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A Proposed Carbon Dioxide Sequestration Method Based on Cavitation

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***Abstract*— A methodology is presented in the paper for carbon dioxide (CO_2) sequestration, based on the use of cavitation and some other ways of mixing gases with fluids, towards its application as an effective mean to reduce CO_2 emissions to the atmosphere. The method was generated as an integral measure that will capture important amounts of CO_2 coming from a point source, e.g. a thermo power plant, and then transfer such amounts of the captured flow of CO_2 to a stream of wastewater, very likely serving as a pre-treatment of wastewater, in a wastewater treatment plant by the means of cavitation and/or some other ways of mixing gases with fluids. A future second stage on this study will be to demonstrate that the flow of CO_2 integrated into the stream of wastewater in a wastewater treatment plant, will have a significant effect as a mean of pre-treatment of the polluted water. Such an unexplored consequence might be considered as a beneficial side effect, being the main purpose of the proposed methodology the capture of some important amounts the flow of CO_2 with an effective sequestration procedure to incorporate as much as it is possible the amount of emissions to the atmosphere of such gas coming from a point source, e.g., a thermal power plant.**

Keywords—Carbon dioxide, CO_2 sequestration, global warming, global climate change, cavitation, wastewater, mixture of gases with fluids

I. INTRODUCTION

The publication of the IPCC's Fifth Assessment Report, [1], with its statement that "There is very high confidence that the net effect of human activities since 1750 has been one of warming", and the arrival last May, 2013 to the level of 400 ppm of CO_2 in the atmosphere, [2], have driven a lot of interest on how to develop measures of CO_2 sequestration, among other measures that are taking place nowadays to reduce the greenhouse effect gases (GHG) emissions to the atmosphere. It is a matter of speculation that such CO_2 concentration levels in the atmosphere had not took place on Earth since the mid-Pliocene about 2-4 million of years ago.

In [3], the following observed impacts, vulnerability, and adaptation in a complex and changing world:

1) In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*)
2) Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change (high confidence).
3) Based on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts (high confidence).
4) Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes (very high confidence)
5) Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (very high confidence).
6) Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (high confidence).

In [4] it has been has stated: "Climate change poses one of the most formidable challenges of the twenty-first century. It has planet-wide causes and consequences, but its impacts are asymmetrical among regions, countries, sectors and socio-economic groups, with those that have contributed the least to global warming being the hardest-hit." Furthermore, they have let us know that: "The challenge posed by climate change is associated with unsustainable production and consumption patterns that are largely based on the use of carbon-intensive fossil fuels. Climate change has ushered in a number of constraints that make it imperative to rework these production paradigms and consumption patterns. The multi-faceted challenge of adapting to new climate conditions and implementing mitigation measures while, at the same time, recognizing the existence of common but differentiated responsibilities and differing capacities is clearly a formidable one that will shape the development process of the twenty-first century."

The CO_2 emissions coming from thermal power plants that are used all over the world to generate electricity, by burning fossil fuels, mainly heavy oils and natural gas, have been neglected and there is very little information about them in order to get a real figure about their contribution to GHG emissions in the overall budget of the contributions of GHG to the actual global warming.

It has been stated that "The CO_2 emissions coming from thermal power plants are estimated to be the largest emitting sector globally of all man-made CO_2 emissions to the atmosphere", [5]. It is estimated that the number of thermal power plants are more than 30,000 facilities all over the world. The Arizona State University has created the *Ventus* website project to collect data from thermal power plants globally, [5].

More recently, [6], it has been drawn the attention to the fact that the reservoirs of dams might be producing as much as 20% of methane (CH_4) of total inland waters. They have stated that: "GHG emissions (transferred into carbon dioxide (CO_2) equivalents) from some tropical reservoirs even exceed CO_2 emissions from thermal power plants if the same amount of electricity is generated."

Finally, there is evidence of GHG production in wastewater treatment plants, [7].

II. ON THE USE OF CO_2 IN WASTEWATER TREATMENT

The industry has used for long time different ways of mixing gases to a stream of liquid in order to mix a gas and integrate it into the liquid. The most common example is that of mixing CO_2 with soft beverages to produce carbonated soft drinks. There are other applications in the dairy industry, in pulp and paper mills, mostly leather in the textile industry, in galvanic processes and in concrete handling.

It is well-known that by introducing CO_2 into a stream of wastewater the following advantages will be observed, [8]:

1) Safe and simple pH control, with no overdosing
2) Low investment costs
3) No impact in salt content and reduced discharge fees
4) Avoids corrosion problems when the effluents are recycled
5) It is a good candidate for the neutralization of industrial wastewater
6) Storage and handling simple and safe
7) Inert gas
8) No corrosion

The following are considered the most popular means to incorporate CO_2 into wastewater, [8]:

1) Pumped tube reactor with static mixer
2) Pumped tube reactor with multiple loops
3) Gas-liquid injector nozzles (dH > 40°)
4) Diffusers
5) Pressure vessel
6) Submerged aerators
7) Hose mats

The benefits of introducing CO_2 into an industrial wastewater stream was reported by [9]. They were seeking to substitute the use of sulfuric acid (H_2SO_4) by means of using of CO_2 in a modified wastewater treatment scheme. More than 90% of the vented CO_2 produced in a nearby ammonia plant was directly injected into the industrial wastewater to neutralize it to an acceptable standard pH of 7.0. It is a well-known fact that CO_2 in contact with water produces carbonic acid (H_2CO_3), and hence reduces the values of the pH. The final values achieved were: pH of 7.56, TDS of 155.15 ppm, and heavy metals of 1.49 ppm. The values using the old H_2SO_4 procedure were: pH of 8.77, TDS of 1000 ppm, and heavy metals of 2.90 ppm. The quantified benefits of this new process against the old one was an operational cost save of \$100,813 US dollars, with the avoidance of the additional inconvenience that H_2SO_4 has to be purchased. It was observed that it took 45 minutes longer to achieve those results with the new process compared with the old process.

III. USES OF CAVITATION IN WATER AND FOR OTHER APPLICATIONS

Cavitation is the phenomenon in which a bubble of gas is collapsed into a mass of liquid, see figure 1, [10].

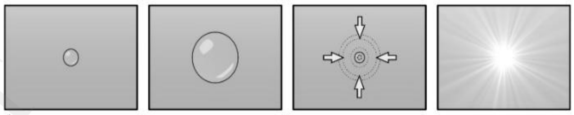

Figure 1. The phenomenon of cavitation in water, [10].

Usually, cavitation is found more frequently in hydraulic machinery, like turbines and pumps, and it is considered a very damaging phenomenon which produces the replacing of moving parts of such hydraulic machinery from time to time, [11].

Nowadays, there are three main fields for research in cavitation, [12]:

1) Elaboration of the model of the phenomenon itself reflecting the dynamics of imploding bubbles both with reference to a single bubble and the whole population
2) The negative influence of the hydrodynamic cavitation in liquids and consists in limiting its negative effects in ship propulsion system or in pump propellers
3) The search for application, to a larger extend, the positive effects of the cavitation phenomenon

The use of cavitation for wastewater treatment has been used for many years now.

Several ways to produce cavitation have been proposed:

1) Hydrodynamic cavitation
2) Ultrasonically induced cavitation
3) Acoustic cavitation

Hydrodynamic cavitation was used as an advanced oxidation process to oxidize the contaminants produced in landfill leachate, namely high concentration of organic carbon, total nitrogen in the form of ammonia nitrogen and some toxic refractive compounds, namely polycyclic aromatic hydrocarbons, polychlorinated biphenyls and heavy metals, [13]. After 30 minutes of hydrodynamic cavitation, the pH changed from 7.53 to 8.49 and there was an increase on temperature of 11 °C. They found the COD and TOC values were reduced by 6.7% and 5.1%, respectively, after 30 minutes of hydrodynamic cavitation. They expect to achieve better results if the arrangement of the holes on the orifice plates will be modified in the cavitation reactor, producing a change in the flow conditions and geometry of such reactor. CO_2 coming from a landfill as a mixture of landfill gas, was used to neutralize the pH of wastewater using a chemical absorption technique, [14]. They found that alkaline wastewater proved to be a highly effective CO_2 absorbent because of its high alkalinity, which occurred from the presence of ammonia.

Ultrasonically induced cavitation had been used for several purposes, from wastewater treatment, [15], to cosmetic non-surgical non-invasive liposuction. Another use of ultrasonically induced cavitation is that for stone kidney pulverization after the stone fragmentation was produced by the usual procedure using an medical ultrasound device for such purpose.

The most common applications of ultrasonically induced cavitation are, [16]:

1) Homogenizing for dispersing/de-agglomeration, emulsifying, wet milling/grinding
2) Disintegration for cell extraction and hot water disinfection
3) Sono-chemistry for transesterification (biodiesel)
4) Degassing for leak detection (bottles and cans)
5) Cleaning for wire/strip

There has been successful experiments, [17] and [18], at the laboratory level, of the molecular dissociation of the CO_2 by the use of an ultrasound bath and flotation cell, reaching levels of dissociation of 98.1%, [17], and of 96.5%, [18]. The volume of CO_2 used in the experiment was 500 ml and the time of exposure to ultrasonic and cell flotation was made for several durations ranging from 1 to 3 hours, [17], and then for 2 hours and 40 minutes, [17].Copper was used as catalyst. The author argued that "it is possible to apply this process to remove the CO_2 generated from gasoline by motor vehicles and to remove CO_2 from the smokestacks of industrial power plants that burn carbonaceous fuels". Furthermore, he stated "The use of an ultrasound bath and flotation cell is and efficient and inexpensive method for the dissociation of CO_2 gas and can be scaled-up for industrial application", [17].

IV. PROPOSED METHODOLOGY FOR CO_2 SEQUESTRATION

Using the property of the high solubility of CO_2 in water, being 200 times higher to the corresponding value for oxygen in water, reaching almost 0.90 cm^3 of CO_2 per 100 ml of water at room temperature and at atmospheric pressure, [19] and [20], this feature may be used to create an effective way to produce a way to perform CO_2 sequestration into a stream of wastewater in a wastewater treatment plant.

A secondary benefit will bethe pre-treatment of such wastewater. The behavior of the solubility of CO_2 in water for various temperatures at atmospheric pressure is depicted in figure 2.

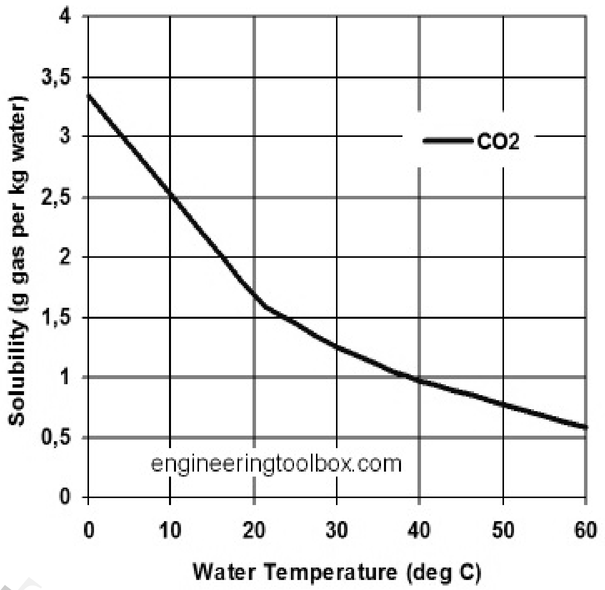

Fig. 2. Graph of solubility of CO_2 in water at atmospheric pressure for different temperatures, [19].

Carbon dioxide, like many other gases, is soluble in water. However, unlike many other gases, e.g. oxygen, it reacts with the ions present in water and forms a balance of several ionic and non-ionic species (collectively known as dissolved inorganic carbon, or DIC). These are dissolved free carbon dioxide (CO_2 (aq)), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}), and they interact with water as follows, [21]:

$$CO_2\,(aq) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2\,H_+$$

The balance of these carbonate species (which ultimately affects the solubility of carbon dioxide), is dependent on the chemical characteristics of water such as pH.

The proposed sequestration measure to capture CO_2 coming for a point source, e. g., a thermal power plant, is that of integrating such GHG component into a wastewater stream in a wastewater treatment plant, by any mixing procedure to incorporate a gas into a liquid stream.

The way we are proposing to perform the former, is to mix the CO_2 with a wastewater stream by the means of a cavitation producing device in a process before entering to the wastewater treatment plant, see figure 3, which it seems to be the more efficient way to do it. Other procedure is to mix CO_2 with wastewater through the use of a millipore membrane that will produce nano-bubbles of CO_2 and then they will eventually collapse producing implosions and they will then become part of the wastewater stream in a site before entering a wastewater treatment plant.

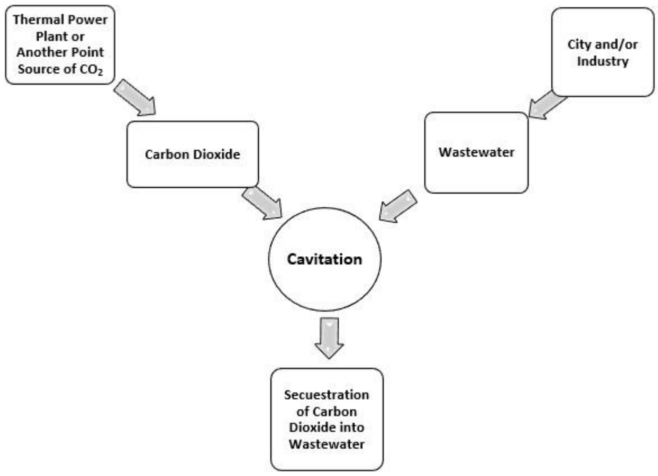

Fig. 3. Proposed Procedure for CO_2 Sequestration Based on Cavitation.

Three different devices that produce cavitation are being considered in this proposed methodology. The first one is the Multiphasecavitator-Insert for Ultrasonic Flow Cell produced by Hielscher, [16], see figure 4.

The concept is easy to incorporate into existing processes, [16]:

1. Feed phase A into liquid entry port at the bottom of the flow cell
2. Feed phase B into smaller liquid entry port(s) at the side of the flow cell. This feed will be injected into the cavitational area through 48 fine pipes
3. Adjust reactor pressure using a back-pressure valve at the flow-cell outlet port

At bench-top level a UIP1000hd (1kW) can process flow rates from 100 to 1000 lt/hr (25 to 250 gal/hr) for process demonstration and for the optimization of the sonication parameters. Hielscher ultrasonic processors are designed for linear scale-up to larger processing volumes at pilot or production scale. The table below lists processing volumes and recommended equipment sizes, [16].

The second way to produce the mixture of CO_2 with wastewater through cavitation considered is by using nanostructured ceramic membranes, [22], or by using Millipore membranes to produce nano-bubbles that will collapse by the hydrostatic pressure within the fluid of wastewater.

The third mean, is by using a device consisting in a nozzle of carbon ceramic that produces nano-bubbles of a gas, was developed by [23], see figure 5.
The manufacturer stated that such device can be escalated to any dimension in order to be used in industry and laboratory scale as well.

They have applied the use of such nano-bubbles generator to increase the dissolved oxygen concentration and thus restore aquatic life in a site of the seashore of Yokohama City at the Nippon-maru Memorial Park with very good results after the period of six months, which was the period of time that such experiment took place.

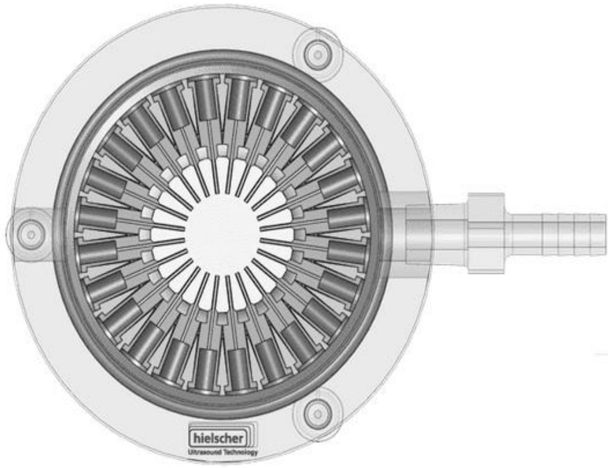

Fig. 4. Multiphasecavitator-Insert for Ultrasonic Flow Cell, [16].

Table 1. Hielscher ultrasonic processors processing volumes and recommended equipment sizes, [16]

Batch Volume	Flow Rate	Recommended Devices
0.2L	0.25 to 2m^3/hr	UIP1000hd, UIP2000hd
0.2L	1 to 8m^3/hr	UIP4000
n.a.	4 to 30m^3/hr	UIP16000
n.a.	above 30m^3/hr	cluster of UIP10000 or UIP16000

The comparison between the size of the generator of nano-bubbles with the size of a pen is shown in figure 6. The nano-bubbles generator is shown in operation in figure 7.

Each system will be evaluated in the laboratory under four criteria:

1) Cost of the device itself.
2) Efficiency of the system under different conditions.
3) Durability of the system.
4) Ease for system escalation for real-world applications.

The proposed arrangement for the carbon dioxide sequestration method proposed here it is shown in figure 8.

In a future stage of our research, we will be looking for other beneficial side effects as products of the pre-treatment of wastewater before entering the wastewater treatment plant with CO_2, like the well-known effect of the stabilization of pH of wastewater when carbon dioxide is applied to it.

Fig.5. Nano bubbles generator, [23].

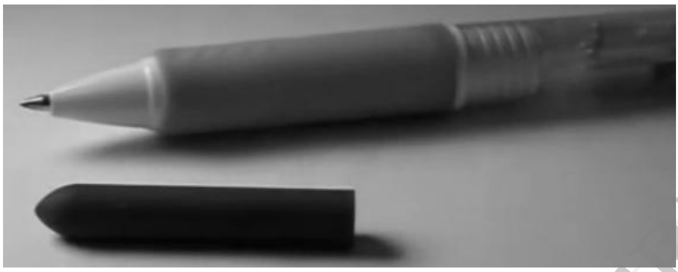

Fig. 6. Comparison between the size of the nano-bubbles generator with the size of a pen, [23].

Fig.7. Nano-bubbles generator in operation, [23].

CONCLUSIONS

The following conclusions could be drawn so far at the stage of this study:

a) Giving the high solubility of CO_2 in water, its sequestration in wastewater prior treatment seems feasible with several positive side effects.

b) There is very few studies looking at the side effects of increasing the CO_2 in wastewater as a pre-treatment.

c) There is a wide range of devices to mix CO_2 with water in the market. Each one needs to be evaluated to determine which one is the best alternative to be escalated to real life treatment systems and to determine the troubleshooting and limitations of each one when in presence of wastewater.

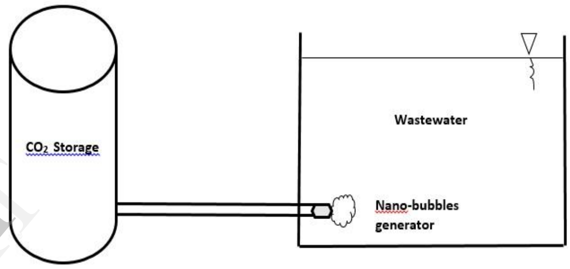

Fig. 8. Proposed arrangement for CO_2 sequestration into wastewater.

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REFERENCES

[1] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2013: The Physical Science Basis. Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.). IPCC, Geneva, Switzerland. 2013

[2] The Guardian, 2013 Record 400ppm CO2 milestone 'feels like we're moving into another era'. Fen Montaigne for Yale Environment 360, part of the Guardian Environment Network, theguardian.com, Tuesday 14 May 2013 17.02 BST

[3] Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers", Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.Contribution of Working Group II to the Fifth Assessment Report ofthe Intergovernmental Panel on Climate Change, C.B. Field and others,(eds.), Cambridge, Cambridge University Press. 2014

[4] ECLAC, The economics of climate change in Latin America and the Caribbean: Paradoxes and challenges. 2014

[5] Gurney, K. and O'Keeffe, D.,Crowdsourcing power plant carbon dioxide emissions data, EOS, 94(43), pp 385-386, 22 October 2013.

[6] Keller, J. and Hartley, K., Greenhouse gas production in wastewater treatment: process selection is the major factor, Water Sci. Technol. 47(12), 43-48, 2003.

[7] Yang, L., Lu, F., Wang, X., 2014, Measuring Greenhouse Emissions from China's Reservoirs, EOS, Vol. 95, No. 1, 7 Jan, 2014.

[8] Messer, Effective cleaning of industrial wastewater, 2014. http://www.elmemesser.lv/assets/media/201124/3d826f46b9f6bf4e11e316439c55dafe.pdf

[9] Enyi, C.G. and Appah, D., Improved wastewater treatment using carbon dioxide, Advanced Materials Research, 18-19, 569-575, 2007. DOI: 10.4028/www.scientific.net/AMR.18-19.569

[10] Wikipedia, http://en.wikipedia.org/wiki/Sonoluminescence, 2014

[11] Roberson, J. A., Cassidy, J. J. and Chaudhry, M. H., Hydraulic Engineering, 2nd Ed., John Wiley and Sons, New York, 1998.

[12] Ozonek, J. and Lenik, K., Effect of different design features of the reactor on hydrodynamic cavitation process, Archives of Materials Science and Engineering, 52(2), 112-117, 2011

[13] Korniluk, M. and Ozonek, J., Application of hydrodynamic cavitation for leachate of municipal landfill site, Environmental Engineering, Proc. 8th International Conference, Vilnius, Lithuania, 584-587, May 2011.

[14] Gaur, A., Park, J. W., Jang, J. H., Maken, S., Joonjae Lee, and Song, H. J., Characteristics of Alkaline Wastewater Neutralization for CO2 Capture from Landfill Gas (LFG), Energy Fuels, 23, 5467–5473 : DOI:10.1021/ef900615h, 2009

[15] Mahvi, A. H., Application of ultrasonic technology for water and wastewater treatment, Iranian J. Publ. Health, 38(2), 1-17, 2009.

[16] Hielscher, Ultrasound Technology: Multiphasecavitator-Insert for Ultrasonic Flow Cel, 2014. http://www.hielscher.com/technolo.htm

[17] Abrego, J. F., Carbon dioxide (CO_2) dissociation and capture by means of ultrasound and flotation cell, J. Appl. Sci. Res., 6(5), 469-472, 2010.

[18] Abrego, J. F., Energetic determination on carbon dioxide (gas) dissociation by means of ultrasound and flotation cell, J. Basic Appl. Sci. Res., 2(2),1193-1196, 2012.

[19] Engineeringtoolbox (ETB), 2014.
http://www.engineeringtoolbox.com/gases-solubility-water-d_1148.html

[20] Pool Water Treatment Advisory Group (PWTAG), Carbon dioxide in water equilibrium, 2014.
http://www.pwtag.org/researchdocs/Used%20Ref%20docs/52%20Carbondioxide%20in%20water%20equilibrium.pdf

[21] Harned, H. S. and Davis, R, The ionization constant of carbonic acid in water and the solubility of carbon dioxide in water and aqueous salt solutions from 0 to 50°, J. Am. Chem. Soc., 65 (10), 2030–2037, 1943.

[22] Nwogu, N. C., Gobina, E. and Kajama, M. N., Improved carbon dioxide capture using nanostructured ceramic membranes, Low Carbon Economy, 4, 125-128, 2013.

[23] Anzaikantetsu (2014).
http://anzaimcs.com/en/main/examplenanobubble.html