

5. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $M = \text{Co, Zn}$

6. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $M = \text{Co, Zn}$

7. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $M = \text{Co, Zn}$

8. The method of claim 1 wherein said catalyst compound has a chemical formula:

where $M = \text{Co, Zn}$
where \( M = \text{Co, Zn} \).

9. The method of claim 1 wherein said acid gas scrubbing solvent includes an amine.

10. The method of claim 1, wherein said acid gas scrubbing solvent includes a mixture of a primary or secondary amine and a tertiary amine.

11. The method of claim 1, wherein said acid gas scrubbing solvent includes a material selected from a group consisting of monoethanolamine (MEA), 1-amino-2-propanol (1A2P), 3-amino-1-propanol, 2-amino-1-propanol, 2-amino-1-butanol, 1-amino-2-butanol, 3-amino-2-butanol, 2-(alkylamino)ethanol (MAE), diglycolamine, morpholine, piperazine (PZ), 1-methylpiperazine (NMP), 2-methylpiperazine, hydroxypiperidine, hydroxyalkylpiperazine, 2-piperidineethanol, N-aminoethypiperazine (AEP), aminopropylmorpholine, 4-aminopiperidine, 3-aminopiperidine, 2-amino-piperidine, diethanolamine, 2-amino-2-methyl-1-propanol (AMP), diethanolamine (DEA), disopropanolamine (DTPA), glycine, alanine, \( \beta \)-alanine, sarcosine, isopropanolamine, benzylamine, methylidethanolamine (MDEA), triethanolamine (TEA), alkali carbonate, \( N,N,N' \)-dialkyethanolamine, \( N,N,N',N' \)-tetraalkyl-1,8-naphthalenediamine, \( N,N,N',N' \)-dialkybenzylamine, 1,4-dialkypiperazine, \( N,N,N',N' \)-tetraalkyl-1,6-hexanediame, \( N,N,N',N' \)-tetraalkyl-1,5-pentanediame, \( N,N,N',N' \)-tetraalkyl-1,4-butanediame, \( N,N,N',N' \)-tetraalkyl-1,3-propanediame, \( N,N,N',N' \)-tetraalkyl-1,2-ethanediame, \( N,N,N',N' \)-tetraakis (2-hydroxyethyl)ethylenediamine, \( N,N,N',N' \)-pentalaalkyldiethylenetriame, \( N,N,N',N' \)-pentalaalkylidipropylaminetemineramme, \( N,N,N',N' \)-dialkycyclohexylamine, \( N,N,N',N' \)-tetraalkylbis(amine)ether, \( N,N,N',N' \)-dimethyl-2-(2-aminoethoxy)ethanol, where alkyl represents any methyl, ethyl, propyl, butyl isomer, and mixtures thereof.

12. The method of claim 1, wherein said catalyst compound is provided at a concentration of between about 0.05 mM and about 100 mM.

* * * * *