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# Numerical and experimental approach on energy dissipation in nano colloidal damper

T. W. Ku[1], S. B. Jeon[2], V. H. Bui[3], W. J. Song[4], M. S. Park[5] and B. S. Kang[6,*]

[1]*Department of Aerospace Engineering, Pusan National University, Busan 609-735, S. Korea*
[2]*Samsung Heavy Industry, Geoje, Gyeongnam 656-710, S. Korea.*
[3]*Department of Aerospace Engineering, Pusan National University, Busan 609-735, S. Korea*
[4]*Industrial Liaison Innovation Cluster, Pusan National University, Busan 609-735, S. Korea*
[5]*Defense R&D Center, S&T Daewoo, Busan 609-600, S. Korea*
[6]Corresponding Author, *Department of Aerospace Engineering, Pusan National University, Busan 609-735, S. Korea*

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## Abstract

Mechanical damping systems have been widely used to various mechanical structures and systems, and are mainly hydraulic and pneumatic devices nowadays. New damping system such as nano colloidal damper (NCD) is complementary to the hydraulic one, having a cylinder-piston-orifice structure. This study includes numerical and experimental investigation about energy dissipation of NCD by using porous silica particles. In numerical approach, the dissipated energy was obtained between compression and relaxation processes for porous silica particle in NCD according to the capillary tube theory. Furthermore, for colloidal damper, the hydraulic oil was replaced by a colloidal suspension that was consisted of a nano-porous matrix with controlled architecture and a lyophobic fluid. NCD test rig and the measuring technique of the hysteresis were described in this study. Performance of the energy dissipation between numerical and experimental results was investigated and compared. As a result, the proposed NCD was proved to efficiently dissipate the mechanical energy.

*Keywords*: Energy dissipation system; Colloidal suspension; Porous particle; Nano colloidal damper

## 1. Introduction

Shock absorber device has been widely used to various mechanical damping structure and systems such as automobile, landing gear of aircraft, and so on. As one of this shock absorber, hydraulic damper (HD) which used the energy dissipation concept by operating viscous fluids has been generally applied. However, hydraulic damper has disadvantages such as the change of the viscous characteristics of working fluid and the variation in view of efficiency of hydraulic one in operation against external shocks.

The novel concept of heterogeneous structure based on nano-technology in the field of engineering proposed by Eroshenko and Fadeev can accumulate and/or dissipate the mechanical energy [1, 2]. One of the energy dissipated structure is called nano colloidal damper (NCD). This new damping system could be complementary to the hydraulic one and has a cylinder-piston-orifice structure [3]. This kind of colloidal damping system could be replaced with hydraulic one as an anti-vibration structure in all of industrial fields.

The mechanism of mechanical energy dissipation in damping system based on the colloidal suspension with nano porous particles is different from that of the existing hydraulic one as shown in Fig. 1.

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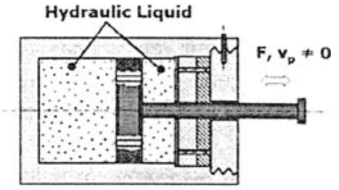
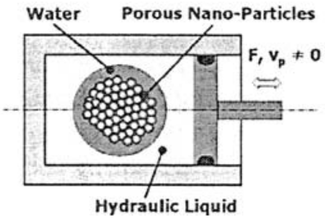
[*] Corresponding author. Tel.: +82 51 512 4491, Fax.: +82 51 510 2310
E-mail address: bskang@pusan.ac.kr



(a) Hydraulic damper

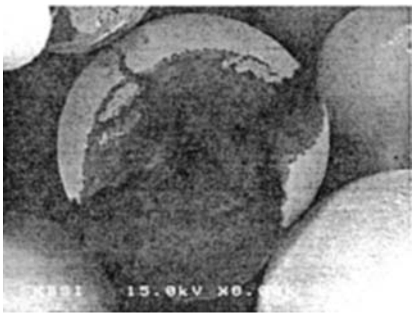


(b) Nano colloidal damper

Fig. 1. Schematic view of hydraulic damper (HD) and nano colloidal damper (NCD).

The colloidal suspension consists of lyophobic fluid and hydrophobic-coated porous particles or matrix. This porous matrix is composed of silica gel with labyrinth or central-cavity architecture as shown in Fig. 2. Water as a working fluid is considered to be associated lyophobic fluid. At compression operation, working fluid is forced to penetrate the porous matrix. Since the entire surface of the hydrophobic-coated porous matrix is hydrophobized, the external pressure works against the Laplace capillary pressure and the pressure of the gas trapped inside of the porous matrix, which tend to push out the water. Although the related studies have been made on introductory static experiments and theoretical investigation, there seems to be no diverse application of experimental study for the prediction of the performance of colloidal damping system [4, 5]. The absorbed energy of the damping system using colloidal suspension occurred because of the superficial tension of liquid-gas interface of the hydrophobic surface in nano porous particles [6].

This study includes numerical and experimental investigation about energy dissipation of the NCD by using porous silica particles. In numerical approach, the dissipated energy was obtained between compression and relaxation processes for porous silica particle in NCD according to the capillary tube theory. Furthermore, for colloidal damper, the hydraulic oil was replaced by a colloidal suspension that was consisted of a nano-porous matrix with controlled architecture and a lyophobic fluid. NCD test rig and the measuring technique of the hysteresis were described in this study. Performance of the energy dissipation between numerical and experimental results was investigated and compared. As a result, the proposed NCD was proved to dissipate the mechanical energy.



(a) Labyrinth architecture

(b) Central cavity architecture

Fig. 2. Architecture of nano porous particles.

## 2. Numerical approach for nano colloidal damper

### 2.1 Mechanism of Energy Dissipation

The performance for colloidal damping system can be estimated through the numerical approach using governing mechanical equilibrium conditions of capillary system, which is consisted with working fluid and nano porous particles having pores as nano-sized passages. Fig. 3 and Fig. 4 show a complete cycle from compression to relaxation of colloidal damping system. When colloidal damper is under external shock, working fluid percolates through nano-sized passage of porous particle.

The compression phase could be consisted of two steps like step A and step B in Fig. 3 with respect to the radius of capillary system. One (step A) is the process when the working fluid penetrates a nano-sized passage of the porous particle; the other (step B) is the process when the working fluid fills a cavity of

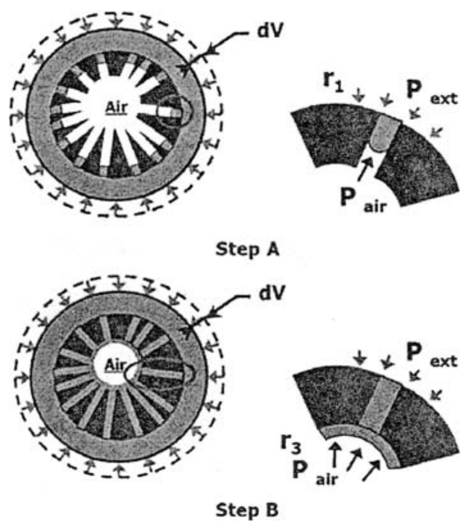


Fig. 3. Schematic description with steps of compression phase of total energy dissipation cycle.

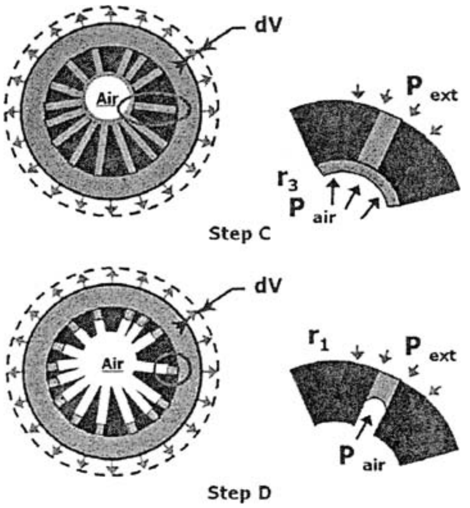


Fig. 4. Schematic description with steps of relaxation phase of total energy dissipation cycle.

the porous particle through the nano-sized passage. For step A, the angle of liquid-gas interface in the solid surface changes from 90° to 180° with loading the external pressure, and the radius of capillary system is that of the passage of a porous particle. For step B, the radius of capillary system is that of thecavity of a porous particle, and the angle of liquid-gas interface in the solid surface is considered as 180° regardless of loading the external pressure. And the working pressure in these steps of the capillary system in a porous particle is the external pressure.

The relaxation phase could be consisted of two operations like step C and step D as shown in Fig. 4 with respect to the radius of capillary system. One (step C) is the process when the working fluid flow off a cavity of the porous particle; the other (step D) is the process when the working fluid passes through a nano-sized passage of the porous particle. For a step C, the radius of capillary system is that of the cavity of a porous particle, and the angle of liquid-gas interface in the solid surface is considered as 180° regardless of loading the external pressure. For a step D, the angle of liquid-gas interface in the solid surface changes from 90° to 180° with loading the external pressure, and the radius of capillary system is that of the passage of a porous particle. And the working pressure in these of a porous particle is the pressure in the cavity of particle.

### *2.2 Capillary Phenomenon*

The performance of NCD is determined by the amount of dissipated-energy to that of absorbed-energy during compression phase of total cycle. In order to estimate the performance of that, variation of the absorbed volume of the working fluid should be calculated with respect to loading external pressure. Before the relationship with the variation of the absorbed volume to the external pressure is determined through the mechanical equilibrium of capillary system in porous particle with nano-sized passages, there are several assumptions to be considered as follows;

(a) A total cycle from compression to relaxation of nano colloidal damping system is isothermal process.

(b) Air in porous particle is considered as an ideal gas.

(c) The working fluid is considered as an incompressible one.

The governing mechanical equilibrium of capillary system in porous particles with the pores as nano-sized passages could be expressed as follows [5]:

$$P_{ext} = \frac{-2\sigma\cos\theta}{R} + P_{air} \qquad (1)$$

where $P_{ext}$ is the external pressure loaded, and $P_{air}$ the pressure in the cavity of porous particles. And $\sigma$ is superficial tension, $\theta$ angle of liquid-gas interface in the solid surface, $R$ and radius of capillary system, respectively.

Using the equation of state of ideal gas for isothermal process, the following relation between pressure and volume for two different states of ideal gas could be obtained.

$$P_{air} = P_{ATM}V_{ATM}\frac{1}{V_{air}}, \quad V_{air} = V_{ATM} - \frac{\Delta V}{N} \tag{2}$$

where $V_{air}$ is the volume of porous particle, $N$ the total number of porous particles, and $\Delta V$ variation of the absorbed volume, respectively. Then the governing mechanical equilibrium of capillary system in a porous particle with pores as nano-sized passages could be expressed from Eq. (2).

$$P_{ext} = \frac{-2\sigma\cos\theta}{R} + P_{ATM}V_{ATM}\frac{1}{V_{ATM} - (\Delta V / N)} \tag{3}$$

The relation with variation of the absorbed volume to the external pressure could be determined through Eq. (3).

### 2.3 *Results of numerical approach*

The numerical approach using the governing mechanical equilibrium condition of capillary phenomenon was carried out. Fig. 5 represents the hysteresis for one cycle as the results of numerical approach with low hydrophobic-coated nano porous particles at loading frequency of 0.1 Hz. In this case, nano porous particles were assumed to be the same mean particle diameter of 8 $\mu m$ and the mean pore diameter of 3 $nm$ as nano-sized passage, total volume of working fluid with nano colloidal particles in chamber of 100 *cc*, the maximum loading stroke of 57 *mm*, and the loading input was sin-waveform.

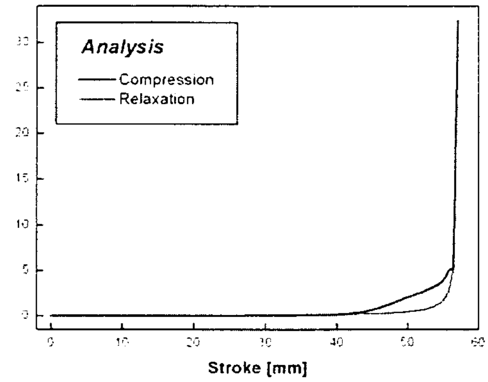


Fig. 5. Numerical analysis result for capillary system of nano porous particle in NCD.

## 3. Experimental approach for nano colloidal damper

### 3.1 *Experimental equipment setup for quasi-static test*

Fig. 6 shows the test equipments of NCD. In order to confirm the efficiency of mechanical damping system using colloidal suspension, the test apparatus was established. The inside diameter of cylinder was 30 *mm*, the inside permissible volume of cylinder approximately 120 *cc*, and the practicable stroke of the piston 85 *mm*. And high-pressure and temperature sensor was attached at the test rig. The equipment for calculating the inner pressure was used by the pressure sensor as PA-23S-400FAP which was 1,000 bar of pressure gauge. Furthermore, for measuring the inner temperature of the cylinder, temperature gauge applied was the PKE-PT100 with the temperature range as -50 ~200 . The indicated values of pressure and temperature operated by this system were recorded in time scale, by employing LabVIEW. Also displacement and load data were recorded in time scale by MAX of INSTRON software. The loading cycle from compression to relaxation was applied using the dynamic tester, INSTRON 8516. In addition, nano porous particles were assumed the same mean particle diameter of 8 $\mu m$ and mean pore diameter of 3 $nm$ as nano-sized passage.

### 3.2 *Influence of Working Fluid*

The influence of working fluid on mechanical damping system using NCD was analyzed through experiments.

The dissipated energy and efficiency of NCD could be expressed as follows;

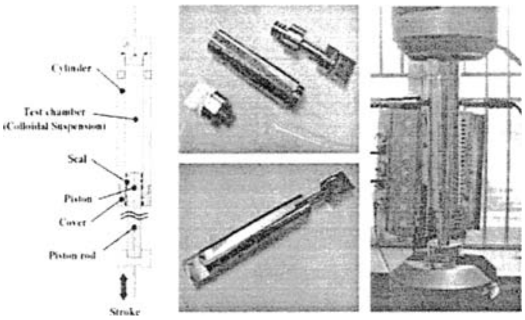


Fig. 6. Schematic diagram and experimental equipment for NCD.

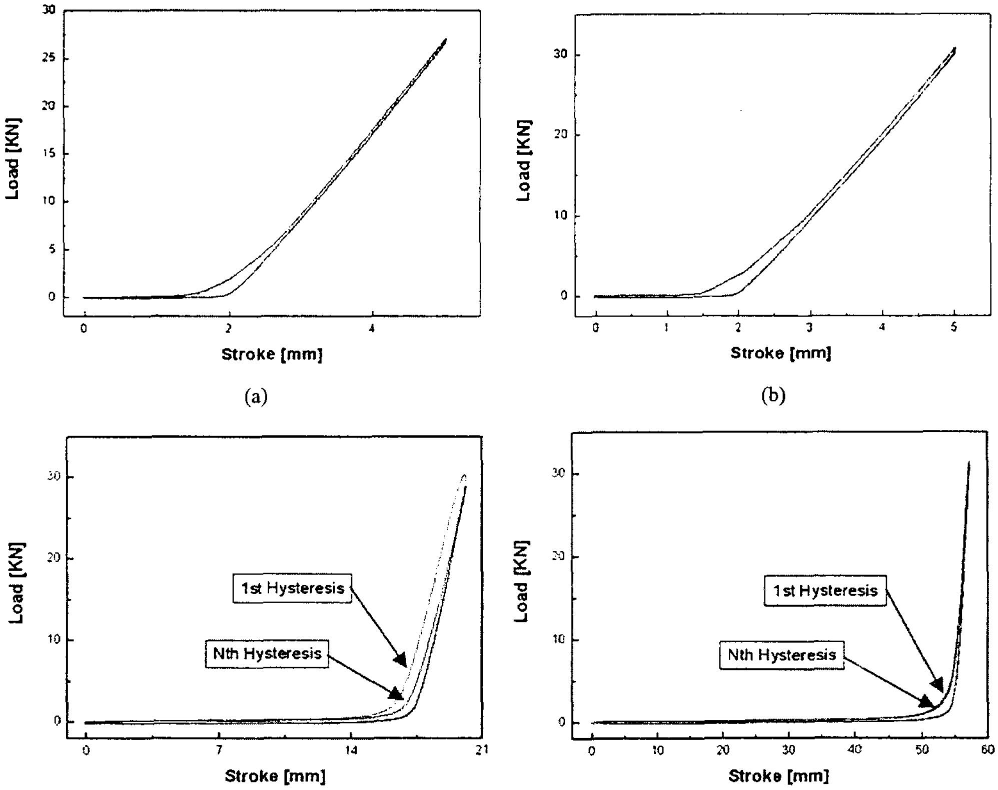
$$E_D = \int_0^{S_{max}} (L_C - L_R)\cdot dS\ ,\quad \eta = E_D / \int_0^{S_{max}} L_C \cdot dS \qquad (4)$$

where $E_D$ is the dissipated energy, $L_C$ the compression load, $L_R$ the relaxation load, and $\eta$ the efficiency of NCD, respectively.

Fig. 7 shows the influence by the composition types of working fluid in NCD. The first hysteresis was considerably larger than the N$^{th}$ cycles, which were identical. The inner range of the hysteresis represented the dissipated energy of NCD.

It shows the various hysteresis according to the strokes as shown in Fig. 7. For the experiments, the additives such as antifoaming agent and surface-active agent were composed with the distilled water. Fig. 7(a) shows the hysteresis in case of the composition with only distilled water. Fig. 7(b) exhibits the hysteresis when the composition consisted of distilled water, nano porous particle and surface-active agent. The cyclic loop as shown in Fig. 7(c) displays the result from the composition with the distilled water, nano porous particle and antifoaming agent. In the other hands, another cyclic loop in Fig. 7(d) is noticed in case of the composition with the distilled water and nano porous particle. Because the result of Fig. 7(d) has the effect by air-bubble between distilled water and hydrophobic porous particle, the efficiency in this case couldn't relied.

In terms of the additives, amount of the energy dissipation was considerable compared with other compositions and the efficiency was higher than others as shown in Fig. 7(c). The hysteresis loop means that the distilled water was absorbed in the pore space owing to the surface-active agent in Fig. 7(b). As results of absorption, the efficiency was lower than any other and then the value of the efficiency was 8.70 %. It was similar with the hysteresis loop of Fig. 7(a) within the case of the composition of the distilled water except nano porous particle.



(a) (b)

(c) (d)

Fig. 7. Influence of the working fluid on nano colloidal damper: (a) Only distilled water; (b) Surface-active agent and water mixture with nano porous particle( $\eta$ =8.7 %); (c) Antifoaming agent and water mixture with nano porous particle( $\eta$ =43.2 %); (d) Distilled water with nano porous particle( $\eta$ =46.9 %).

### 3.3 Influence of Loading Pressure

Fig. 8 shows the maximum loading pressure with the specified strokes as 55, 56, 57 *mm* at the first hysteresis, respectively. The inner range of the hysteresis which represents the dissipated energy of NCD increased with the increment of the inner pressure of cylinder. During operation the test equipment, the inner pressure of cylinder was increased at Case I (about 126 bar) with the stroke of 55 *mm*, Case II (about 281 bar) with the stroke of 56 *mm*, and Case III (about 447 bar) with the stroke of 57 *mm*, respectively.

After each loading was completed, the inner pressure was released to zero. And the efficiency of each case according to the various loading pressure for mechanical damping system using NCD was arranged at Table 1. Case I was higher than the efficiency of the others, but the dissipated energy was lower than any other.

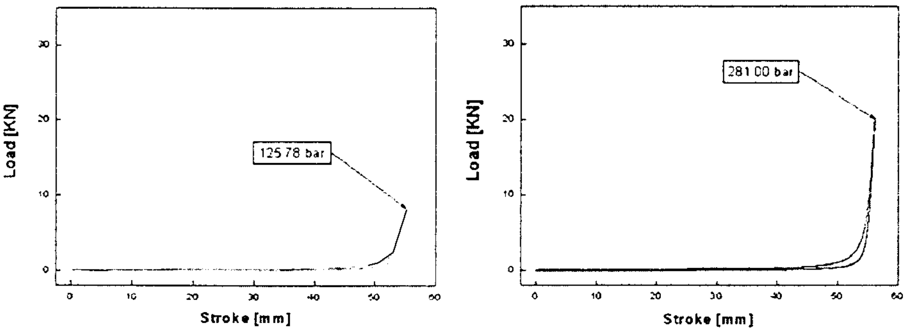
Table 1. Results of the experiment according to loading pressure.

| Case | Loading pressure [bar] | Dissipated energy [ J ] | Damper efficiency [%] |
|---|---|---|---|
| I | 125.78 | 16.56 | 64.89 |
| II | 281.00 | 23.53 | 55.47 |
| III | 446.83 | 30.94 | 46.86 |

## 4. Comparison between numerical and experimental results

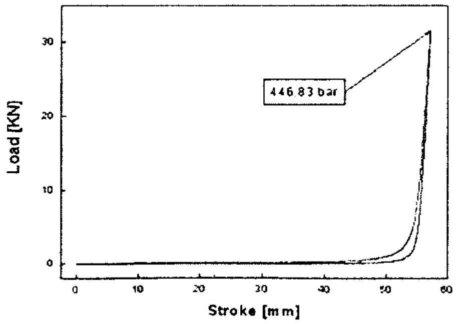
In order to validate the result of numerical approach using the governing mechanical equilibrium condition of capillary phenomenon, experiments were conducted with a test apparatus. Comparison conditions were that the diameter of nano porous particles was the same of 8 $\mu m$ and the pore diameter was equal of 3 *nm* as nano-sized passage, total volume of working fluid with nano colloidal particles in the chamber was 100 *cc*, the maximum loading stroke was 57 *mm*, inside diameter of cylinder was 30 *mm* between numerical and experimental approach, respectively.

Based on these conditions, numerical analysis result for capillary system of nano porous particle in NCD as shown in Fig. 5 could be compared with the experimental result from Fig. 8(c) because they had same piston stroke as 57 *mm*. Fig. 9 shows the comparison result between numerical analysis and experiments at the same stroke range. As shown in



(a) Case I

(b) Case II



(c) Case III

Fig. 8. Influence of the loading pressure on the NCD hysteresis.

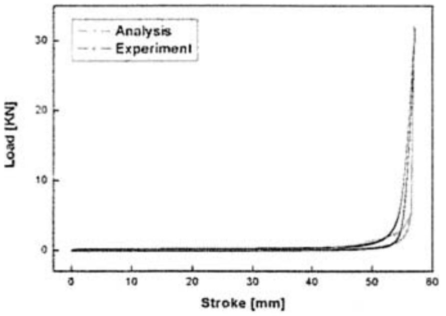


Fig. 9. Comparison between numerical and experimental results.

Fig. 9, the load distribution for the numerical analysis result by capillary theorem had similar trend to that of experimental one according to the stroke distance. Furthermore, the maximum load and the dissipated energy between numerical and experimental approach were almost the same as about 32 kN and 30 J, respectively.

## 5. Concluding remarks

The novel concept of nano colloidal damping system using colloidal suspension with nano porous particles and working fluid was investigated and the elementary researches through numerical and experimental approach were carried out in this study. In these approaches, NCD was consisted of lyophobic fluid and hydrophobic-coated porous matrix. The porous matrix of the colloidal damper was composed of silica gel with labyrinth or central-cavity porous architecture.

The influence of working fluid and the loading condition on this mechanical damping system of NCD was analyzed through numerical and experimental studies. From the results, the energy dissipation amount was observed differently according to the composition of working fluid and the stroke distance for mechanical damping system using the suggested NCD. In view of the composition of working fluid, the energy absorption by the damping system using NCD was occurred because of the superficial tensions of liquid-gas interface of the hydrophobic surface in nano porous particles. Furthermore, the stroke distance as a loading condition played an important role to control the performance in energy dissipation of mechanical damping system using colloidal damper with hydrophobic-coated porous particle and working fluid. Especially, the characteristics of mechanical damping system using colloidal suspension could be confirmed experimentally by a series of quasi-static tests for various loading conditions.

Resultantly, it was confirmed that new mechanical damping system by using NCD could be applicable in diverse mechanical structures under various loading conditions. The results of this study could be summarized as follows:

(1) The characteristics of NCD system could be determined by the suitable composition of the additives with working fluid and nano porous particle.

(2) It was confirmed that the energy dissipation and their efficiency of mechanical damping system using NCD was observed differently with respect to the composition of working fluid and the loading condition.

From comparison between numerical and experimental result, the capillary theorem could be applied to nano colloidal damping system with working fluid including nano porous particles.

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