HEAD ON COLLISION OF TWO VORTEX RINGS IN WATER

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Abstract. *Vortex rings occur in nature and artificial devices, such as the mushroom cloud from an explosion or a volcanic eruption and the breakup of aircraft wing-tip vortices. In laboratory, they can be generated in quiscent media by ejecting fluid throughout a cylindrical nozzle for a short period of time. The topological structure of such kind of vortex is quite simple in contrast with its complex dynamical behavior. At low Reynolds numbers stable toroidal structures can be formed, but at higher Reynolds numbers instabilities are created and amplified. As two vortex rings collide frontally, their diameters increase due to mutual interaction and a series of complicated events take place. In the present work, head on collision of vortex rings in a water tank is studied using a dye tracing visualization tecnique. The experiments have been conduced for Reynolds numbers up to* 10^3*. Important mechanisms – including pairing, merging, cancellation, reconnection and stretching of vortices – are identified and discussed based exclusivelly on the information obtained through several images of visualized flows.*

Keywords*: Flow visualization, vortex rings, head on collision.*

1. INTRODUCTION

Vortex rings are frequently found in nature and artificial devices, such as the mushroom cloud from a volcanic eruption and the breakup of aircraft wing-tip vortices. The propulsion system of cephalopods, salps, jellyfishes, and others aquatic creatures are based on vortex rings shedding. Some important technological applications of vortex rings are cataloged by Shariff and Leonard (1992), including underwater drilling, artificial olfaction, drag reduction of sub aquatic vehicles, and fighting oil well fires. Kiya *et al*. (2001) present a novel active method to reduce the separation zone of an inclined flat plate by bombarding rolling-up vortices in the separated shear layer with a chain of vortex rings introduced from the side of the main flow. Mohseni (2006) discuss a possible method for low-speed maneuvering of small underwater vehicles utilizing pulsatile jet actuators.

Due to their scientific interest and technological importance, vortex rings have been investigated for more than one century. For decades, that class of vortex has been qualitatively studied with the help of flow visualization tools. Nowadays, with the enormous advances of the computers and the notable evolution of the measurement instrumentation, a growing number of numerical and experimental studies are dedicated to the quantitative analysis of vortex rings. These researches have contributed to the understanding of the mechanisms of formation, propagation, and persistence of vortex rings as well as their interaction with solid obstacles and other vortical structures. A comprehensive review about this subject is presented by Shariff and Leonard (1992).

Vortex ring formation by long-duration non-conservative forces has been numerically considered by Mohseni *et al*. (2001), simulating experimental vortex ring generation with large stroke ratio. An investigation of the invariance of the leading vortex ring to the forcing parameters has been carried out, confirming previous experiments and predictions of Gharib *et al*. (1998) and Mohseni and Gharib (1998).

Although the fundamental topological structure of a vortex ring is relatively simple, the dynamic associated to its movement is quite complex. According to Maxworthy (1972), at Reynolds number lower than 600 stable vortex rings are formed, but at higher Reynolds number an azimuthal wave develops and grows causing the vortex degeneration.

Dazin *et al*. (2002) have carried out a series of experiments to study the unstable displacement of vortex rings traveling in a quiet medium to look through an agreement with theoretical models. Interpreting tomoscopic images and performing PIV (particle image velocimetry) measurements the authors have identified two phases during the development of the instability in water: a) a linear phase, during which the patterns are the consequence of the existence of a three dimensional azimuthal wave developing around the initially stable vortex ring, and b) a non-linear phase, in which the instability is characterised by the formation of secondary vortical structures. The latter one come just before the destruction of the ring.

In order to find some properties of vortex rings propagation through a stratified fluid, experiments have been conducted by Scaze and Dalziel (2006). Vortex rings have been fired at oblique angle to the horizontal and at different speeds. The buoyancy frequency of the fluid has been also varied among different series of experiments.

The flow field induced by a vortex ring approaching or impinging a solid body has been investigated by many researchers. The chock of a single vortex colliding against a plane wall has been examined in detail by Naitoh et al. (2001) using the smoke visualization method. The authors have observed that longitudinal vortex like fingers play a crucial role in forming azimuthal coherent structures, which conduce the flow into a turbulent state.

The flow field induced by a high speed vortex ring approaching a solid wall has been experimentally and numerically studied by Minota *et al.* (1997). As the vortex ring approaches the solid surface, a boundary layer is induced and a wall vortex is formed.

The formation of vortex rings generated by an impulsively started jet in the presence of uniform background co-flow inside a tube has been experimentally studied by Krueger *et al*. (2006). Using DPIV (digital particle image velocimetry) to measure the development of the ring vorticity, the authors have identified a physical mechanism responsible for the premature termination of the vortex ring formation at large co-flow values.

Frontal collision of vortex rings is a classical problem in fluid mechanics, frequently used as a model for studying vortex stability and vortex dynamic. When two vortex rings approach each other, their sizes increase due to mutual induction, as experimentally shown by Oshima (1978). The vortex cores are deformed, and instability waves develop in the vortex core filaments. In such a situation some complex mechanisms can be observed, as pairing, merging, cancellation, reconnection, and stretching of vortices. So, various works in literature are dedicated to this subject.

Experiments have been accomplished by Voropayev *et al*. (2004) to investigate two laminar round jets colliding in water to form a zero-momentum toroidal vortex. This flow is modeled theoretically using the proper superposition of two linearized solutions for a starting jet induced by a concentrated force in a viscous fluid. Resulting flow patterns have been compared with the experiments and a good qualitative agreement has been reached.

Mansfield *et al*. (1999) use large eddy simulation, associated to a Lagrangian particle method and a dynamic eddy viscosity model, to represent the collision of coaxial vortex rings in three dimensions. In this study, several experimentally observed features of the ring collisions, including turbulent breakdown into small-scale structures and the generation of small-scale radially propagating vortex rings, have been captured.

Fluid motion induced by two vortex rings approaching each other at a high speed has been experimentally and numerically studied by Minota *et al*. (1998). Calculated results combined with visual information obtained by means of optical shadowgraph have shown that shock formation is due to the same mechanism present in the convergent-divergent nozzle flow.

In spite of the studies already undertaken concerning with frontal collision of vortex rings, many aspects associated to this phenomenon are yet misunderstood. In the present work, head on collision of vortex rings in a water tank is qualitatively studied using flow visualization. Preliminary experiments have been conduced for Reynolds numbers up to 10^3, and some important mechanisms already describe in the literature have been identified.

2. VORTEX RING GENERATION

Vortex rings can be produced by suddenly expelling a mass of fluid from a reservoir through a nozzle or orifice into a quiescent medium. A rustic vortex ring generator can be easily built using a small tubular piece equipped, at one extremity, with a circular flat plate having a concentric passage and, at the other side, with a flexible membrane, as indicated in Fig. 1. By mildly percussing on the membrane, vortex rings are ejected into atmosphere. If the surrounding air is sufficiently calm, stable vortex rings are formed, which are able to travel over long distance holding their shape and velocity. Displacement of these vortices can be visualized by using, as a tracer, smoke from burning incense stick inside the chamber.

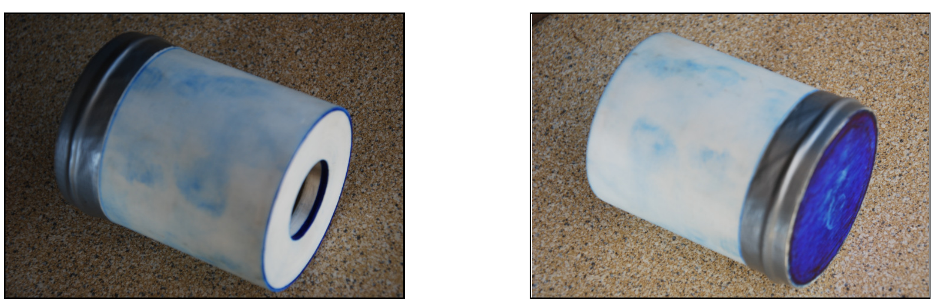


Figure 1: Rustic vortex ring generator.

In scientific works, several ways have been employed to produce vortex rings, as pointed in the comprehensive review of Shariff and Leonard (1992). Some of that employ a piston-cylinder generator, which can be improvised utilizing a medical injection syringe. A number of other creative methods have been proposed in the literature in more recent years. Mohseni (2006), for example, has been conceived a compact and well elaborate system to generate jet ring employing a flexible diaphragm and an electric/magnetic actuator. According to the author, this apparatus is loosely inspired by the propulsion of cephalopods, salp, and jellyfish.

In the experiments of Dazin *et al*. (2002), vortex rings are generated in a water tank by pushing fluid throughout the cylindrical nozzle of a pipe connected to a pressurized tank. Between the pipe and the tank, an electromagnetic valve opens the circuit for an adjustable duration. A polystyrene piston has been also fitted into the pipe in order to isolate the flow in the reservoir from the perturbations of the generating system. The stroke of this piston is adjustable. By setting the tank pressure and the opening time of the valve, it is possible to control the velocity of the piston.

Vortex rings in a co-flow system have been created in water by Krueger *et al*. (2006) using a piston-cylinder vortex generator. A constant-head tank has been used to supply flow to the vortex ring generator while an independent pump supplied the co-flow. Separate solenoid valves, actuated by a computer, controlled the initiation of each flow, allowing independent actuation of the jet and co-flow velocities.

A piston-cylinder arrangement has been also used by Lim (1997) to produce vortex rings in a water tank. The piston motion has been done through a stepper motor controlled by computer. By giving the piston an impulsive motion, a cylindrical vortex sheet is formed which quickly rolls up into a circular vortex ring, as described by the author.

In gaseous medium, sequences of vortex rings can be easily produced in controlled conditions through woofers and speakers connected a orifice. In this case, the woofer can be driven by square-wave input from a power control unit as made for Kiya *et al*. (2001).

By using a cylindrical shock-tube, compressible vortex rings have been generated and then emitted into the atmosphere by Minota *et al*. (1997). In a porterior work, Minota *et al*. (1998) have been used the same dispositive to produce and study head on collision of high speed vortex rings.

Lugomer (1999) have been created micro scale vortex rings by vaporizing a tantalum surface by means of a short time pulse laser. Laser-matter interaction at short time scale (about 10 ns) produces a vaporization of the solid surface showing a formation of a micro vortex ring with various levels of the organization and complexity.

3. FLOW VISUALIZATION

In spite of the new methods of flow analysis, flow visualization still occupies a prominent role in the study of the problems associated with mass, momentum and energy transport. Indeed, flow visualization is perhaps the most useful experimental tools to obtain, by a fast and cheap way, qualitative information on flow structure.

Many experimental flow visualization techniques are described in the technical literature. Only to exemplify, Yang (1989), Merzkirch (1987), Goldstein (1976), and Freymuth (1993) represent classical references about this subject. In the last decades, the traditional techniques of flow visualization have been improved and new techniques have been created. Consequently, flow visualization reviews are numerous.

In a broad sense, flow visualization is more easily performed in liquids than in gaseous medium, since there are many ways of making a liquid flow visible, by using different color inks, gaseous bubbles or solid dust in suspension. Werlé (1973) details hydrodynamics facilities and different techniques to make water flow visible.

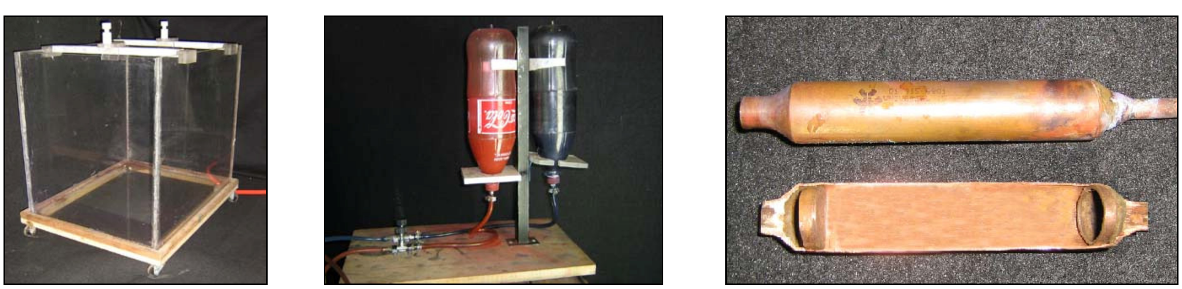
Particularly in studies concerning with vortex rings, qualitative and quantitative flow visualization techniques have been exhaustively applied in the experimental works of Dazin *et al*. (2002), Kiya *et al*. (2001), Laursen *et al*. (1997), Naitoh *et al*. (2001), Oshima (1978), Voropayev *et al*. (2004), Minota *et al.* (1998), among many other authors.

4. EXPERIMENTAL APPARATUS

Experiments have been performed in the water tank shown in Fig. 1(a) with 450 × 580 × 500 mm of size and has been built with Plexiglas 10 mm thickness. Essentially, each the vortex ring generator is composed by a pressurized reservoir, a control valve, and an injection dispositive connected by flexible tubes.

The pressurized reservoirs shown in Fig. 2(b) contain the liquid tracer used for flow visualization purpose. This tracer is composed by a mixture of bi-distilled water, commercial PVA pigments, and ethyl alcohol. The addition of alcohol to the mixture has been made to remain its density close to that of the water in the tank. In such an experiment accurate density control is necessary, since small differences in density can cause rapid loss of the flow symmetry.

Figure 2(c) presents an external view (upper image) and a longitudinal cut (lower image) of the injection device. In order to provide a uniform profile in the jet root, this dispositive is formed by a plenum chamber equipped with a perforated plate and a fine screen, positioned respectively downstream the entrance orifice and upstream the outlet nozzle. Two pairs of injection device, with different outlet diameters (d), have been used in the experimental tests – the first one with d = 4 mm, and the second one with d = 7 mm.



(a) Water clear tank. (b) Pressurized dye reservoirs. (c) Injection device.

Figure 2: Experimental apparatus.

Experiment has been carefully mounted and conduced in order to reduce influence of external disturbances like unwelcome mechanical vibrations and temperature oscillations. The tests have been performed in the range of Reynolds number from 300 to 10^3, based on the internal diameter of the nozzle (d = 4 mm or 7 mm) and on the mean translation velocity of the vortex immediately after the injection. The translational velocity has been determined by means of cinematographic sequences captured at 30 fps. Dye solution viscosity has been measured with the help of a Hagen-Poiseuille viscosimeter, while density has been determined using a pycnometer and a precision balance. In the more adverse condition, experimental uncertainty of the Reynolds number has been estimated accordingly to Moffat (1982) in less than 3%.

Incandescent photo flood and halogen lamps produce high thermal radiation. In some cases, intense convection can be produced affecting the flow field in an inconvenient way. Use of fluorescent lamps, by its turn, provides a cold illumination that eliminates the requirement of fans and other cooler devices. In this work, a diffuse backward illumination has been obtained by using nine fluorescent lamps shielded by a translucent screen. These lamps have been distributed in three groups, each one of which is fed by a different phase of a three-phase power supply in order to minimize illumination ripples inherent to fluorescent lamps.

Images have been captured by a high resolution DVC 3CCD video camera equipped with a 105 mm macro lens in deep color of 8 bits, and directly stored in a hard drive by means of an IEEE 1394 connection.

5. RESULTS

The temporal sequence presented in Fig. 3 shows the frontal approximation of two vortices generated in the smaller injection device (with 4 mm of nozzle exit diameter) by using red and blue dyes. The Reynolds number is about 330 and a very stable flow is observed. The first instabilities appear only after the vortex collision. At this a new condition, the images show a sensible increasing of the vortex diameters caused by the mutual interference. By means of a moment compensation mechanism, thicknesses of the vortical structures decrease as their diameters increase. In this case, the propagation of the wavy instabilities is limited by the low magnitude of the Reynolds number and the vorticity are almost completely canceled.

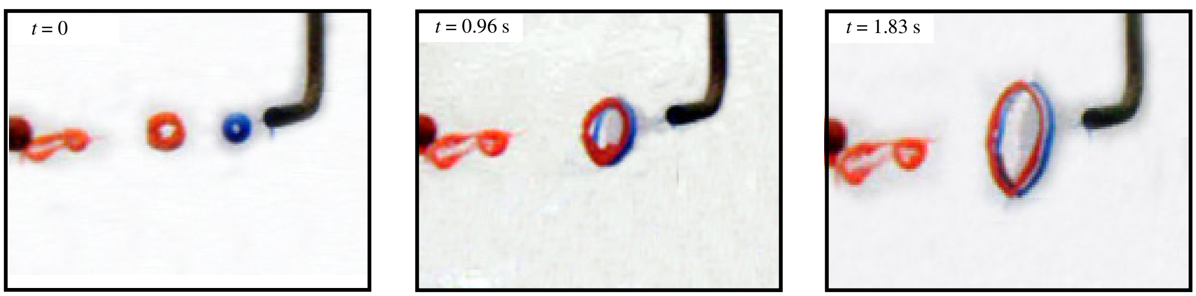


Figure 3: Temporal evolution of two torus vortices on frontal approximation – d = 4 mm and Re = 330.

The images shown in Fig. 4 have been obtained using the same injection device (d = 4 mm) employed in the precedent test. In this case, the Reynolds number has been fixed in 560. After the collision, t = 0.34 s, the ring diameters increase and instabilities are clearly identified through ring oscillations. At the subsequent instant, t = 2.26 s, these initial instabilities are amplified and the double ring loses its identity by exploding in several smaller rings.

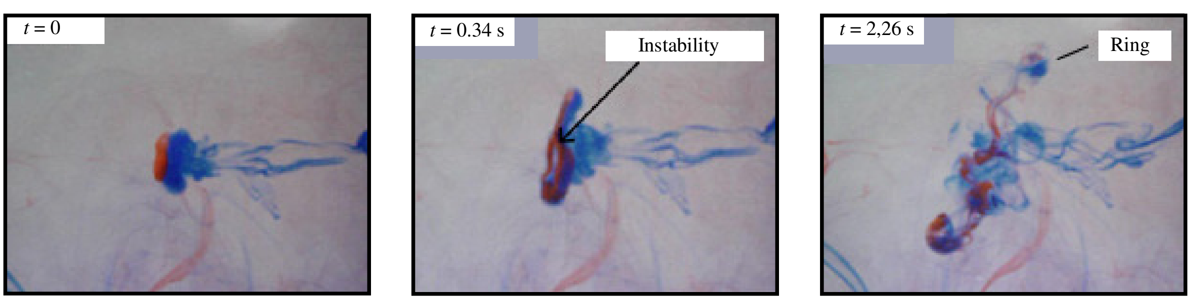


Figure 4: Head on collision of two vortex rings – d = 4 mm and Re = 560.

The successive images presented in the Fig. 5 have been also obtained using the 4 mm exit nozzle, and show that an unstable flow occurs at Reynolds number of 820. Subsequently the shock instant, t = 0.36 s, the two vortex rings grow and intertwine, intensifying instabilities formation. Once again, in this process small rings are formed and the large scale structures degenerate.

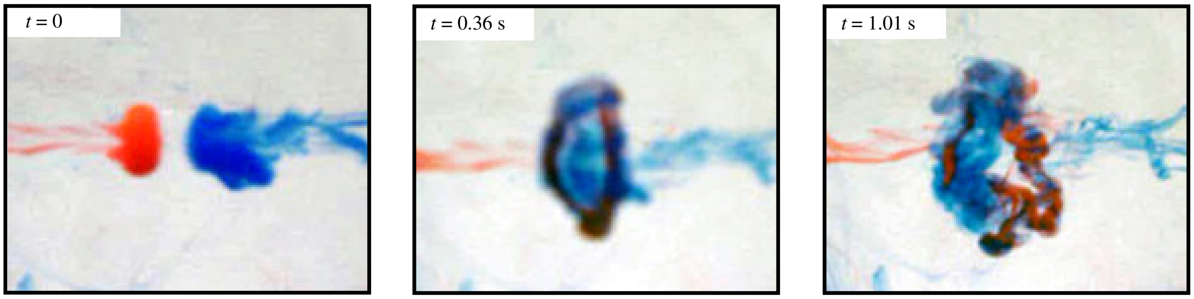


Figure 5: Turbulent head on collision – $d = 4$ mm and $Re = 820$.

Figure 6 shows four different stages of the approximation process of two vortex rings generated by using the larger injection device ($d = 7$ mm). The Reynolds number is 520 and a laminar flow is established. As observed in the earlier results, while the two vortices approach to each other their diameters remain unchanged. Nevertheless, after the collision a rapid increasing of their sizes befalls. Rings present an oscillating pattern, which can be sharply observed at $t = 2.2$ s.

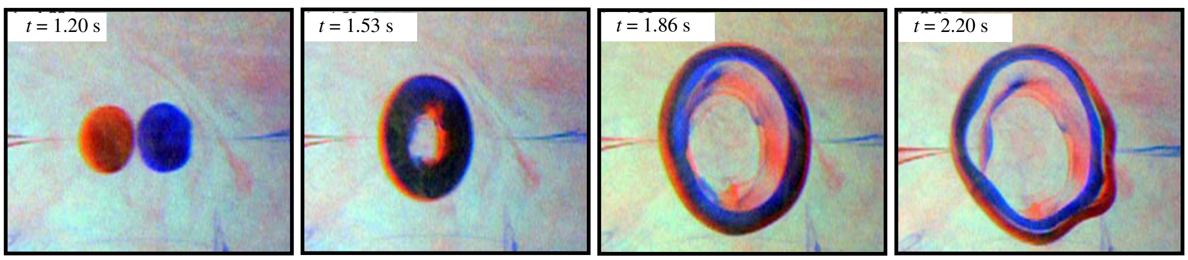


Figure 6: Laminar flow vortex rings collision – $d = 7$ mm and $Re = 520$

As can be seen in Fig. 7, for Reynolds number about 790 and $d = 7$ mm, vortices collide, interrupt their displacement, and increase their sizes yelding a zero net momentum. Undulating instabilities are easily observed along the surface of the rings. At the following instants, the interaction between the two vortical structures is intensified and a radical change in the toroidal shape of the vortices takes place. At $t = 1.66$ s and $t = 2.06$ s nine small rings and reconnecting filaments can be identified.

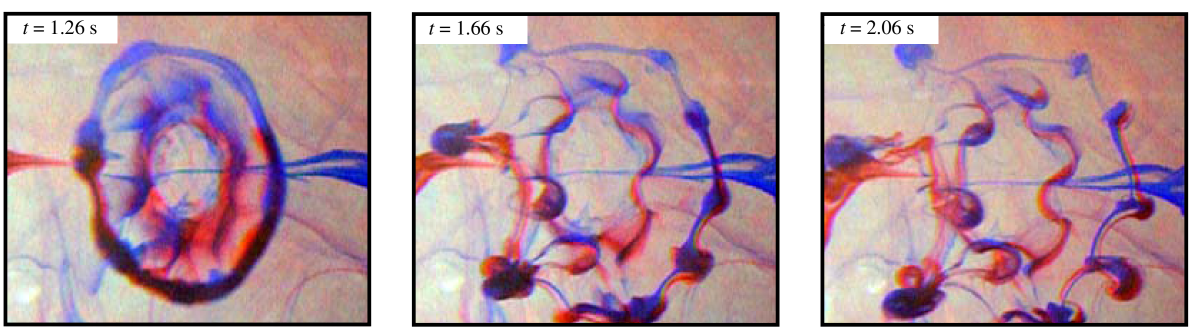


Figure 7: Images sequence of the formation of number of small rings – $d = 7$ mm and $Re = 790$.

As the flow reaches a turbulent regime, visualization of vortical structures always became more difficult. Figure 8 show images corresponding to a turbulent collision of two vortex rings created with $d = 7$ mm and $Re = 10^3$. According to Lim and Nickels (1992), for $860 \leq Re \leq 1500$ the probable number of reconnection vortex vary from 11 to 24. In the present tests, twelve reconnections of vortices have been found.

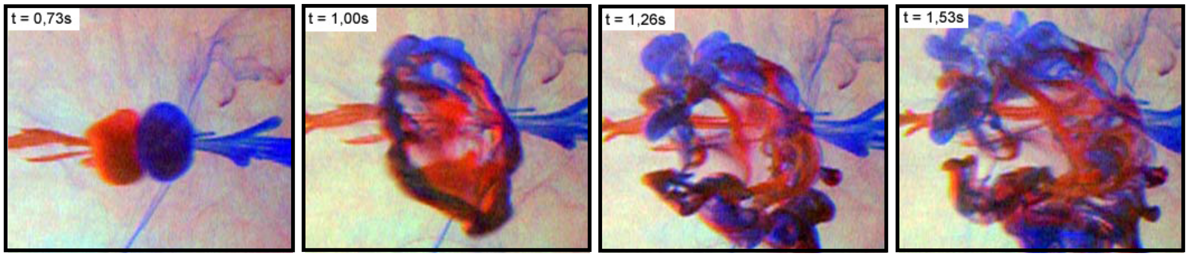


Figure 8 – Turbulent head on collision – $d = 7$ mm and $Re = 10^3$.

5. CONCLUSION

A preliminary study concerning with the frontal collision of a pair of vortex rings with opposite circulation have been carried out for Reynolds number up to 10^3. In this investigation, only qualitative flow visualization has been used as tool, and important mechanisms have been identified.

The apparatus used have been considerate adequate to generate vortex rings, offering experimental consistency and repeatability. The use of PVA commercial pigments as liquid tracer provides a sharp contrasted and very well defined images.

When two identical vortex rings collide, each one of them slows down and expands its diameter. The results obtained confirm the production of an azimuthal wave around the ring after the shock.

Increasing the initial velocity of the vortex rings, wavy instabilities were observed along the circumference of the rings. Then the two vortex rings change their shape, originating a number of small rings, which are reconnected by vortex filaments. The increasing of Reynolds number makes difficult visualization of reconnection process of small vortices on the toroidal vortex.

The images showed indicate that Kelvin-Helmholtz-like instabilities play an important role in the vortex ring dynamics. In this context, the effect of the exit diameter of the nozzle injector on the vortex topology has been observed. Obviously, different nozzle diameters produce different levels of turbulence. The influence of the turbulence spectra and intensity produced by the nozzle injector are important aspects to be considered in future works.

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