ISSN 1070-3632, Russian Journal of General Chemistry, 2019, Vol. 89, No. 12, pp. 2333–2340. © Pleiades Publishing, Ltd., 2019.
Russian Text © The Author(s), 2019, published in Zhurnal Obshchei Khimii, 2019, Vol. 89, No. 12, pp. 1807–1815.

Colloidal and Nanosized Catalysts in Organic Synthesis: XXIII.[1] Reductive Amination of Carbonyl Compounds Catalyzed by Nickel Nanoparticles in a Plug-Flow Reactor

V. M. Mokhov[a],*, Yu. V. Popov[a], A. N. Paputina[a], D. N. Nebykov[a], and E. V. Shishkin[a]

[a] *Volgograd State Technical University, Volgograd, 400005 Russia*
**e-mail: tons@vstu.ru*

Received May 30, 2019; revised May 30, 2019; accepted June 6, 2019

Abstract—Reductive amination of aldehydes and ketones with primary and secondary amines under catalysis with nickel nanoparticles supported on zeolite X, MgO, or activated carbon in the gas phase or in the gas-liquid system in a plug-flow reactor proceeds at atmospheric pressure of hydrogen with the formation of secondary or tertiary amines in high yield.

Keywords: catalysis, nanoparticles, nickel, hydrogenation, reductive amination, amines

DOI: 10.1134/S1070363219120016

Secondary and tertiary amines are widely used as semi-products in the preparation of drugs, solvents, polymers, dyes, and agricultural chemicals [2–5].

Reductive amination of carbonyl compounds is commonly widely applied methods of amines synthesis [6–8], due to the possibility of preparation of a wide range of amines bearing various alkyl groups (depending on the precursor) and ease of the process. The synthesis occurs via sequential condensation of the carbonyl compound with the amine to give the imine (enamine) and hydrogenation of the C=C or C=N multiple bonds in the intermediates. Both stages often require prolonged duration, and in certain cases periodic process using an autoclave is exclusively possible. Continuous process of reductive amination has been used mainly for the synthesis of low-molecular primary amines from spatially non-hindered aldehydes and ketones. The side reactions of sequential alkylation of a secondary amine with a carbonyl compound into the tertiary amine as well as hydrogenation of a carbonyl compound into the alcohol reduces the process selectivity.

Reductive amination of aldehydes or ketones catalyzed by the Raney nickel is performed in an autoclave at hydrogen pressure of 100–150 atm and 100°C [9]. The reaction between aniline and acetone in the presence of hydrogen catalyzed by copper chromite in a continuous mode performed at 300°C has been accompanied by side reactions of aniline C-alkylation [10]. Homogeneous reductive amination of aldehydes and ketones catalyzed by rhodium(I) complexes occurs at room temperature, hydrogen pressure being 50 atm to yield a mixture of the corresponding amine and the alcohol, a product of the carbonyl compound reduction [11].

Reductive amination of carbonyl compounds under catalysis of various iridium complexes (30–35°C, 5–60 atm of hydrogen, 12–13 h) has been studied [12, 13]. The yield of the amines was up to quantitative.

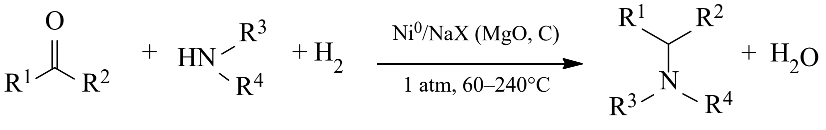
The reaction in the presence of copper immobilized at different carriers has been performed in a periodic mode (5–24 h, 100–130°C) under vigorous stirring and bubbling with hydrogen (1 atm) [14]. Copper applied on silica or its combinations with alumina or titania has exhibited high activity. When alumina was used as the carrier, the alcohols yield was up to 75%.

Reductive amination of aldehydes and ketones catalyzed by supported cobalt oxide nanoparticles under quasi-homogeneous periodic conditions (50 atm of hydrogen, 150°C, 15 h) [15] have resulted in the yield of secondary or tertiary amines of 10 to 95%, depending on the substrate. The catalyst has been regenerated at least five times without any loss of activity.

---

[1] For communication XXII, see [1].

Scheme 1.



1a–1j **2a–2k** **3a–3r**

R^1 = H, R^2 = Et (**1a**), Pr (**1b**), *i*-Pr (**1c**), *i*-Bu (**1d**), $CH_3(CH_2)_5$ (**1e**), $CH_3(CH_2)_6$ (**1f**), Ph (**1g**); R^1 = Me, R^2 = Ph (**1h**), R^1 = R^2 = Et (**1i**), R^1–R^2 = $(CH_2)_5$ (**1j**); R^3 = H, R^4 = Bu (**2a**), *i*-Bu (**2b**), *t*-Bu (**2c**), $CH_3(CH_2)_5$ (**2d**), Cy (**2e**), Ph (**2f**), $PhCH_2$ (**2g**); R^3 = R^4 = Bu (**2h**); R^3–R^4 = $(CH_2)_4$ (**2i**), $(CH_2)_5$ (**2j**), $(CH_2)_6$ (**2k**); R^1 = R^3 = H, R^2 = *i*-Pr, R^4 = *i*-Bu (**3a**), $CH_3(CH_2)_5$ (**3b**); R^1 = R^3 = H, R^4 = Ph, R^2 = Et (**3c**), *i*-Pr (**3d**), *i*-Bu (**3e**); R^1 = R^3 = H, R^2 = *i*-Pr, R^4 = Cy (**3f**); R^1 = R^3 = H, R^2 = Ph, R^4 = Bu (**3g**); R^1 = H, R^2 = $CH_3(CH_2)_6$, R^3 = R^4 = Bu (**3h**), R^2 = *i*-Pr, R^3–R^4 = $(CH_2)_4$ (**3i**), R^2 = Pr, R^3–R^4 = $(CH_2)_6$ (**3j**), R^2 = $CH_3(CH_2)_5$, R^3–R^4 = $(CH_2)_6$ (**3k**); R^1–R^2 = $(CH_2)_5$, R^3 = H, R^4 = Bu (**3l**), $CH_3(CH_2)_5$ (**3m**), Ph (**3n**); R^1–R^2 = Et, R^3–R^4 = $(CH_2)_5$ (**3o**); R^1–R^2 = $(CH_2)_5$, R^3–R^4 = $(CH_2)_5$ (**3p**); R^1 = Me, R^2 = Ph, R^3 = H, R^4 = *i*-Bu (**3q**), $CH_3(CH_2)_5$ (**3r**).

Reductive amination of carbonyl compounds has been performed by metal (palladium or platinum) nanoparticles applied onto zeolites or alumina [16] in a continuous reactor (5 atm of hydrogen, 100°C, 7 h) [16]. The studied catalysts have been found more active than the commercial ones (Pt/C or Pd/Al_2O_3).

A few reports have discussed reductive amination of carbonyl compounds in a continuous mode. Benzylpiperazine derivatives have been obtained from substituted benzaldehydes and piperazine in a continuous mode using Pd/C, Pt/C, and $Pd(OH)_2/C$ [17–18]. The use of gold nanoparticles (2–3 nm) on titania for the catalysis of amines alkylation in a flow system has been described [19]. Alcohols have been used as alkylating agents instead of carbonyl compounds. The reaction in toluene (50 atm, 180–200°C, 24 h) has yielded up to 92% of the amines. The reaction between phenylethylamine and levulinic acid in continuous mode (Fe/Ni catalyst, 150°C, hydrogen pressure 85 atm) has afforded the N-substituted pyrrolidone with 91% yield [20]. A continuous method of reductive amination of ketones with ammonium formate catalyzed by Pd/C has been described [21]. Commercial Pd/C has been used for the catalysis of the reaction between amines and ketones supplied separately as 0.1 M solutions in toluene (40–140°C), the products yield has been 63–100% [22].

Development of available and highly active as well as selective heterogeneous catalysts of reductive amination has remained a topical issue. Hydrogenation of enamines and imines catalyzed by nickel nanoparticles on zeolite or activated carbon has been studied earlier [23].

We investigated the possibility of reductive amination of aldehydes and ketones with primary and secondary amines in continuous mode under atmospheric pressure of hydrogen; in detail, the catalyst stability in the presence of reaction water and the regularities of the reaction (Scheme 1) selectivity were probed. The following substrates were used: propionaldehyde, butyraldehyde, 2-methylpropionaldehyde, 3-methylbutyraldehyde, hexanal, heptanal, benzaldehyde, diethyl ketone, cyclohexanone, and acetophenone (carbonyl compounds); butylamine, isobutylamine, *tert*-butylamine, hexylamine, cyclohexylamine, aniline, pyrrolidine, piperidine, hexahydroazepine, and dibutylamine (amines). Nickel nanoparticles were deposited onto the corresponding support (NaX zeolite, bulk magnesia, or Norit RX 3 EXTRA activated carbon) as described elsewhere [24, 25]; the Ni^0/NaX, Ni^0/MgO, Ni^0/C nanoparticles size was of 20–100 nm.

The reaction was performed under a stream of 5–15-fold excess of hydrogen at atmospheric pressure and temperature 60–240°C in a continuous reactor (a metal tube with inner diameter 9 mm and heating zone height 100 mm put in an electric oven). The catalyst layer was put in a middle part of the reactor, surrounded by inert filler (quartz attachment).

The starting compounds **1a–1j** and **2a–2k** were supplied to the reactor separately, without any solvent, simultaneously with hydrogen (1 atm). The post-reaction mixture composition was determined by means of mass spectrometry. Majority of the products were identified by comparison of their masses with the instrument internal database, other products were identified by the molecular ions and the characteristic decomposition.

When the Ni^0/NaX catalyst was used [feeding rate of carbonyl compounds and amines 0.9–1.8 L/(kg_{cat} h), **1a–1j** to **2a–2k** molar ratio (1–1.5) : (1–3), 5–15-fold excess of hydrogen, 60–240°C], the yield of amines **3a–3r** was 37–97% depending on the substrate structure.

Intermediate imines and enamines were detected in the reaction mixture during preparation of amines **3d**, **3m**, **3p**; those intermediates disappeared upon the increase in the hydrogen excess or temperature.

When the Ni^0/NaX catalyst was used, the reaction mixture practically did not contain the products of hydrogenation of the aldehydes and ketones **1a–1j** (the corresponding alcohols): their content at reaction temperature below 180°C did not exceed 1.5–2%. It was shown that the conversion of cyclohexanone into cyclohexanol under the same conditions in the absence of an amine was of 2%, whereas colloidal nickel is known to promote liquid-phase hydrogenation of aliphatic ketones within 10–12 h [24]. Hence, Ni^0/NaX turned out to be a selective catalyst of reductive amination of carbonyl compounds, and its use would avoid the side hydrogenation reaction.

Since the interaction of aliphatic aldehydes with primary and certain secondary amines occurs in the absence of a catalyst, we also investigated the possibility of the synthesis when carbonyl compounds and amines were supplied to the reactor as equilibrium mixture with the imine (enamine) and water. The yield and selectivity of the process were found marginally different from those obtained with separate supply of the reagents.

At high excess of primary amines **2a**, **2b**, **2d**, **2e**, **2g**, a competitive reaction of their disproportionation occurred, leading to the formation of symmetric dialkylamines. That reaction has been studied earlier using the same catalyst [26]. For example, reductive amination of cyclohexanone **1j** with butylamine **2a** (molar ratio 1 : 3), *N*-butylcyclohexanamine was formed along with dibutylamine (12 wt % in the products mixture, conversion of amine **2a** 95%, selectivity with respect to dibutylamine 14%). The use of secondary amines (morpholine, piperidine, etc.) not prone to disproportionation allowed performing the reaction at significant (3–5-fold) excess of the amine, the conversion of the carbonyl compound being complete at 120–160°C.

Amines **3b–3d**, **3k** were prepared using excess of the carbonyl compound with respect to the amine. Reductive amination of excess of propionaldehyde **1a** with aniline **2f** gave the secondary amine **3c** along with the tertiary one, *N*,*N*-dipropylaniline with yield 28%. The reaction of aniline **2f** with excess of 2-methylpropionaldehyde **1c** occurred selectively, and the fraction of the corresponding tertiary amine in the products mixture was as low as 3 wt %.

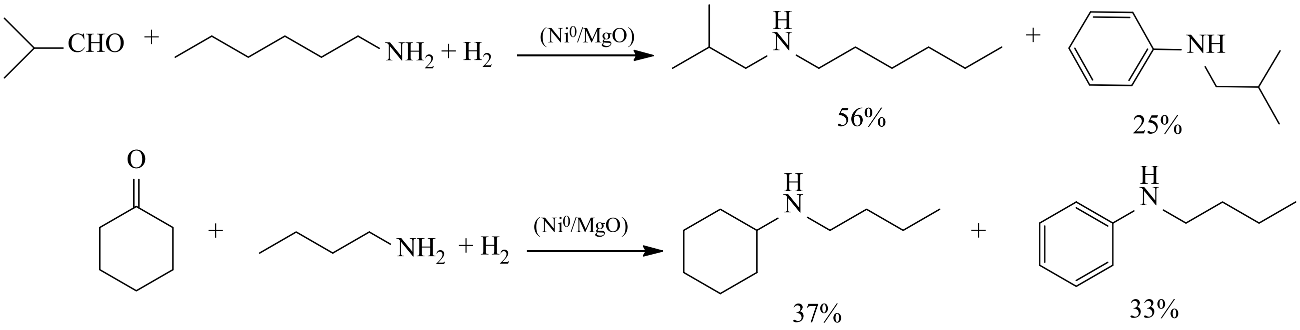
The increase in temperature above 200°C led to the reduction of 5–10% of the non-converted carbonyl compounds into alcohols. At equimolar ratio of the substrates and temperature decreased to 160–180°C, the side reactions were not observed, yet the conversion was typically of 60–80% and could be improved via heating above 200°C or decrease in the substrates feeding rate.

Reductive amination of aliphatic aldehydes with sterically non-hindered amines occurred readily at temperature even below 100°C. The reaction of hexanal **1e** with hexahydroazepine **2k** at 60°C with the Ni^0/NaX catalyst led to complete conversion of the substrates and almost quantitative yield of compound **3k** even at equimolar ratio of the reactants **1d** and **2k**. When the reaction was performed at 20 and 40°C, the yield of the secondary amine **3k** was of 70–80%, the substrates conversion being 80–90%. The intermediate enamine (3.5%) was detected at 20°C along with compound **3k**. Similar results were revealed for the reaction of the C_4–C_7 aldehydes with cyclic secondary amines. The high yield of the reductive amination products under mild conditions and their slight dependence on temperature could be explained by high catalyst activity as well as the increase in the duration of its contact with liquid reactants.

The support nature only slightly affected the catalytic activity of nickel in the reaction of reductive amination, whereas its influence on the reaction selectivity was significant. When the Ni^0/MgO catalyst was used for reductive amination of 2-methylpropionaldehyde **1c** with hexylamine **2d**, the secondary amide **3c** was formed along with *N*-isobutylaniline (yield 25%), the product of dehydroaromatization of the hexyl group (Scheme 2). Similarly, the interaction of cyclohexanone **1j** with butylamine **2a** gave *N*-butylaniline (yield 33%) as the side product.

When the Ni^0/MgO or Ni^0/C catalyst was used, the side reaction of carbonyl compounds reduction occurred at lower temperature as compared to the Ni^0/NaX one; that resulted in the decrease in the selectivity of reductive amination. The Ni^0/C catalyst revealed the best performance in reductive amination of 2-methylpropionaldehyde **1c** with *tert*-butylamine **2c**. *N*-*tert*-Butylisobutylamine **3a** was obtained with 48% yield, whereas the intermediate imine was exclusively formed when using the Ni^0/NaX catalyst. The Ni^0/C catalyst was more efficient in reductive amination of ketones with secondary amines at 120°C. The yield of *N*-cyclohexylpiperidine **3p** upon the interaction of cyclohexanone **1k** with piperidine **2j**

Scheme 2.



was 73% as compared to 57% with the Ni^0/NaX catalyst under the same conditions. The Ni^0/C catalyst was operative at even lower temperature. The yield of amine **3p** at 80 and 60°C was 64 and 36%, respectively.

In summary, the use of the Ni^0/NaX, Ni^0/MgO, and Ni^0/C heterogeneous catalysts in the reaction of reductive amination of carbonyl compounds afforded secondary and tertiary amines with yield 37–97% and selectivity 49–100% at 60–240°C and atmospheric pressure of hydrogen in continuous mode; the reaction water did not affect the activity and stability of the catalysts.

EXPERIMENTAL

Chromato–mass spectral analysis was performed using a Saturn 2100 T/GC3900 instrument (EI, 70 eV).

Catalyst preparation. The catalysts were prepared via impregnation of a solid support (NaX zeolite, magnesium oxide MgO, or Norit RX 3 EXTRA activated carbon) with an aqueous solution of nickel(II) chloride hexahydrate $NiCl_2 \cdot 6H_2O$ during 5–6 h. The obtained solid product was filtered off, washed with distilled water, and treated with aqueous solution of sodium borohydride $NaBH_4$ at 20–25°C during 20–30 min. The size of nickel particles on the support was of 70–100 nm [23]. The obtained moisty catalyst was charged to the reactor and dried in a hydrogen stream at 120–300°C just before the reaction.

Reductive amination (*general procedure*). The reaction was performed in a continuous reactor at atmospheric pressure and temperature 60–240°C. Depending on the boiling point of the substrates, the reaction could occur either in gas phase or in the gas–liquid–solid catalyst system. The laboratory-scale reactor was manufactured of a 12X18H10T steel tube with inner diameter 9 mm and the heating zone height 50 mm (electric oven heating). The catalyst layer was positioned in the middle part of the reactor, sandwiched between the pieces of inert filler (quartz attachment). Liquid aldehyde (or ketone) and amine were fed at certain ratio, and the desired hydrogen feeding rate was set. Feeding rate of the liquid mixture 0.9–1.8 L/(kg_{kat} h). Hydrogen supply rate 250–1500 L/(kg_{cat} h) (5–15-fold molar excess).

***N*-*tert*-Butyl-2-methylpropane-1-amine (3a).** Hydrogen [1500 L/(kg_{cat} h)] and a mixture of 2-methylpropionaldehyde **1c** and *tert*-butylamine **2c** [1.8 L/(kg_{cat} h), molar ratio **1c** : **2c** = 1 : 2] was fed on 2 g of Ni^0/C at 160°C. Conversion of aldehyde **1c** 48%. Selectivity with respect to the product **3a** 100%, yield 48%. Mass spectrum, *m/z* (I_{rel}, %): 130.8 (8.8) $[M+2]^+$, 129.8 (100) $[M+1]^+$, 128.0 (4.2) $[M-1]^+$, 115.0 (8.5), 114.0 (95.0), 85.8 (2.8), 58.0 (26.2), 57.0 (6.7), 56.0 (2.6), 54.9 (2.0), 42.0 (6.4), 41.0 (8.5).

***N*-Isobutylhexane-1-amine (3b).** *a*. Hydrogen [750 L/(kg_{cat} h)] and a mixture of 2-methylpropionaldehyde **1c** [1.08 L/(kg_{cat} h) and hexane-1-amine **2d** [0.72 L/(kg_{cat} h), molar ratio **1c** : **2d** = 1.5 : 1] was fed on 2 g of Ni^0/NaX at 180°C. Conversion of amine **2d** 100%. Selectivity with respect to the product **3b** 55.8%, yield 55.8%. Mass spectrum, *m/z* (I_{rel}, %): 157.0 (9.8) $[M]^+$, 156.0 (100) $[M-1]^+$, 154.1 (5.6), 112.9 (6.5), 112.0 (91.9), 83.0 (3.2), 70.0 (6.5), 68.0 (3.6), 57.0 (2.5), 56.0 (14.4), 54.9 (10.2), 53.0 (2.2), 43.9 (2.2), 43.0 (2.6), 42.0 (2.5), 41.0 (10.1). ***N*-Hexyl-2-methylpropane-1-imine**, yield 12.9%. Mass spectrum, *m/z* (I_{rel}, %): 157.0 (11) $[M+2]^+$, 156.0 (100) $[M+1]^+$, 154.2 (4) $[M-1]^+$, 112.1 (46), 84.2 (2), 70.0 (2), 56.0 (5), 55 (11), 43 (6), 42 (4), 41 (8). **Dihexylamine**, yield 22.3%. Mass spectrum, *m/z* (I_{rel}, %): 187.1 (8) $[M+2]^+$, 186.1 (50) $[M+1]^+$, 184.8 (4) $[M]^+$, 114.0 (60), 44.0 (100). ***N*-Hexylhexane-1-imine**, yield 7.3%. Mass spectrum, *m/z* (I_{rel}, %): 185.1 (13) $[M+2]^+$, 184.1 (100) $[M+1]^+$, 182.2 (3) $[M-1]^+$, 112.0 (37), 41.0 (4).

b. Hydrogen [1000 L/($\mathrm{kg_{cat}}$ h)] and a mixture of 2-methylpropionaldehyde **1c** [1.08 L/($\mathrm{kg_{cat}}$ h)] and hexane-1-amine **2d** [0.72 L/($\mathrm{kg_{cat}}$ h), molar ratio **1c** : **2d** = 1.5 : 1] was fed on 4 g of $\mathrm{Ni^0}$/MgO at 200°C. Conversion of amine **2d** 100%. Selectivity with respect to the product **3b** 56.3%, yield 56.3%. Mass spectrum, *m/z* (I_{rel}, %): 157.0 (9.8) $[M]^+$ 156.0 (100) $[M-1]^+$, 154.1 (5.6), 112.9 (6.5), 112.0 (91.9), 83.0 (3.2), 70.0 (6.5), 68.0 (3.6), 57.0 (2.5), 56.0 (14.4), 54.9 (10.2), 53.0 (2.2), 43.9 (2.2), 43.0 (2.6), 42.0 (2.5), 41.0 (10.1). ***N*-Isobutylhexane-1-imine**. Yield 19.7%. Mass spectrum, *m/z* (I_{rel}, %): 156.0 (3.7) $[M+1]^+$, 154.1 (1.2) $[M-1]^+$, 144.4 (16.9), 142.8 (10.9), 112.0 (16.1), 100.8 (2.9), 74.0 (5.7), 72.9 (100), 70.8 (15.9), 57.0 (4.4), 56.0 (7.3), 54.9 (49.3), 45.0 (3.8), 43.0 (19.5), 41.0 (17.8). ***N*-Isobutylaniline**, yield 24.9%. Mass spectrum, *m/z* (I_{rel}, %): 150.9 (10.4) $[M+2]^+$, 150.0 (100) $[M+1]^+$, 149.0 (48.5) $[M]^+$, 148.1 (4.6) $[M-1]$, 107.1 (5.6), 106.2 (64.2), 79.1 (3.1), 77.0 (3.0).

***N*-Propylaniline (3c).** Hydrogen [1500 L/($\mathrm{kg_{cat}}$ h)] and a mixture of propionaldehyde **1a** and aniline **2f** [1.8 L/($\mathrm{kg_{cat}}$ h), molar ratio **1a** : **2f** = 1 : 1.5] was fed on 2 g of $\mathrm{Ni^0}$/NaX at 2000°C. Conversion of aldehyde **1a** 99%. Selectivity with respect to the product **3c** 57%, yield 56.4%. Mass spectrum, *m/z* (I_{rel}, %): 136.9 (3.5) $[M+2]^+$, 136.0 (39.7) $[M+1]^+$, 134.8 (41.4) $[M]^+$, 106.9 (7.5), 105.9 (100), 104.0 (4.1), 79.0 (14.1), 77.0 (19.1), 65.0 (3.6), 50.9 (9.4), 50.0 (6.1), 43.9 (1.4). ***N*,*N*-Dipropylaniline**, yield 42.5%. Mass spectrum, *m/z* (I_{rel}, %): 178.9 (12.3) $[M+2]^+$, 177.9 (100) $[M+1]^+$, 177.2 (36.6) $[M]^+$, 176.2 (5.0) $[M-1]^+$, 107.0 (3.2), 106.1 (38.9), 104.0 (1.2), 77.0 (1.2).

***N*-Isobutylaniline (3d).** *a*. Hydrogen [1500 L/($\mathrm{kg_{cat}}$ h)] and a mixture of 2-methylpropionaldehyde **1c** [0.9 L/($\mathrm{kg_{cat}}$ h)] and aniline **2f** [0.9 L/($\mathrm{kg_{cat}}$ h), molar ratio **1c** : **2f** = 1 : 1] was fed on 2 g of $\mathrm{Ni^0}$/NaX at 200°C. Conversion of aldehyde **1c** 95.7%. Selectivity with respect to the product **3f** 100%, yield 95.7%.Mass spectrum, *m/z* (I_{rel}, %): 150.9 (5) $[M+2]^+$, 150.0 (41) $[M+1]^+$, 149.0 (34) $[M]^+$, 107.0 (8), 106.0 (100), 77.0 (11), 51.0 (6).

b. Hydrogen [1500 L/($\mathrm{kg_{cat}}$ h)] and a mixture of 2-methylpropionaldehyde **1c** and aniline **2f** [1.8 L/($\mathrm{kg_{cat}}$ h), molar ratio **1c** : **2f** = 1 : 1.5] was fed on 2 g of $\mathrm{Ni^0}$/NaX at 180°C. Conversion of aldehyde **1c** 89.3%. Selectivity with respect to the product **3d** 100%, yield 89.3%.

***N*-Isopentylaniline (3e).** Hydrogen [500 L/($\mathrm{kg_{cat}}$ h)] and a mixture of 3-methylbutyraldehyde **1d** and aniline **2f** [0.9 L/($\mathrm{kg_{cat}}$ h), molar ratio **1d** : **2f** = 1 : 1] was fed on 4 g of $\mathrm{Ni^0}$/NaX at 160°C. Conversion of aldehyde **1d** 89.7%. Selectivity with respect to the product **3e** 100%, yield 89.7%. Mass spectrum, *m/z* (I_{rel}, %): 164.8 (1.2) $[M+2]^+$, 163.9 (13.2) $[M+1]^+$, 163.0 (25.3) $[M]^+$, 107.0 (7.2), 105.9 (100), 93.0 (4.1), 79.1 (9.8), 78.1 (3), 77.0 (13.2), 65.0 (3.4), 51.0 (5.8), 50.0 (3.4), 41.0 (3.5).

***N*-Isobutylcyclohexanamine (3f).** *a*. Hydrogen [1500 L/($\mathrm{kg_{cat}}$ h)] and a mixture of 2-methylpropionaldehyde **1c** and cyclohexylamine **2e** [1.8 L/($\mathrm{kg_{cat}}$ h), molar ratio **1c** : **2e** = 1 : 1.5] was fed on 2 g of $\mathrm{Ni^0}$/NaX at 180°C. Conversion of aldehyde **1c** 99%. Selectivity with respect to the product **3f** 88.3%, yield 87.4%. Mass spectrum, *m/z* (I_{rel}, %): 156.9 (6) $[M+2]^+$, 156.0 (54.5) $[M+1]^+$, 154.1 (4) $[M-1]^+$, 112.0 (100), 84.0 (13.6), 70.0 (14.5), 56.0 (13), 43.0 (18.5), 41.0 (21).

b. Hydrogen [500 L/($\mathrm{kg_{cat}}$ h)] and a mixture of cyclohexanone **1j** and isobutylamine **2b** [0.9 L/($\mathrm{kg_{cat}}$ h), molar ratio **1j** : **2b** = 1 : 3] was fed on 4 g of $\mathrm{Ni^0}$/MgO at 200°C. Conversion of ketone **1j** 88%. Selectivity with respect to the product **3f** 100%, yield 88%.

***N*-Benzylbutane-1-amine (3g).** Hydrogen [1000 L/($\mathrm{kg_{cat}}$ h)] and a mixture of benzaldehyde **1g** [0.45 L/($\mathrm{kg_{cat}}$ h)] and 1-butylamine **2a** [1.35 L/($\mathrm{kg_{cat}}$ h), molar ratio **1g** : **2a** = 1 : 3] was fed on 2 g of $\mathrm{Ni^0}$/NaX at 200°C. Conversion of aldehyde **1g** 96.5%. Selectivity with respect to the product **3g** 88.1%, yield 85%. Mass spectrum, *m/e* (I_{rel}, %): 163.9 (9.4) $[M+1]^+$, 162.0 (3) $[M-1]^+$, 119.9 (44.4), 105.9 (11), 91.0 (100), 77.0 (3), 65.0 (11), 51 (3), 41 (3). ***N*-Butylbenzylidenamine**, yield 4.9%. Mass spectrum, *m/z* (I_{rel}, %): 163.0 (5.7) $[M+2]^+$, 162.0 (40) $[M+1]^+$, 160.9 (9) $[M]^+$, 160.0 (29) $[M-1]^+$, 132.0 (32), 119.0 (13), 118.0 (88), 117.0 (10.4), 105.0 (11), 104.0 (28), 91.0 (100), 89.1 (13), 77.0 (12.3), 65.1 (13), 51 (12.6), 50.0 (10), 41 (9). ***N*,*N*-Dibytulbenzylamine**, yield 6.5%. Mass spectrum, *m/z* (I_{rel}, %): 221.2 (2) $[M+2]^+$, 220.1 (11.6) $[M+1]^+$, 219.1 (3) $[M]^+$, 218.1 (13.7) $[M-1]^+$, 177.0 (12), 176.0 (100), 142.1 (2), 134.1 (22), 91.1 (15), 65.0 (2), 41 (2).

***N*,*N*-Dibutylheptane-1-amine (3h).** Hydrogen [200 L/($\mathrm{kg_{cat}}$ h)] and a mixture of heptanal **1f** and dibutylamine **2h** [0.9 L/($\mathrm{kg_{cat}}$ h), molar ratio **1f** : **2h** = 1 : 2] was fed on 4 g of $\mathrm{Ni^0}$/NaX at 180°C. Conversion of aldehyde **1f** 100%. Selectivity with respect to the product **3h** 80.9% yield. Mass spectrum, *m/z* (I_{rel}, %): 229.1 (6.1) $[M+2]^+$, 228.2 (40.2) $[M+1]^+$, 226.2 (11.8) $[M-1]^+$, 185.1 (12.5), 184.2 (100), 183.2 (10.2), 143.2 (6.1), 144.2 (66.3), 140.2 (4.4), 101.1 (4.2), 100.0 (64.2), 98.2 (8.4), 58.1 (62.2), 57.2 (3.9).

***N*-Isobutylpyrrolidine (3i).** Hydrogen [500 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of 2-methylpropionaldehyde **1c** [0.72 $\mathrm{L/(kg_{cat}\ h)}$] and pyrrolidine **2i** [1.08 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1c** : **2i** = 1 : 1.5] was fed on 2 g of $\mathrm{Ni^0/NaX}$ at 140°C. Conversion of aldehyde **1c** 90.6%. Selectivity with respect to the product **3i** 100%, yield 90.6%. Mass spectrum, *m/z* (I_{rel}, %): 129.0 (3) $[M + 2]^+$, 128.0 (37.6) $[M + 1]^+$, 126.0 (11) $[M - 1]^+$, 112.0 (1), 84.9 (5), 84.0 (100), 83.0 (8).

***N*-Butylhexahydroazepine (3j).** Hydrogen [1500 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of butyraldehyde **1b** and hexahydroazepine **2k** [1.8 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1b** : **2k** = 1.5 : 1] was fed on 2 g of $\mathrm{Ni^0/NaX}$ at 180°C. Conversion of amine **2k** 93.8%. Selectivity with respect to the product **3j** 100%, yield 93.8%. Mass spectrum, *m/z* (I_{rel}, %): 157.0 (5) $[M + 2]^+$, 156.0 (550) $[M + 1]^+$, 154.2 (14.6) $[M - 1]^+$, 113.1 (9), 112.3 (100), 111.3 (17), 98.0 (1.5), 58.0 (45), 57.2 (5).

***N*-Hexylhexahydroazepine (3k).** Hydrogen [1500 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of hexanal **1e** [0.9 $\mathrm{L/(kg_{cat}\ h)}$] and hexahydroazepine **2k** [0.9 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1e** : **2k** = 1 : 1] was fed on 4 g of $\mathrm{Ni^0/NaX}$ at 60°C. Conversion of amine **2k** 84.4%. Selectivity with respect to the product **3k** 100%, yield 84.4%. Mass spectrum, *m/z* (I_{rel}, %): 185.1 (1.6) $[M + 2]^+$, 184.1 (10.7) $[M + 1]^+$, 182.1 (3.8) $[M - 1]^+$, 113.0 (7.3), 112.0 (100), 84.1 (2.6), 58.2 (31.8), 44.2 (2.2), 42.0 (2.4).

***N*-Butylcyclohexanamine (3l).** *a*. Hydrogen [1000 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of cyclohexanone **1j** [0.72 $\mathrm{L/(kg_{cat}\ h)}$] and butylamine **2a** [1.08 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1j** : **2a** = 1 : 1.5] was fed on 4 g of $\mathrm{Ni^0/MgO}$ at 240°C. Conversion of ketone **1j** 76.3%. Selectivity with respect to the product **3l** 48.8%, yield 37.3%. Mass spectrum, *m/z* (I_{rel}, %): 157.1 (5.6) $[M + 2]^+$, 156.0 (43.3) $[M + 1]^+$, 154.8 (4.6) $[M]^+$, 154.2 (3.3) $[M - 1]$, 126.0 (3.9), 112.9 (10.1), 112.0 (100), 84.0 (3.5), 70.0 (7.6), 67.0 (3.8), 57.0 (4.7), 56.0 (12.6), 55.1 (6.3), 44.1 (5.7), 41.0 (7.7). ***N*-Butylaniline**, yield 33.4%. Mass spectrum, *m/z* (I_{rel}, %): 150.0 (8.1) $[M + 1]^+$, 149.0 (23.7) $[M]^+$, 148.1 (2.5) $[M - 1]^+$, 118.0 (2.8), 107.0 (6.8), 106.1 (100), 104.0 (2.7), 79.1 (10.9), 78.2 (3.1), 77.0 (15.9), 65.1 (3.9), 51.0 (5.9), 50.0 (3.4).

b. Hydrogen [1500 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of butyraldehyde **1b** and cyclohexylamine **2e** [1.8 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1b** : **2e** = 1 : 1] was fed on 2 g of $\mathrm{Ni^0/NaX}$ at 200°C. Conversion of aldehyde **1b** 100%. Selectivity with respect to the product **3l** 97%, yield 97%.

***N*-Hexylcyclohexanamine (3m).** Hydrogen [750 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of cyclohexanone **1j** and hexylamine **2d** [0.9 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1j** : **2d** = 1 : 1] was fed on 4 g of $\mathrm{Ni^0/NaX}$ at 240°C. Conversion of ketone **1j** 100%. Selectivity with respect to the product **3m** 86%, yield 86%. Mass spectrum, *m/z* (I_{rel}, %): 185.1 (12) $[M + 2]^+$, 184.2 (100) $[M + 1]^+$, 140.3 (4.2), 112.2 (9.7), 56 (1.8). **Dihexylamine**, yield 13.7%. Mass spectrum, *m/z* (I_{rel}, %): 187.1 (4.6) $[M + 2]^+$, 186.1 (31.8) $[M + 1]^+$, 184.3 (2.5) $[M - 1]^+$, 115.0 (4.7), 114.1 (55.8), 56.0 (3.1), 55.1 (3.4), 45.1 (2.8), 44.2 (100), 43.2 (8.5), 42.2 (4.8), 41.1 (7.5).

***N*-Cyclohexylaniline (3n).** Hydrogen [1500 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of cyclohexanone **1j** [0.9 $\mathrm{L/(kg_{cat}\ h)}$] and aniline **2f** [0.9 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1j** : **2f** = 1 : 1] was fed on 2 g of $\mathrm{Ni^0/MgO}$ at 200°C. Conversion of ketone **1j** 79%. Selectivity with respect to the product **3n** 88.5%, yield 70%. Mass spectrum, *m/z* (I_{rel}, %): 177.0 (3.8) $[M + 2]^+$, 176.0 (33.8) $[M + 1]^+$, 175.0 (67.1) $[M]^+$, 146.0 (7.3), 133.0 (10.7), 132.0 (100), 130.1 (5.0), 119.1 (8.7), 118.0 (18.6), 117.1 (11.5), 106.1 (6.8), 104.0 (4.3), 93.1 (6.5), 91.1 (5.7), 77.0 (9.9), 65.0 (4.9), 51.0 (7.1), 50.0 (4.3). ***N*-Phenylcyclohexanimine**, yield 8.4%. Mass spectrum, *m/z* (I_{rel}, %): 175.0 (8.1) $[M + 2]^+$, 174.0 (64.9) $[M + 1]^+$, 173.0 (100) $[M]$, 172.2 (13.4), 144.1 (8.7), 131.0 (8.8), 130.1 (83.4), 117.1 (6.5), 77.0 (5.6), 51.0 (4.7), 50.0 (2.8).

***N*-(Pentan-3-yl)piperidine (3o).** Hydrogen [250 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of pentan-2-one **1i** and piperidine **2j** [0.9 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1i** : **2j** = 1 : 3] was fed on 4 g of $\mathrm{Ni^0/NaX}$ at 200°C. Conversion of ketone **1i** 44.8%. Selectivity with respect to the product **3o** 100%, yield 44.8%. Mass spectrum, *m/z* (I_{rel}, %): 157.0 (1.1) $[M + 2]^+$, 156.0 (8.7) $[M + 1]^+$, 154.1 (3.2) $[M - 1]^+$, 127.0 (10.3), 126.1 (100), 124.2 (2.5), 110.1 (1.4), 98.2 (1.6), 70.1 (1.4), 42.0 (2.1).

***N*-Cyclohexylpiperidine (3p).** *a*. Hydrogen [1500 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of cyclohexanone **1j** and piperidine **2j** [0.9 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1j** : **2j** = 1 : 2] was fed on 2 g of $\mathrm{Ni^0/C}$ at 160°C. Conversion of ketone **1j** 70.2%. Selectivity with respect to the product **3p** 99.3%, yield 69.7%. Mass spectrum, *m/z* (I_{rel}, %): 169.0 (4.3) $[M + 2]^+$, 168.1 (35.3) $[M + 1]^+$, 167.0 (13.3) $[M]^+$, 166.2 (10.5) $[M - 1]^+$, 138.1 (2.5), 125.0 (9.8), 124.1 (100), 122.3 (2.0), 110.1 (3.5), 96.3 (4.6).

b. Hydrogen [500 $\mathrm{L/(kg_{cat}\ h)}$] and a mixture of cyclohexanone **1j** and piperidine **2j** [0.9 $\mathrm{L/(kg_{cat}\ h)}$, molar ratio **1j** : **2j** = 1 : 2] was fed on 2 g of $\mathrm{Ni^0/NaX}$ at 180°C.

Conversion of ketone **1j** 96.7%. Selectivity with respect to the product **3p** 98.5%, yield 95.2%. Mass spectrum, *m/z* (I_{rel}, %): 169.0 (4.3) $[M+2]^+$, 168.1 (35.3) $[M+1]^+$, 167.0 (13.3) $[M]^+$, 166.2 (10.5) $[M-1]^+$, 138.1 (2.5), 125.0 (9.8), 124.1 (100), 122.3 (2.0), 110.1 (3.5), 96.3 (4.6).

2-Methyl-*N*-(1-phenylethyl)propane-1-amine (3q). Hydrogen [250 L/(kg$_{cat}$ h)] and a mixture of acetophenone **1h** and isobutylamine **2b** [0.9 L/(kg$_{cat}$ h), molar ratio **1h** : **2b** = 1 : 5] was fed on 2 g of Ni^0/MgO at 180°C. Conversion of ketone **1h** 100%. Selectivity with respect to the product **3q** 42.4%, yield 42.4%. Mass spectrum, *m/z* (I_{rel}, %): 178.8 (9.6) $[M+2]^+$, 177.9 (87.4) $[M+1]^+$, 176.2 (3.5) $[M-1]^+$, 162.0 (21.9), 133.9 (10.5), 105.9 (16.0), 105.0 (100), 104.2 (5.4), 103.1 (9.9), 79.1 (8.9), 77.0 (7.9), 51.0 (3.7), 41.0 (3.4). **Ethylbenzene**, yield 55.4%. Mass spectrum, *m/z* (I_{rel}, %): 106.7 (2.9) $[M+1]^+$, 105.8 (33.1) $[M]^+$, 105.0 (7.7) $[M-1]^+$, 102.9 (3.7), 91.9 (6.6), 91.0 (100), 79.0 (3.0), 78.1 (3.0), 77.0 (4.5), 65.0 (11.4), 63.0 (3.8), 51.0 (5.9), 50.0 (4.4).

***N*-(1-Phenylethyl)hexane-1-amine (3r).** Hydrogen [750 L/(kg$_{cat}$ h)] and a mixture of acetophenone **1h** and hexylamine **2d** [0.9 L/(kg$_{cat}$ h), molar ratio **1h** : **2d** = 1 : 1.5] was fed on 4 g of Ni^0/NaX at 220°C. Conversion of ketone **1h** 92.1%. Selectivity with respect to the product **3r** 80.4%, yield 74%. Mass spectrum, *m/z* (I_{rel}, %): 206.8 (11.2) $[M+2]^+$, 205.8 (100) $[M+1]^+$, 204.2 (3.9) $[M-1]^+$, 191.1 (9.2), 190.2 (63.1), 134.0 (4.3), 120.0 (6.1), 106.0 (17.6), 105.1 (53.6), 103.2 (5.9), 79.0 (6.9), 77.9 (3.7), 77.0 (6.5), 51.2 (3.5), 41.1 (5.5). **Dihexylamine**, yield 18.1%. Mass spectrum, *m/z* (I_{rel}, %): 186.9 (8.1) $[M+2]^+$, 186.0 (74.1) $[M+1]^+$, 184.5 (2.3) $[M]^+$, 115.1 (4.1), 114.2 (29.6), 113.2 (6.6), 112.2 (2.6), 55.2 (2.8), 44.2 (100), 42.2 (4.6), 41.2 (6.6).

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

1. Nebykov, D.N., Popov Yu.V., Mokhov, V.M., Latyshova, S.E., Shcherbakova, K.V., Nemtseva, N.V., and Shishkin, E.V., *Russ. J. Gen. Chem.*, 2019, vol. 89, no. 10, p. 1985. https://doi.org/10.1134/S1070363219100013
2. Higassio, Y.S. and Shoji, T., *Appl. Catal. (A)*, 2001, vol. 221, nos. 1–2, p. 197. https://doi.org/10.1016/s0926-860x(01)00815-8
3. Rani, V.R., Srinivas, N., Kulkarni, S.J., and Raghavan, K.V., *J. Mol. Catal. (A)*, 2002, vol. 187, no. 2, p. 237. https://doi.org/10.1016/s1381-1169(02)00208-x
4. Ward, J. and Wohlgemuth, R., *Curr. Org. Chem.*, 2010, vol. 14, no. 17, p. 1914. https://doi.org/10.2174/138527210792927546
5. Nador, F., Moglie, Y., Ciolino, A., Pierini, A., Dorn, V., Yus, M., Alonso, F., and Radivoy, G., *Tetrahedron, Lett.*, 2012, vol. 53, no. 25, p. 3156. https://doi.org/10.1016/j.tetlet.2012.04.054
6. Menche, D., Bçhm, S., Li, J., Rudolph, S., and Zander, W., *Tetrahedron, Lett.*, 2007, vol. 48, no. 3, p. 365. https://doi.org/10.1016/j.tetlet.2006.11.082
7. Wang, C., Pettman, A., Basca, J., and Xiao, J., *Angew. Chem. Int. Ed.*, 2010, vol. 49, no. 41, p. 7548. https://doi.org/10.1002/anie.201002944
8. Jung, Y.J., Bae, J.W., Park, E.S., Chang, Y.M., and Yoon, C.M., *Tetrahedron*, 2003, vol. 59, no. 51, p. 10331. https://doi.org/10.1016/j.tet.2003.09.054
9. Quintin, W.D. and Marcus, E., USA Patent 4190601, 1978.
10. Pillai, R.B.C., *Proc. Indian Nat. Sci. Acad.*, 1995, vol. 61, no. 2A, p. 97.
11. Tararov, V.I., Kadyrov, R., Riermeier, T.H., and Börner, A., *Chem. Commun.*, 2000, no. 19, p. 1867. https://doi.org/10.1039/B005777K
12. Huang, H., Zhao, Y., Yang, Y., Zhou, L., and Chang, M., *Org. Lett.*, 2017, vol. 19, no. 8, p. 1942. https://doi.org/10.1021/acs.orglett.7b00212
13. Li, C., Villa-Marcos, B., and Xiao, J., *J. Am. Chem. Soc.*, 2009, vol. 131, no. 20, p. 6967. https://doi.org/10.1021/ja9021683
14. Santoro, F., Psaro, R., Ravasio, N., and Zaccheria, F., *ChemCatChem.*, 2012, vol. 4, no. 9, p. 1249. https://doi.org/10.1002/cctc.201200213
15. Pisiewicz, S., Stemmler, T., Surkus A.-E., Junge, K., and Beller, M., *ChemCatChem.*, 2015, vol. 7, no. 1, p. 62. https://doi.org/10.1002/cctc.201402527
16. Domine, M.E., Hernández-Soto, M.C., Navarro, M.T., and Pérez, Y., *Catalysis Today*, 2011, vol. 172, no. 1, p. 13. https://doi.org/10.1016/j.cattod.2011.05.013
17. Liu, J., Fitzgeraldand, A.E., and Mani, N.S., *Synthesis*, 2012, vol. 44, no. 15, p. 2469. https://doi.org/10.1055/s-0032-1316550
18. Sharma, S.K., Lynch, J., Sobolewska, A.M., Plucinski, P., Watson, R.J., and Williams, J.J.M., *Catal. Sci. Technol.*, 2013, vol. 3, p. 85. https://doi.org/10.1039/C2CY20431B
19. Zotova, N., Roberts, F.J., Kelsall, G.H., Jessiman, A.S., Hellgardt, K., and Hii, K.K., *Green Chem.*, 2012, vol. 14, p. 226. https://doi.org/10.1039/C1GC16118K
20. Chieffi, G., Braun, M., and Esposito, D., *ChemSusChem.*, 2015, vol. 8, no. 21, p. 3590.

https://doi.org/10.1002/cssc.201500804

21. Falus, P., Boros, Z., Hornyanszky, G., Nagy, J., Darvas, F., Urge, L., and Poppe, L., *Tetrahedron Lett*., 2011, vol. 52, p. 1310. https://doi.org/10.1016/j.tetlet.2011.01.062
22. Laroche, B., Ishitani, H., and Kobayashi Sh., *Adv. Synth. Catal*., 2018, vol. 360, p. 4699. https://doi.org/10.1002/adsc.201801457
23. Popov, Yu.V., Mokhov, V.M., Latyshova, S.E., Nebykov, D.N., Panov, A.O., and Davydova, T.M., *Russ. J. Gen. Chem*., 2018, vol. 88, no. 10, p. 2035. https://doi.org/10.1134/S1070363218100018
24. Popov, Yu.V., Mokhov, V.M., Nebykov, D.N., Shcherbakova, K.V., and Dontsova, A.A., *Russ. J. Gen. Chem*., 2018, vol. 88, no. 1, p. 20. https://doi.org/10.1134/S1070363218010048
25. Popov, Yu.V., Mokhov, V.M., Latyshova, S.E., Nebykov, D.N., Panov, A.O., and Pletneva, M.Yu., *Russ. J. Gen. Chem*., 2017, vol. 87, no. 10, p. 2276. https://doi.org/10.1134/S107036321710005X
26. Mokhov, V.M., Popov, Yu.V., and Nebykov, D.N., *Russ. J. Gen. Chem*., 2014, vol. 84, no. 9, p. 1656. https://doi.org/10.1134/S1070363214090023