

# PRESSURE MANIPULATION METHOD FOR THE EFFECTIVE SELF-ALDOL CONDENSATION UNDER SUBCRITICAL AND SUPERCRITICAL CO<sub>2</sub>

**Hajime Kawanami,\* Keitaro Matsui, Hiromichi Hayashi, Yutaka Ikushima**

Supercritical Fluid Research Center, National Institute of Advanced Science and Technology, and CREST, Japan Science and Technology, 4-2-1 Nigatake, Miyagino-ku, Sendai 983-8551, Japan  
E-mail: h-kawanami@aist.go.jp, Fax: +81-22-237-5215

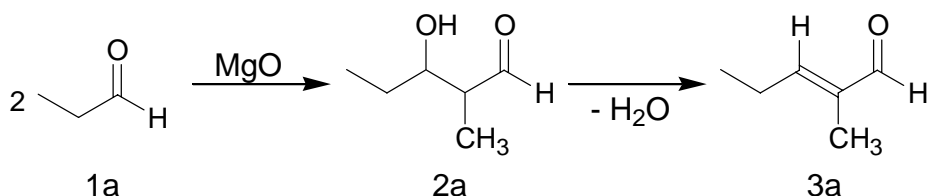
Under supercritical CO<sub>2</sub> conditions, simply the adjustment of pressure was found to successfully control the ratio of aldol product to enal one in the self-aldol condensation of aldehyde, in which the enal product was obtained in a maximum selectivity of 94% at the critical pressure of 12MPa, whereas 85% of selectivity to the aldol one was achieved at the subcritical region.

## INTRODUCTION

From the view point of greener processes, the design of organic synthetic method using supercritical carbon dioxide (scCO<sub>2</sub>) has become of much interest in recent years, because scCO<sub>2</sub> is considered as an environmentally benign and a cheap synthetic medium.<sup>1-7</sup> It has several advantages for chemical syntheses such as a relatively moderate physical properties (T<sub>c</sub> = 304.2 K, P<sub>c</sub> = 7.38 MPa) and easy tunable physicochemical properties such as density and solubility for substrate by adjusting the pressure and temperature.<sup>7</sup>

Though quite large number of homogeneous catalytic reactions have been reported so far, it has suffered from a serious disadvantages of the separation of reactant/product and of side reactions like decomposition, which could occur during the distillation after the reaction. Hence, the solid heterogeneous catalyst characteristic, such as thermostability and easy catalyst/product separation, is of great advantage than a homogenous catalyst for reuse.

The aldol reaction is one of the most important reactions to form C-C bonds.<sup>8</sup> Many attempts have been made to obtain aldol or enal product in high selectivity from unmodified aldehydes using heterogeneous catalysts such as alkaline oxides, alkaline earth oxides,<sup>9,10</sup> zeolite,<sup>11</sup> and hydrotalcites.<sup>12</sup> However, it is difficult to obtain the aldol or enal product in satisfactory selectivity, because of high reactivity of aldehyde group. In this work, we thus demonstrate that the self-aldol condensations of unmodified aldehydes can produce the aldol derivatives and unsaturated aldehydes in high selectivity in scCO<sub>2</sub>. Such a high selectivity can be successfully achieved by simply pressure manipulation without the improvement of catalysis by the addition of other metal cations.



**Scheme 1** Self-aldol reaction of propionaldehyde.

## I - MATERIALS AND METHODS

MgO (JRC-MGO-4 100A) used in this study was purchased from The Catalysis Society of Japan, and its physical properties are as follows: particle size: ca. 14 nm, BET surface area; 120 m<sup>2</sup>/g. MgO was heated at 100 °C under air for 1 h before the reaction.

The typical experiment procedure is as follows: acetaldehyde (10 mmol) or propionaldehyde (10 mmol), and MgO (50 mg) were charged into a 25 cm<sup>3</sup> stainless steel reactor at room temperature. In the case of addition of water, water (0.1 mL) was mixed with aldehydes and MgO. The reactor was heated at 80 °C and CO<sub>2</sub> was charged into the reactor to the desired pressure. Pressure control was achieved by a back-pressure regulator. The reactions were started by stirring the mixture, continued for 6 h. After reaction, the reactor was cooled to 0 °C with ice and the pressure was released slowly. The MgO was removed by filtration, and the products and yields were determined by GC-MS (HP 6890 GC System and 5973 Mass Selective Detector) with tridecane as an internal reference.

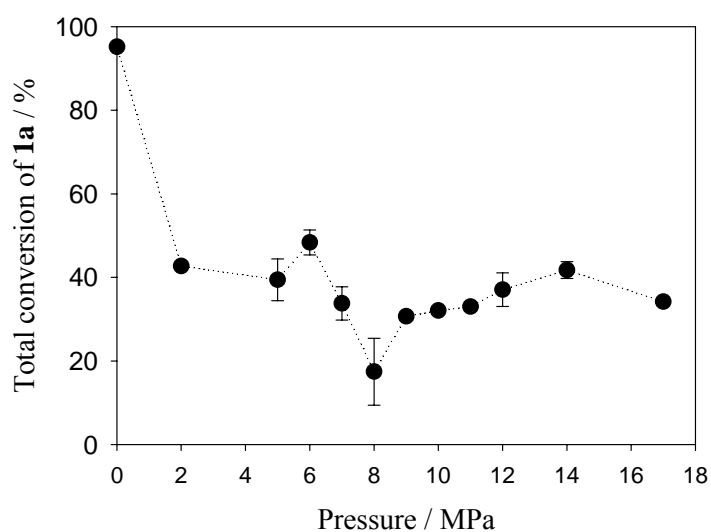
## II – RESULTS AND DISCUSSIONS

The self-aldol condensation of propionaldehyde was conducted in a batchwise operation. The results are summarized in Table 1. In the presence of MgO, the total conversions remarkably drop from 95% (run 2) to 20% (run 8) with increasing CO<sub>2</sub> pressure, because the basic site of MgO was inactivated by forming carbonic acid on the MgO surface, and the reactant was diluted by liquid and scCO<sub>2</sub> with increasing pressure which is disadvantage for the bimolecular reaction. However, the highest selectivity of 93% to 3-hydroxy-2-methylpentanal **2a** was obtained at CO<sub>2</sub> pressure of 5 MPa (run 5). The addition of water to the MgO system at a fixed CO<sub>2</sub> pressure of 5MPa remained a good selectivity to **2a** (run 6), but increasing the pressure up to 12 MPa led to the significant changes in selectivity for both MgO and MgO+water system (runs 8, 9), especially, in the MgO+water system the selectivity of **3a** showed a dramatic increase from 15 to 94%, as opposed to the drop in selectivity to **2a** from 85 to 5 % (runs 6, 9).

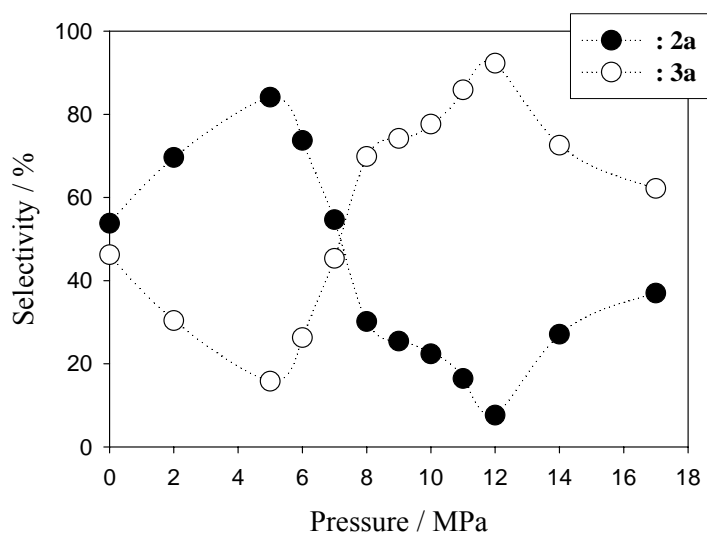
This enhancement in the selectivity to **3a** with pressure may be due to the dehydration of **2a** to **3a**, being catalyzed by carbonic acid as a Brønsted acid catalyst which

**Table 1** Aldol reactions of propionaldehyde in the presence of MgO catalyst.

Run	Subst.	Press. / MPa	Cat.	Conv / %	Y. of <b>2a</b> / %	Select. of <b>2a</b> / %	Y. of <b>3a</b> / %	Select. of <b>3a</b> / %
1		0	non	27	17	60	2	5
2		0	MgO	95	61	64	34	36
3		0	MgO	95	51	54	44	46
			+water					
4		5	non	18	11	61	0	0
5	Propion aldehyde	5	MgO	59	55	93	4	7
6		5	MgO	39	33	85	6	15
			+water					
7		12	non	18	10	55	4	22
8		12	MgO	20	9	45	10	50
9		12	MgO	37	2	5	35	94
			+water					



**Fig. 1** Pressure dependence of the total conversion of **1a** in the presence of MgO+water.



**Fig. 2** Pressure dependence of the selectivity of **2a** and **3a** in the presence of MgO+water.

was derived from a small amount of water and CO<sub>2</sub>. Thus the product distribution as the **2a/3a** ratio can be varied with simply controlling the pressure of CO<sub>2</sub>.

Figure 1 shows the CO<sub>2</sub> pressure dependence of the total conversion of **1a** in MgO in the presence of a small amount of water. One can see an interesting pressure dependence, in which the conversion decreases, reaching a minimum at 8 MPa, and then, increases to the maximum at the near-critical pressure around 14 MPa. Such a pressure dependence was previously reported when the CO<sub>2</sub> is used as a solvent or a reactant.<sup>2,3</sup> The pressure dependence of the selectivity was further investigated. Interestingly the selectivities toward **2a** and **3a** which vary in opposite manner with pressure can be seen in Fig. 2. In the lower pressure range below about 5 MPa, an increase in pressure accelerated only the formation of **2a** and led to the maximum selectivity to **2a** of 85% around 5 MPa, when the dehydration for the formation of **3a** from **2a** was depressed. However, further increase in pressure above 5 MPa attributed the higher selectivity to **3a**, attaining the maximum value of 94% at the critical pressure of 12 MPa. This pressure dependence would be due to the changing

property on the surface of MgO catalyst by adsorption of CO<sub>2</sub> and water at each pressure. At lower pressures below 8 MPa, CO<sub>2</sub> is adsorbed on the surface of MgO catalyst, and carbonic acid is formed by the reaction of CO<sub>2</sub> with added water which is also adsorbed on the surface of MgO, and the Brønsted acid derived from generated carbonic acid is considered to be neutralized with the basic sites of MgO, resulting the increase in selectivity to aldol **2a**. In supercritical condition, above at 8 MPa, water is more soluble than in gaseous CO<sub>2</sub>,<sup>13,14</sup> and the solvated water reacts with CO<sub>2</sub> likely to generate carbonic acid which could promote the dehydration of **2a** as a Brønsted acid. Thus, under supercritical conditions, the selectivity to **3a** would be higher than that under subcritical conditions at lower pressure region. We also investigated another aldol reaction of acetaldehyde under the same condition in the presence of MgO, and a similar pressure dependence on the product selectivity has been observed.

## CONCLUSION

In conclusion, we found that the selectivity of the self-aldol condensation of propionaldehyde can be tuned simply by the pressure of CO<sub>2</sub> in the presence of MgO catalyst with small amount of water. At the supercritical region the unsaturated aldehyde **3a** was obtained in a 94% high selectivity around the critical pressure of 12 MPa, while the aldol derivative **2a** was attained in a satisfactory selectivity of 85% at the subcritical region. Furthermore, acetaldehyde can be also converted into aldol or unsaturated aldehyde in good selectivity by pressure manipulation of CO<sub>2</sub>.

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## REFERENCES :

- [1] J. Hyde, W. Leitner and M. Poliakoff in *High Pressure Chemistry*, R. Eldik, and F.-G. Klärner Eds., Wiley-VCH, Weinheim, 2002, 369.
- [2] S. Fujita, B. M. Banage, Y. Ikushima, M. Arai, *Green Chem.*, 2001, **3**, 87.
- [3] H. Kawanami and Y. Ikushima, *Chem. Commun.*, **2000**, 2089
- [4] H. Kawanami and Y. Ikushima, *Tetrahedron Lett.*, 2002, **43**, 3841.
- [5] H. Kawanami and Y. Ikushima, *J. Jpn. Petrol. Inst.*, 2002, **45**, 321.
- [6] H. Kawanami, A. Sasaki, K. Matsui and Y. Ikushima, *Chem. Commun.*, **2003**, 896.
- [7] Y. Ikushima and M. Arai in *Chemical Synthesis Using Supercritical Fluids*, P. G. Jessop and W. Leitner Eds., Wiley-VCH, Weinheim, 1999.
- [8] W. Carruthers, *Some Modern Methods of Organic Synthesis – 3rd ed.*, Cambridge Univ. Press., New York, 1986.
- [9] K. Tanabe, G. Zhang and H. Hattori, *Appl. Catal.*, 1989, **48**, 63.
- [10] H. Tsuji, F. Yagi, H. Hattori and H. Kita, *J. Catal.*, 1994, **148**, 759.
- [11] E. Dumitriu, V. Hulea, I. Fechete, A. Auroux, F.-F. Lacaze, C. Guimon, *Microporous and Mesoporous Materials*, 2001, **43**, 341.
- [12] (a) Y. Anzai, M. Goto, A. Kodama, T. Hirose, *Proc. 14th Kyusyu-Taejin/Chungnam Symp. On Chem. Eng.*, 2001, 13; (b) M. Goto, Y. Anzai, A. Komada, M. Yoshida, *Chemical Engineering Transactions*, 2002, **2**, 85.
- [13] R. Wiebe and V. L. Gaddy, *J. Am. Chem. Soc.*, 1941, **63**, 475.
- [14] R. Wiebe, *Chem. Rev.*, 1941, **29**, 475.