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Visualization of supersonic non-Newtonian liquid jets

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Abstract. This paper describes the characteristics of supersonic non-Newtonian liquid jets injected in ambient air. The main focus is to visualize three types of time-independent non-Newtonian liquid jet and to describe their behaviors. Moreover, comparisons between their dynamic behaviors with Newtonian liquid jet are reported. The supersonic liquid jets are generated by impact driven method in a horizontal single-stage power gun. Jets have been visualized by the high speed digital video camera and shadowgraph method. Effects of different liquid types on the jet penetration distance, average jet velocity and other characteristics have been examined. From shadowgraph images, the unique dynamic behaviors of each non-Newtonian liquid jets are observed and found obviously different from that of the Newtonian liquid jet. The maximum average jet velocity of 1,802.18 m/s (Mach no. 5.30) has been obtained. The jet penetration distance and average velocity are significantly varied when the liquid types are different.

Introduction

Recently, high speed liquid jets are well known in extensive engineering applications such as the cleaning and cutting technologies, mining, and tunneling, SCRAM (Supersonic Combustion RAM) jets, direct injection (DI) diesel, drug injection, tissue cutting, and removing of a cerebral thrombus [1-4]. Hence, their characteristics or dynamic behaviors have been intensively gained attention and continuously studied by many researcheres [5-9].

However, most of the previous studies have been interested at only high speed Newtonian liquid jets such as water, diesel fuel, gasoline, kerosene, and alcohol jets while there have been few studies about high speed non-Newtonian liquid jet [7]. Therefore, the understanding on the dynamic behaviors of high speed non-Newtonian liquid jet at the speed of supersonic range is still needed. In this study, supersonic non-Newtonian fluid jets were generated by impact driven method and visualized by shadowgraph technique. Three types of time-independent non-Newtonian fluid jets, which are milk, salad dressing, and toothpaste jets being classified as pseudo plastic, dilatant, and bingham plastic fluids, respectilvely, are clarified. Effect of verious jet types on jet penetration distance and average jet velocity are also analyzed. Moveover, the distinction of charateristics between newtonian and non-Newtonian fluid jets are described.

Experimental apparatus

In this study, supersonic liquid jets are generated by impact driven method [5]. Using this technique, the liquid retained in the nozzle cavity is impacted by a high velocity projectile. The liquid obtains the momentum transfer from the projectile and is injected from the nozzle. The high velocity projectile in this technique has been generated by the horizontal single stage powder gun (HSSPG) as shown in Fig. 1a. The HSSPG consists of the launcher, launch tube, pressure relief section, and test chamber. The launch tube has a diameter of 8 mm and length of 1.5 m. The pressure relief section has a length of 40 cm, which is designed to diminish the blast wave in front of the projectile. The pressure relief section has 3 slots, which each slot has an open grap of 4 mm in width and 36 cm in length. The test chamber is a square tank of 350×350 mm in width and 590 mm in length with polymethyl methacrylate (PMMA) windows on two sides for visualization. The projectile is made of polymethyl methacrylate (PMMA), is cylindrical shape with diameter of 15 mm and length of 8 mm (weight of 0.92 g) as shown in Fig. 1b. This HSSPG has been employed to generate the high speed liquid jet velocity ranged from 550 to 2.290 m/s injected into air. The nozzle being connected to pressure relief section made of mild-steel, whose dimension is shown in Fig. 1c. In this study, the gunpowder of 5 g is used, which can launch the projectile speed of about 952 ± 32 m/s.

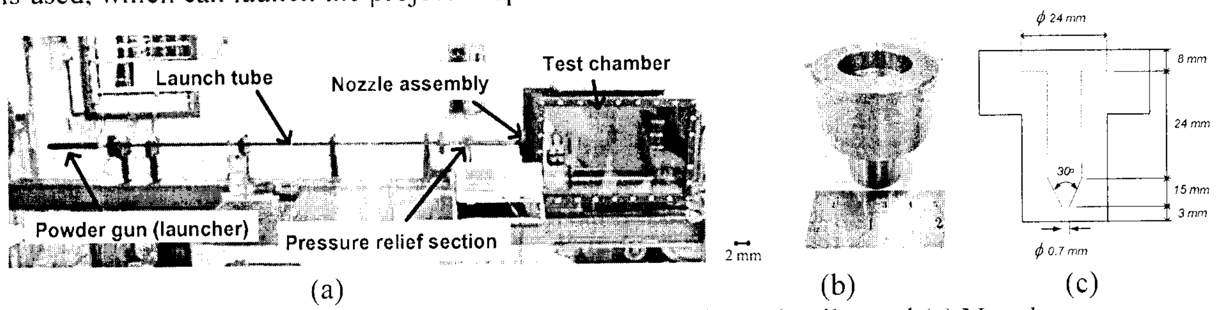


Figure 1 (a) Horizontal Single-Stage Powder Gun, (b) projectile, and (c) Nozzle geometry

Visualization method

In this study, a high speed digital video camera and shadowgraph optical was used for visualization as shown in Figure 2. The dynamic formation of supersonic jets is quanlitatively measured by sequential observations. A Xenon lamp is used as a light source. Thereafter, the source light is passed through a concave lens and a circular slit. The laboratory space is limited so that two plane mirrors of diameter 190 mm are combined in this arrangement. Two paraboloidal schlieren mirrors of diameter 300 mm were used for collimating source light beam passing the test section area. A Nikon 60 mm Macro lens was used to focus the object image on the camera screen. The high speed digital video camera is a Photron SA5 at frame rate of 30,000 f/s, minimum shutter speed of 1 μs, and 5.46 seconds record time at full resolution.

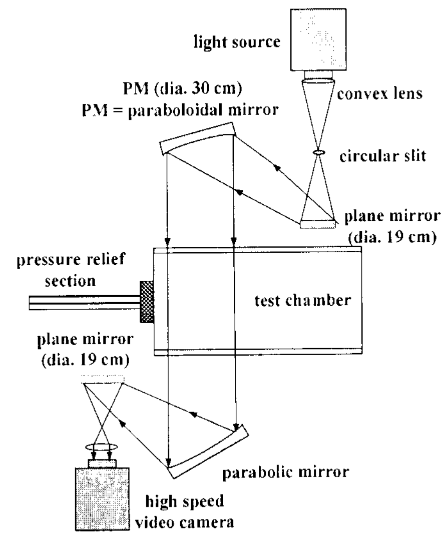


Figure 2 Arrangement of shadowgraph optical system and high speed digital video camera

Results and discussion

Using a high speed digital video camera, Photron SA5 could record shadowgraph images at frame rate of 30,000 f/s and shutter speed of 1 μs. This sequential recording is very useful to observe the jet formation. Four liquids, which are water, milk, salad dressing, and toothpaste being classified as newtonian, pseudo plastic, dilatant, and bingham plastic fluids, respectively, are investigated in this study. Since not all frames from the camera can be displayed in the paper, only twelve sequential images are selected to represent the stages in jet development, as shown in Fig. 3.

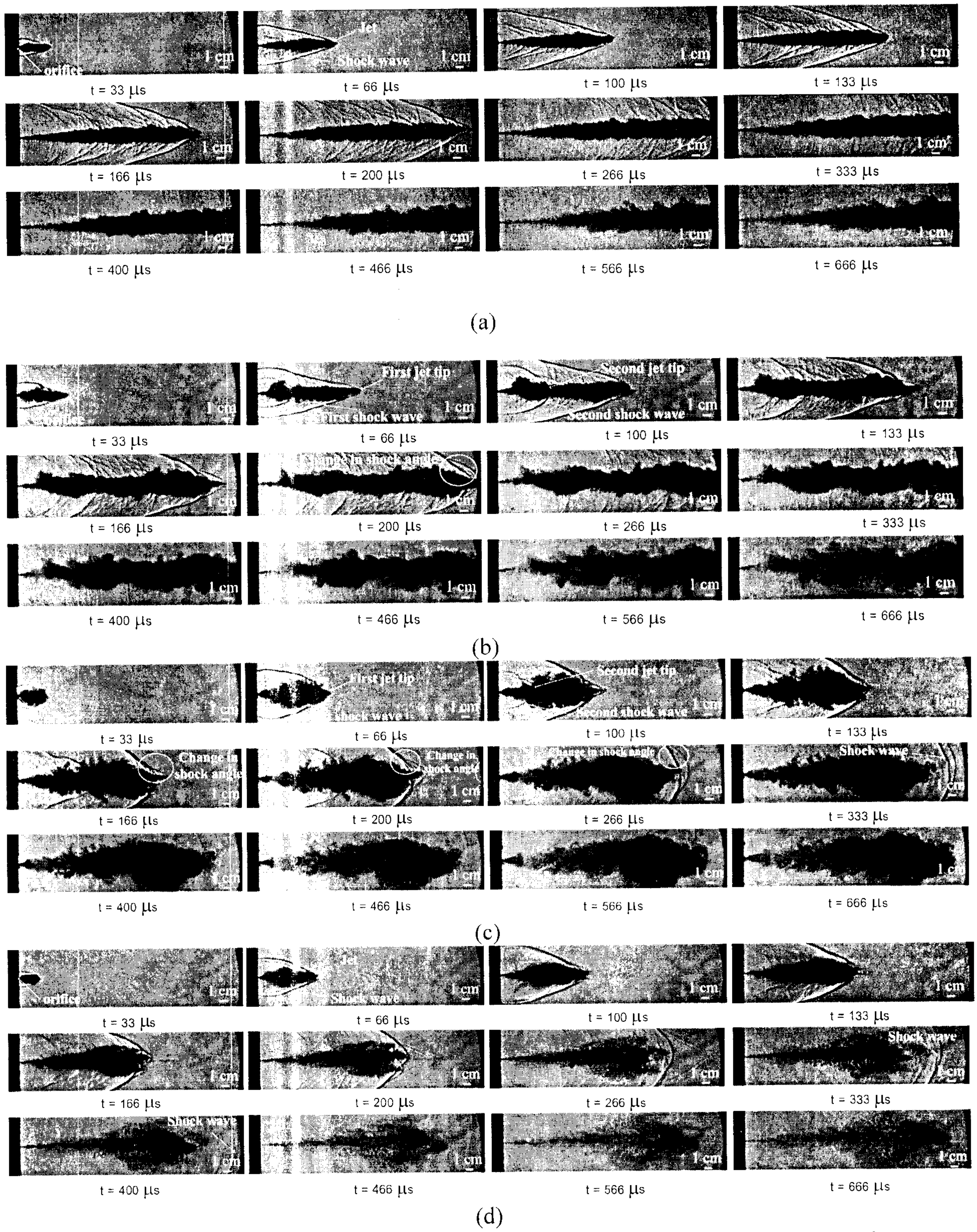


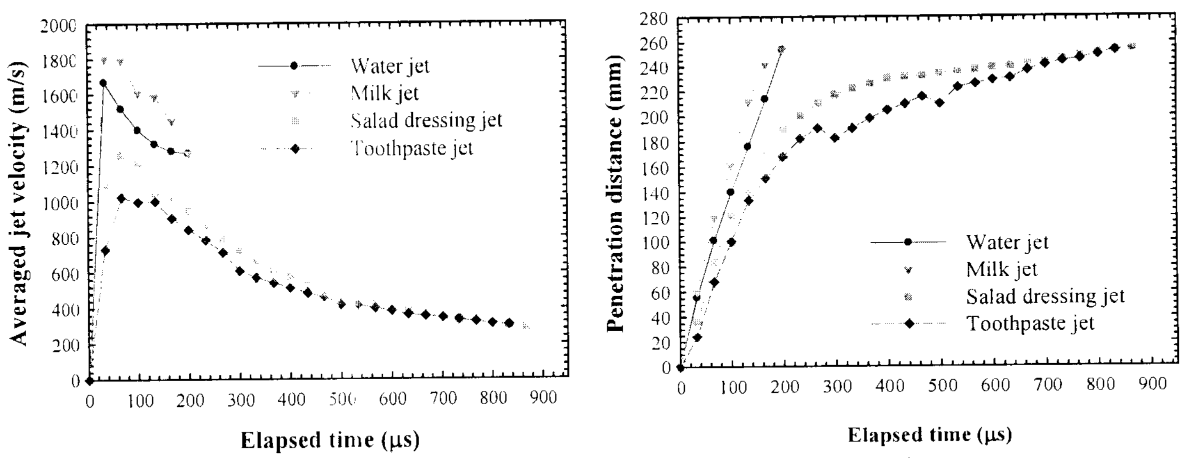
Figure 3 Jet formation (a) water jet (b) milk jet (c) salad dressing jet (d) toothpatse jet

In order to compare with non-Newtonian liquid jet, a water jet formation being classified as newtonian liquid jet is shown in Fig 3a. Its dynamic behaviors have been clearly described in Matthujak's study [10]. The water jet shows the slim width and looks more elongated to be over 213 mm at 166 μs. Its averaged speed at 166 μs is 1,282 m/s being Ms = 3.77 in room temperature air. The jet motion is supersonic so that oblique shock waves are created over its tip and also the jet's nodes as shown in the figure.

Figure 3b shows a milk jet formation, which is classified as pseudo plastic fluid. The milk jet is similar to the water jet at the earlier stage, being the elasped time (t) of 33 to 133 μs. The second shock wave and the change in shock angle was obviously observed at t = 66–133 μs and t = 200 μs, respectively. Such both behaviors were implied that the second jet took place from a single impact of the projectile (this behavior has been described in Pianthong's and Matthujak's study [8, 9]). Base upon the rheology of pseudo plastic fluid, which its dynamic viscosity decreases as the rate of shear increases, therefore, the nodes created over the milk jet look more bulkier than those in water jet at t = 166–333 μs and the atomization of milk jet look more stronger than that of water jet at t = 400–666 μs.

Figure 3c shows a salad dressing jet formation, which is classified as dilatant fluid. The general trend is much different from water and milk jets. The jet was quickly and strongly atomized once it was injected from the orific while the strong atomization of the water and the milk jets took place at the later stage. It may be because of the rheology of dilatants fluid, which its dynamic viscosity increases as the rate of shear increases. From the images, the second shock wave and the change in shock angle was obviously observed at t = 100–200 μs and t = 166-266 μs, respectively. Both behaviors implied that the second jet took place similar to the milk jet. After 333 μs, the jet boundary on images looks blurred. A shock wave is attached at the jet's leading edge but after 333 μs it becomes a detached shock wave because the jet penetration is much slower than the shock motion. The atomization mechanism of the salad dressing jet was seemingly quicker than that of water and milk jets since that of the salad dressing jet was nearly finished at t = 400–666 μs while that of water and milk jets was not at those times.

Figure 3d shows toothpaste jet formation, which is classified as bingham plastic fluid. Its general trend is not much different from water and milk jets at the earlier stage, being the elasped time of 33–133 μs. After t = 166 μs, a shear layer occurring around the toothpaste jet is the strongest, which is implied that its atomization is the strongest. It may be due to the rheology of bingham plastic fluid, which the shear stress must reach a certain minimum value before flow commences. Thereafter, dynamic viscosity decreases as the rate of shear increases, being similar to pseudo plastic fluid. After t = 266 μs, a shock wave was detached at the jet's leading edge due to the slow jet penetration and such shock was still undulated far from the jet tip even though the jet did not penetrate. A strong atomization of the jet was clearly seen at t = 333–666 μs.



(a) (b)

Figure 4 Effect of difference liquids on (a) average jet velocity (b) jet penetration distance

Fig. 4a shows the effect of different liquid jets on the average jet velocity. During the maximum velocity point at the emerging time of around 33 μs, the velocity of all liquid jets drops gradually as obviously seen in the figure. The maximum averag velocity of milk jet is the highest, being 1,802.18 m/s approximately. The next one is water, salad dressing, and toothpatse jets, respectively, which are estimated to be 1,669.03 m/s, 1,262.38 m/s, and 1,024.35 m/s, respectively. The jet velocity certainly affects on the penetration distance as plotted in Fig. 4b. It is found that the faster the average jet velocity is, the longer the jet penetrates. Hence, the penetration distance of the milk jet is the longest at the same elapsed time as shown in the figure. The second one is water and salad dressing jets, respectively. The shortest penetration distance is toothpatse jet. It can be noticed that at the later stage the average velocity of the salad dressing jet and the toothpaste jet is quite similar at the same elasped time.

Concluding remarks

This study reports the formation of supersonic water, milk, salad dressing and toothpaste jets injected in air. These are defined as newtonian, pseudo plastic, dilatant, and bingham plastic fluids, respectively. Using a high speed digital video camera with shadowgraph optical arrangement, the dynamic behaviors of all jets have been clearly revealed. From the visualization results, the shock wave around the jet is clean and smooth. The milk jet is similar to the water jet at the earlier stage, being narrow and long. The salad dressing jet was quickly and strongly atomized once it was injected from the orific. However, a shear layer of the toothpaste jet occurring around the jet or the atomization was seemingly strongest. The jet penetration distance and average jet velocity are significantly varied when the liquid types are different. The maximum average jet velocity of 1,802.18 m/s (Mach no. 5.30) has been obtained from the milk jet. That provides the milk jet to have the longest penetration distance at the same elasped time.

Acknowledgement

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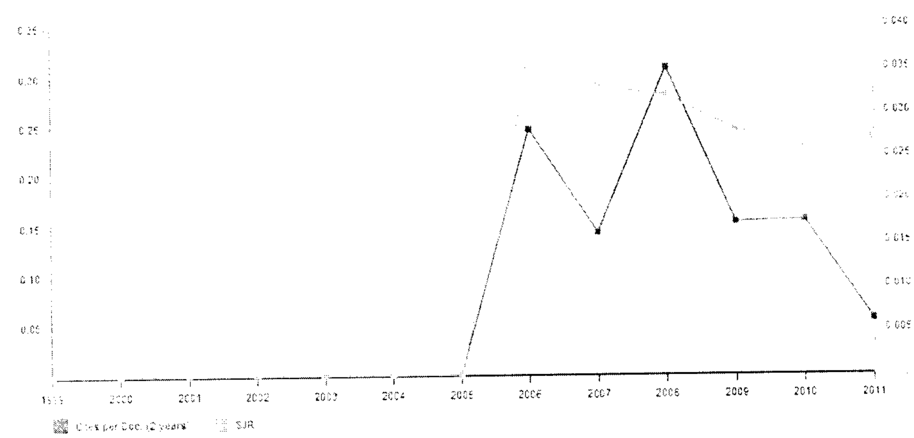
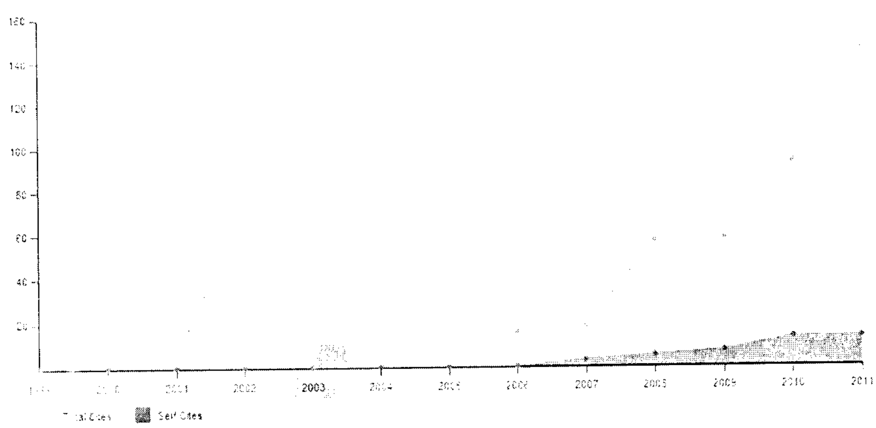
Charts Data

SJR indicator vs. Cites per Doc (2y)



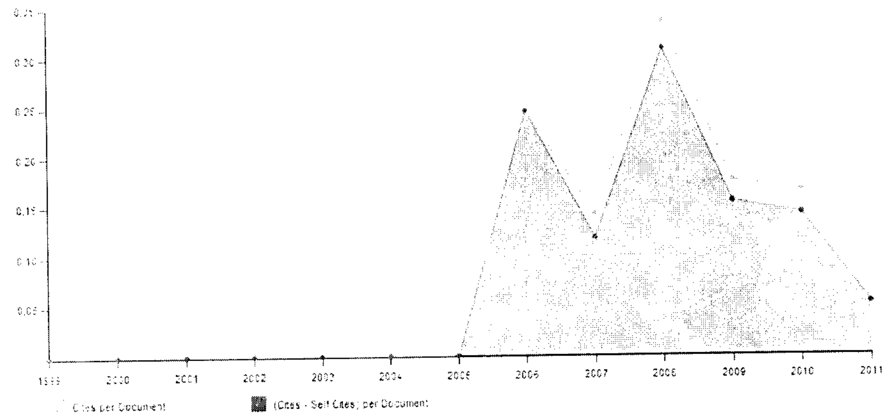
The SJR indicator measures the scientific influence of the average article in a journal, it expresses how central to the global scientific discussion an average article of the journal is. Cites per Doc. (2y) measures the scientific impact of an average article published in the journal, it is computed using the same formula that journal impact factor ™ (Thomson Reuters).

Citation vs. Self-Citation



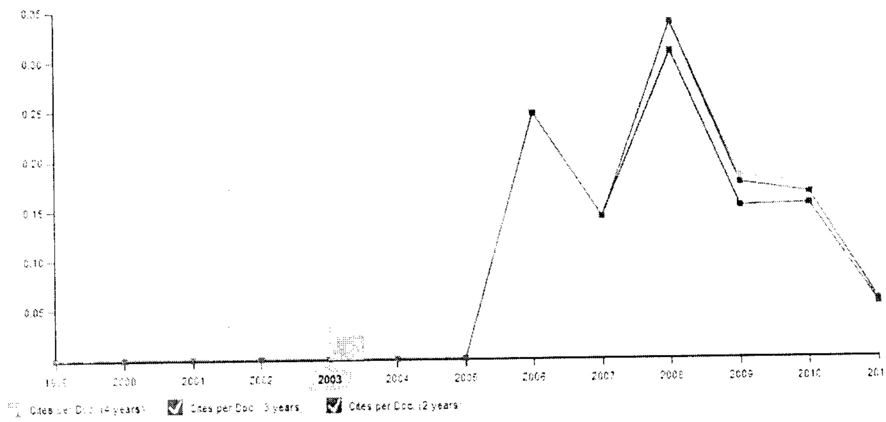
Evolution of the total number of citations and journal's self-citations received by a journal's published documents during the three previous years.

Cites per Document vs. External Cites per Document



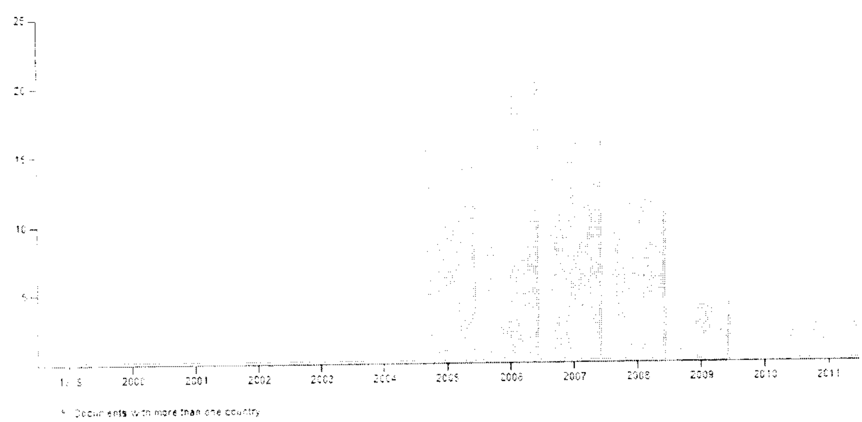
Evolution of the number of total cites per document and external cites per document (i.e. journal self-citations removed) received by a journal's published documents during the three previous years.

Cites per Document in 2, 3 and 4 years windows



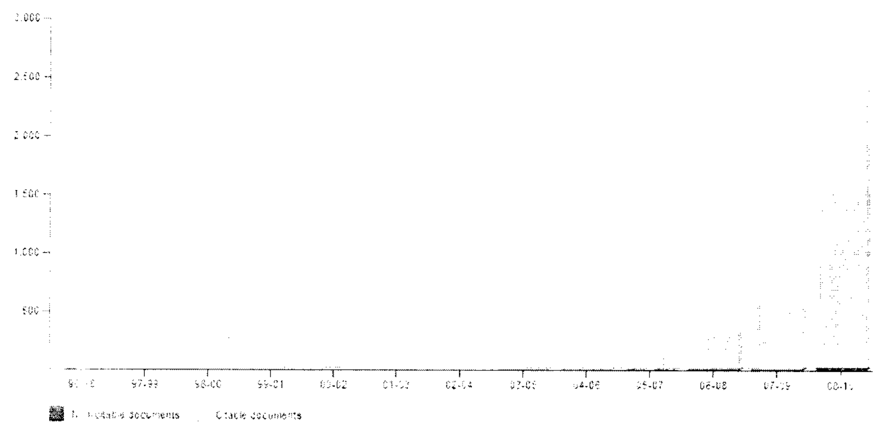
Evolution of Citations per Document to a journal's published documents during the two, three and four previous years. The two years line is equivalent to journal impact factor ™ (Thomson Reuters) metric.

International Collaboration



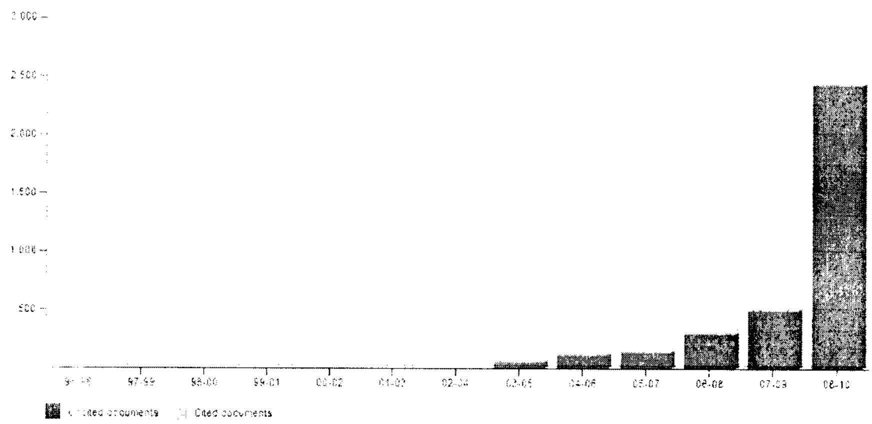
International Collaboration accounts for the articles that have been produced by researchers from several countries. The chart shows the ratio of a journal's documents signed by researchers from more than one country.

Journal's Citable vs. Non Citable Documents



Not every article in a journal is considered primary research and therefore "citable", this chart shows the ratio of a journal's articles including substantial research (research articles, conference papers and reviews) in three year windows.

Journal's Cited vs. Uncited Documents



Ratio of a journal's items, grouped in three years windows, that have been cited at least once vs. those not cited during the following year.