ISRN LUTMDN/TMHP—08/5151—SE
ISSN 0282-1990

Designing a vortex rings generator for sterilizing a bottle with experiments and numerical simulations

Philippe Becart

Thesis for the Degree of Master of Science

Division of Fluid Mechanics
Department of Energy Sciences
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

ECOLE DES MINES D'ALBI
C A R M A U X

Designing a vortex rings generator for sterilizing a bottle with experiments and numerical simulations

Internship realized in Tetra Pak R&D
Ruben Rausings Gata
S-22186 Lund
Sweden

And in the fluid mechanics department of Lund University

Technical Report

Name of the tutors :

Anders Sundberg (Tetra Pak)

Christophe Duwig
(Lunds Tekniska Högskola)

Olivier Louisnard
(Ecole des Mines d'Albi Carmaux)

Philippe Becart
IFI 2007

TABLE OF CONTENTS :

TABLE OF CONTENTS : 2

THANKS TO: 5

SUMMARY 6

RESUME (FRENCH VERSION) 7

INTRODUCTION 8

I – A SHORT PRESENTATION OF TETRA PAK 10

1 – TETRA PAK R&D IN LUND : 10
2 – TETRA PAK R&D AND THE LTH : 11

II – FROM THE IDEA TO USE VORTEX RINGS TO THE FIRST METHODS TO UNDERSTAND THE INTERACTION BETWEEN THEM. 12

1 – BRIEF DESCRIPTION OF THE PROCESS : 12
2 – SOME IMPROVEMENTS MADE TO THE FIRST NOZZLES : HIGH SPEED SWIRL IN ORDER TO OBTAIN A WIDER STERILIZED ZONE 13
a – Increasing speed with a straight nozzle : an idea that was not so efficient 13
b – The "Active Nozzle" principle : the best improvement until now 14
3 – USING LAMINAR JETS : DESPITE OF GOOD NUMERICAL RESULTS, THEY ARE NOT SUITABLE FOR AN INDUSTRIAL PRODUCTION. 15
a – The numerical simulations foresee a return loop on the wall of the bottle but at least, the jet could propagate until the neck of the bottle. 15
b – Time constraints : filling every bottle with active chemical product must not exceed 0.7 seconds 16
4 – THE FORMER STUDIES : WHEN SOMEONE HEARD ABOUT VORTICES AND THEIR ABILITY TO PROPAGATE FAR FROM THEIR "CREATION POINT". 16
a) Blooming jets and vortices studies in the scientific literature : a lot of qualitative work or strictly quantitative description which were hard to understand or to measure with industrial means 16
b – Some assumptions that were chosen : description of the ring as a torus, use of the incompressible Navier-Stokes equations. 18
Reynolds Number 19
Assumption of a local laminar structure of a turbulent flow 20
A good alternative in that case is unexpectedly to come back to a laminar solver, refining the mesh of the grid with a node every 0.8 mm, which was sometimes too wide to describe correctly what was occurring near the boundary layers near the edges of the nozzle and those of the bottle. But this grid was nonetheless a good compromise with the time that was taken before getting the first results. 20
Continuity Equation 22
Incompressible and unsteady Navier-Stokes Equation 23
Energy Equation and Transport species equation : 23
Conclusion of the second part : 24

III – UNDERSTANDING WHY A RING IS CREATED OR NOT, AND HOW TO CREATE STABLE AND FAST VORTEX RINGS : THE KEY PARAMETERS......... 25

1 – A LITTLE TORNADO LOOP : THE BEST PICTURE WE CAN HAVE TO UNDERSTAND WELL BY MIND WHAT A VORTEX RING REALLY IS. 25

a – Vortex rings and tornadoes are organized around a low pressure line which is straight for the tornadoes and circular for the vortex rings :........ 25

b – How to create a low pressure point in motion ? The role of vorticity 26

c – More details about the vortex shape and the velocity field near the rings : 28

2 – IMPROVEMENTS MADE ON THE DEVICE WHICH WAS USED TO GENERATE THE VORTEX RINGS : FROM A SIMPLE PISTON CHAMBER TO MORE COMPLEX SHAPES THAT SHOW THE IMPORTANCE OF THE RECIRCULATION ZONE. 29

a – The influence of the edge of the outlet : increasing the speed and generating a high vorticity path 29

b – The recirculation zone after the outlet of the piston chamber is one of the most important parameter for the growth of the vortex........ 31

3 – THE BEST EXPERIMENTAL PROTOTYPE OF NOZZLES ILLUSTRATES THE MAIN IDEA : ONCE THE VORTEX RING IS CREATED, WE MUST LET IT FREE TO EVOLVE. 33

a – A innovating shape of the recirculation zone : no constraint for the vortex which become almost free to increase its width to its maximal value. 33

b – The new shape of the nozzle allows also some controls on the size, the shape and the ability for the first vortices to reach the neck of the bottle. 35

IV – INTERACTIONS BETWEEN THE RINGS, A NECESSARY KNOWLEDGE TO DETERMINE HOW OFTEN THE RINGS MUST BE SENT. 37

1 – SUMMARY OF WHAT HAS BEEN DONE BEFORE OUR WORK........ 37

2 – THE DIRECTIONAL STABILITY, A CRITICAL ANGLE BETWEEN THE NOZZLE AND THE BOTTLE MUST NOT BE REACHED. 38

3 – THE AREA OF INFLUENCE : THE MOST IMPORTANT NOTION TO UNDERSTAND IN ORDER TO AVOID RING COLLISIONS. 39

a – Most of the flow is invisible, what we call "area of influence" is the zone of the velocity field where the presence of the vortex can be felt. 39

b – Some parasites effects which are linked to the area of influence can affect the rings interaction quite strongly, changing notoriously their speed. 40

Avoiding ring collisions thanks to the "Area of influence model" 40

The speed profile of the velocity inlet inside the nozzle has also an influence on the structure of the flow and can generate secondary rings, or even counter-rings : 40

Secondary Rings : 42

Counter-rings : 42

Velocity inversion zone : 42

c – Discovered by chance, a very empiric approximation can foresee more or less what is the extent of the area of influence. 42

d – Knowing correctly the size of the area of influence allows to determine the maximal frequency which the rings can be sent into the bottle without any risk of collision........ 43

4 – AVERAGE DILUTION AND NUMBER OF RINGS REQUIRED TO FILL THE BOTTLE IN LESS THAT 0.7 SECONDS. 40 RINGS SHOULD BE ENOUGH. 43

a – Dilution of the ring : a hard question to solve since the mixing between the active chemical product and ambient air is not homogeneous. 43

The dilution of active product in the ring is very changing and can vary from 80% on the edge of the ring to only 30% in its heart for the first rings, whereas for the last rings,

after 400 ms of sterilization, the dilution is only 40% on the edge of the ring and 20 % in the heart as shown below on the next page. *43*
b – Volume of the ring and ability of each ring to transport some reactant to sterilize the bottle. *44*
c – Intermediate conclusion about the great advantages of using this methods and last details to be known about the maximal speed. *45*

CONCLUSION **46**

BIBLIOGRAPHY **47**

APPENDIXES **48**

I – SOME KIND OF NOZZLES THAT WAS TRIED BEFORE SELECTING THE BEST ONE 48
II – THE DEMONSTRATION ABOUT HOW WE FOUND THE AREA OF INFLUENCE OF THE RING AND THE MINIMUM DISTANCE THAT MUST SEPARATE TWO RINGS. 48
I – SOME KIND OF NOZZLES THAT WAS TRIED BEFORE SELECTING THE BEST ONE 49
II – THE DEMONSTRATION ABOUT HOW WE FOUND THE AREA OF INFLUENCE OF THE RING AND THE MINIMUM DISTANCE THAT MUST SEPARATE TWO RINGS. 50
III – MORE DETAILS ABOUT THE USE OF THE TERMS “HYDROGEN PEROXIDE” OR “ACTIVE CHEMICAL PRODUCT”. 50

THANKS TO:

Anders Sundberg :
For having helped us to improve our experimental device and for having guided us into our reasearches. A special thanks also to him to be really interested in our experiments and to always have introduced me to the competent people in Tetra Pak to talk to, in order to solve the specific problems that occurred in our researches.

Nicolas Lecomte :
For his sense of the observation in the experiments that we filmed and the really good team work that helped us to progress in the right direction on the experimental fields of the vortex rings description.

Christophe Duwig :
For his good advice about the rings, the scientific articles that were to read to become more familiar with the vortices.

Håkan Hansson, Leif Wålhin and Henrik Brännmo :
For having made our special shape of nozzle, with CAD software, and then with the machines in the workshop. It was really a great moment when we made the first test and we saw that our ideas and what I have seen or what I have suspected on numerical simulations was something that we could do for real.

Lama Ziegelwagner and Magnus Holgersson :
For having helped us for solving the different problems of computer connection on the Tetra Pak network that was encountered. In the field of computational fluid mechanics, it would have been impossible to work with a single off-line computer.

Robert-Zoltan Szasz, Philip Evegren, Magnus Åberg :
For their great help to connect the computer on the Lunds Tekniska Högskola network and to solve many problems linked with some incompatibility between several kinds of software. A special thanks to Philip Evegren and Magnus Åberg for their help to understand some advanced commands on Fluent and to use properly the LUNARC computers network that is used in all the south of Sweden for scientific numerical simulations that require many hours of processing time for each case files to solve.

Pär Olanders :
For his precious information about the conditions of usage by Tetra Pak R&D of the hydrogen peroxide.

SUMMARY

Tetra Pak is a world known company in the field of food packaging industry. One of its concerns is to improve the efficiency of the sterilization of fruit juice bottles or other shape of container such as the milk bricks. The methods which were used before worked quite well except for some parts of the containers which need relatively long time to be reached. That is the reason why applied research focused on some new ways to make this step of the process.

Some years ago, the idea of using vortex rings came, and a first thesis work was performed with the cooperation of the Malmö Högskola. The so-called vortex rings are able to propagate on a great distance if we compared it to their own size. They could be also steady or not, depending on several parameters. The only inconvenient is that they are not so easy to understand and to control.

The main improvement that has been realized in the summer 2006 was to understand better the creation of the rings, and their stability. Even if precise scales can not be really established in a short amount of time, a four months study is enough to show the influence of three key parameters that must be properly controlled for an industrial further implementation of this kind of device on a production line.

First, the vortex rings generator must be as perfectly aligned as possible with the axis of symmetry of the container, or the main axial length, if the shape is more complex than a cylinder. Then, the nozzle shape is probably the second parameter that determines the ability to obtain steady rings for a large range of operating speeds. The volume and the size of the vortex rings are also highly dependent on the geometry of the nozzle. Last but not least, for each axial velocity one may choose, a certain length must be kept between two consecutive rings. This is mainly due to the fact that the rings interact together.

Each ring leaves behind him a kind of trail that we lately call wake. This wake is a low speed stream which is drifting and is sometimes turbulent. The velocity field in that area is not visible in experiments, and only the numerical simulations or some kind of unexplained acceleration of the rings allowed us to understand how important were some data, such as the frequency we were sending the rings.

This point of our research led us to understand why some rings were colliding or not. In case of vortex ring collision, the hydrogen peroxide (or another chemical product that could be used) is not able any longer to propagate farther than half of the container that we used. Thus, a method to avoid any risk of collision has also be found, even if the theoretical model is quite a rough approximation. But the good experimental results that we obtained thanks to that very simple model were encouraging. The great weak point of this model is also that it is based on vorticity, which is something which is hard to measure or to evaluate with a theoretical formula. Two dimensional numerical simulations are very often compulsory to know what will be the behaviour of the rings.

With a new kind of nozzle that was invented, and a speed profile which was a compromise between making a good growth of the vortex ring and avoiding the turbulence of the wake, we finally created improved versions of the experimental device which are suitable for a later industrial process. Of course, some other researches can still be made, in order to improve the qualitative description of the rings, which will remain for a long time difficult to find.

RESUME (French version)

Tetra Pak est une compagnie mondialement connue dans le domaine de l'emballage de produits alimentaires. L'un de ses objectifs est d'améliorer l'efficacité de la stérilisation des bouteilles de jus de fruits ou des briques de lait. Les méthodes précédentes qui étaient utilisées pour ce faire fonctionnaient bien mais laissaient quelques incertitudes sur leur capacité à faire atteindre à l'agent stérilisant même les parties de l'emballage les plus difficiles d'accès. C'est pour cette raison que la recherche appliquée s'est penchée sur de nouvelles voies de réaliser cette opération au sein du procédé.

Quelques années auparavant, une première équipe de doctorants de l'Institut Technologique de Malmö avait réalisé un travail préliminaire à l'étude des anneaux tourbillonnants de fluide. Ces anneaux, appelés *vortex rings* par les anglo-saxons, sont capables de se propager sur de grandes distances comparés à leur taille. Leur stabilité est parfois hasardeuse, et leur principal inconvénient est qu'ils ne sont ni faciles à comprendre ni aisés à contrôler.

La principale amélioration de notre travail de l'été 2006 a été de mieux cerner les mécanismes de création des anneaux. Même si des tables ou des échelles précises concernant leur stabilité ou leur taille n'ont pu être clairement établies avec un temps de travail aussi court, quatre mois d'étude ont été un délai suffisant pour montrer l'importance de trois paramètres clefs pour une future utilisation industrielle.

En premier lieu, le dispositif qui génère les anneaux de fluide doit être aussi bien aligné que possible avec l'axe de symétrie ou la longueur caractéristique de la bouteille ou du récipient qui n'a pas forcément une forme globalement cylindrique. Il faut considérer en second la forme de la buse d'injection qui permet pour une large gamme de vitesse de conditionner la stabilité ou non des anneaux, ainsi que leur volume. Le dernier paramètre à considérer, et non des moindres, est la distance de sécurité que l'on doit maintenir entre chaque anneau pour chaque vitesse axiale que l'on choisit d'utiliser. Ceci est due aux interactions qui existent entre anneaux.

Chacun d'entre eux laisse derrière lui une traînée ou un sillage. Ce sillage est constituté de plusieurs couches de fluides qui dérivent ou qui sont parfois turbulentes. Le champ de vitesse n'est pas visible dans les conditions expérimentales dans cette zone. Seules les simulations ou des accélérations inexpliquées des anneaux nous ont permis de comprendre l'importance de certaines données comme la fréquence à laquelle nous envoyions les anneaux.

Ce point nous a permis de savoir pourquoi certains anneaux entraient en collision ou pas. En cas de collision, le produit actif n'est plus capable de se propager au-delà de la moitié du récipient que nous testions. Ainsi, nous avons mis au point une méthode pour éviter tout risque de collision même si notre modèle théorique repose sur une approximation assez peu fine. Mais les bons résultats expérimentaux que nous avons obtenus grâce à ce modèle relativement simpliste sont encourageants. La faiblesse de ce modèle est qu'il fait intervenir la vorticité, grandeur difficilement mesurable ou déterminable par le calcul. Les simulations 2D sont souvent incontournables pour pouvoir l'évaluer avec précision.

Finalement, nous avons fini par inventé une nouvelle forme de buse, à utiliser avec un profil de vitesse de compromis entre la croissance du vortex et la diminution des turbulence du sillage. Ce prototype expérimental peut servir à la base d'une future application industrielle. Bien sûr, d'autres recherches peuvent être enterprises afin de mieux decrier le comportement des anneaux d'un point de vue quantitatif, qui restera pour longtemps l'aspect le plus difficile à établir avec certitude.

INTRODUCTION

Tetra Pak is a world well known company which sells packaging for bottles of milk or fruit juices. The invention of Ruben Rausing in 1948 was to create tetrahedron shaped packages, which quickly became popular and very adapted for mass production. His company was named according this discovery and still use today the same concept, even if the shape of the tetrahedrons can change a little for commercial purposes. But nowadays making wrapping is maybe one of the easiest tasks of the production line, what is important is to sterilize them before injecting food product.

In fact, some chemical products that can kill bacteria might be added in small quantities for fruit juice, but will not be efficient for a long time, and will not be so good for the health or the taste. So the best way to make the product sterile is to eliminate micro organisms first, by injecting a steam of a chemical reactant into the empty container, such as hydrogen peroxide, which will become water or an other harmless chemical product after the reaction. Then, the steam of sterilizing chemical product is evacuated and then the fruit juice can be injected.

One of the major challenge is to know how much quantities of matter is really required since, if we inject too much, it will be a waste of time and money, and if we do not put enough of active product, there will be still some bacteria which will stay in the bottle and colonize further in time the milk or the fruit juice. The other side of the problem consist in knowing how much time will be necessary to fill the bottle with the chemical product, before it contains the juice. The nozzle which will be at the origin of the flow will have also a great importance, since we must consider also the kind of speed field which will be created.

As some problems occurred with classical turbulent straight flows, Tetra Pak decided to see what was possible to do with vortices flows. Former studies in the research and development department proved that it was possible to generate some vortex rings by a simple piston with a little inward directed edge. But the phenomena was still not understood, and the aim at the beginning of the internship was to know :

- On a theoretical sphere, explain in a better way what kind of laws or interaction between particles can describe the strange behaviour of the torus rings that was observed in the first set of experiments.

- By new experiments, what can be improved or better analysed to have a better understanding of the physical phenomena. This part of the internship was more the task of Nicolas Lecomte.

- With numerical simulations and the usage of a fluent licence, create an accurate model that can foresee quite well the behaviour of the ring.

- In the end, propose a new kind of device for vortex rings generator that can be adapted for industrial use and sterilisation of bottles on a production line.

As a consequence, after a short introducing of the company itself, the problems arisen in the older experiments will be treated. Then, the way how a single ring is created and propagates will be described in a third part. Finally, we will see how several rings can interact together and how those interactions can be exploited for an industrial machine so as to improve the quality of sterilization on the production line.

I – A short presentation of Tetra Pak

1 – Tetra Pak R&D in Lund :

Tetra Pak is a company whose name is world well known and which was created in 1951. It mains activity is to sell packages or lend machines which produce, prepare or fill these packages for fruit juices or milk. More generally, the company extends nowadays to produce every kind of food packaging systems with many various shapes.

Tetra Pak employs 20 900 people over the world and its net sales reached about 7.525 billion € in 2004 which make it one of the most important suppliers of food packaging systems in the world. The research and development facilities in Lund and the production plant also employ 2 500 people. It was also in that city, situated in Scania, in the South of Sweden, that Tetra Pak was founded. One street of Lund was also named after the founder of the company : Ruben Rausing.

The aims of the two hundred people who work at Tetra Pak applied research departments are to develop new kind of carton, or to conceive other colours or shape of the packages. This is due to the trend of the last years, when customers began to care more and more about image and lifestyle, which made Tetra Pak work more on the design. Such a situation was not without any consequence on the machines and the production lines that needed to be more flexible.

Picture 1 : various packages produced by Tetra Pak

As the work of the research and development department is also to be responsible for the service and maintaining of the machines, even after placed at the customers factory, or to optimize those which are used in the process.

2 – Tetra Pak R&D and the LTH :

For some projects that need an important theoretical background, Tetra Pak can also hire some trainees among the students in master thesis at the LTH, Swedish initials of the Lunds Tekniska Högskola of Lund Institute of Technology.

Very often a lecturer or a researcher of the university is also there to help his students or to give them some advice. The great proximity between the LTH and the Tetra Pak research and development offices are very helpful for this cooperation between the teams of the university and Tetra Pak's ones. Those contacts are mutually profitable and can save a lot of time or money especially in the field of fluid mechanics that requires very often good computers, or network of computers, licences for using fluid mechanics software such as Fluent, and people which are trained to work with those methods.

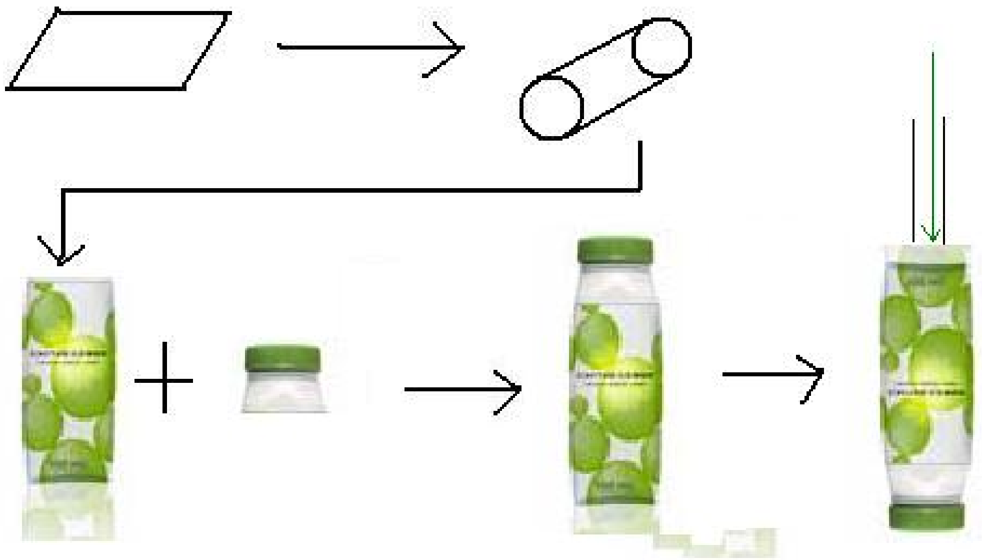
For this placement, which was considered as a thesis work by the university of Lund, three teachers researchers could help us with the assistance of a dozen of physic doctorate students.

II – From the idea to use vortex rings to the first methods to understand the interaction between them.

The first thing that is to know is how the process worked before and why Tetra Pak thought to apply this kind of unusual solution which consist in sterilizing a container with vortex rings.

1 – Brief description of the process :

As it was not possible to take some pictures of the assembly line, here will be only described why some more obvious technical solutions could not work. First, the carton which will make the body of the packaging is rolled around cylinders, and then stuck to the cup of the bottle, made in plastic materials.



Picture 2 : Simplified plan of the process

Of course this picture is only a view of mind. The bottles arrive in the machine being upside down, and must be filled this way. Then, each bottle has to be sterilized before the fruit juice is poured in. To do such an operation Tetra Pak uses a hot steam of hydrogen peroxide at 343 K. So it is not so easy to inject into the bottles or other containers this warm gas which generally tends to go upwards since its density is lighter than ambient sterile air inside the bottles which is colder than the steam.

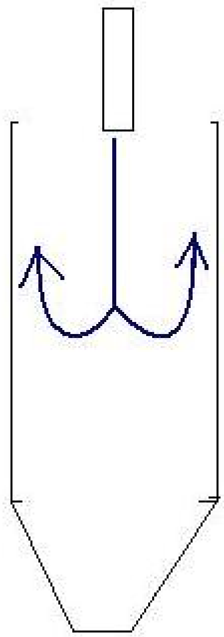
Another aspect of the difficulty to change the machine is that the whole process must be in sterile atmosphere and inside a kind of tank where the bottles are on a conveyor and the nozzle blows continuously a steam made of water, hydrogen peroxide and chemical products to stabilize the mixture.

As it is also very expansive to change radically the machine, it is better to work on the flow than to work on the mechanical parts, since there is not so much space to add new components on the machines. How ever, several attempts have been tried before using the vortex rings.

2 – Some improvements made to the first nozzles : high speed swirl in order to obtain a wider sterilized zone

a – Increasing speed with a straight nozzle : an idea that was not so efficient

The machine which was used before was heating in a first time with hot air and radiative heat transfer the walls of the bottle before blowing a blast of hydrogen peroxide with quite a high speed. Hot air is also injected around the package, approximatively 240 m/s and 343 K, so as to warm the bottle and to prevent the steam of hydrogen peroxide to condensate. This is quite a lot of waste of energy since the machine needs 105 kW of heat and 15 kW of electric power for the fan to be able to blow hot air.



Picture 3 : drawing of the former straight nozzle

Of course the idea was that if the hydrogen peroxide steam has more speed, then it has more chances to propagate downwards. Unfortunately, very quickly, a recirculation zone appeared and when the steam was half way from the neck of the bottle, it turned back upwards. So the weak points of this device were that :

- A lot of energy was wasted to give such a speed to the flow.
- A lot of hydrogen peroxide was also lost since it was a continuous jet that was still working during the waiting time before two bottles.
- It took long time to sterilize properly all the parts of the bottle, especially those far from the nozzle.

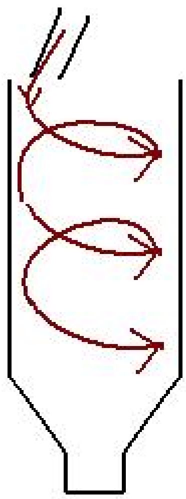
b – The “Active Nozzle” principle : the best improvement until now

Another good idea was to try to make the flow follow the walls of the bottle in an downward circular motion. This kind of nozzle that equips the machines today is quite efficient and use less energy than a straight nozzle.

The so-called active nozzle generates a turbulent jet whom speed is about 60 m/s. Instead of being located in the middle of the bottle, the nozzle is situated on the edge to create a kind of swirl. This device is quite efficient, if we compare it to the old models. The machine which are used today are able to ability to reach efficiently more than the two thirds of the bottle length in a short time.

This configuration is better than to put the nozzle in the center. We could maybe create a device where the injection point will go down and then upward, so as to sterilize first the neck of the bottle, and then its edges. But, unfortunately, this idea would not be so good, since it would cause some troubles for sterility or upkeep of the moving parts. It would also require more electronics to command the engines, or to guide the nozzle on a kind of rail.

As a result, the best thing is still to try to change the nature of the flow itself. Several attempts have been done by increasing speed or the shape of the nozzle, in order to create a swirl or a larger eddy, but there were not really successful. Increasing speed means also a greater turbulence which would be generated and more dissipation of energy, even if it is good for mixing conditions.



Picture 4 : Scheme of the active nozzle and the swirl flow which is generated

3 – Using laminar jets : despite of good numerical results, they are not suitable for an industrial production.

a – The numerical simulations foresee a return loop on the wall of the bottle but at least, the jet could propagate until the neck of the bottle.

Laminar jets could have been very useful in this case, since in steady state, the velocity profile in the bottle with a Reynolds number equal to 688 in the nozzle would have been like in the picture shown below. This screenshot has been made from two dimensional axisymmetric numerical simulations realized at the L.T.H. with the computer fluid dynamics program Fluent 6.0 :

Picture 5 : Laminar jets in steady state : on a scientific point of view, it seems to work. The upper part represents the injection nozzle which has a shrunk diameter at its outlet.

Here above has been represented the axial velocity. The yellow and red parts of the coloured flow show that it might be possible to reach the neck of the bottle with a laminar flow. The only detail here that is to take into account is that the simulation has been made with air injected into air with almost the same temperature. The situation may be different with hot steam blown into cold air prisoner of the bottle.

But the major problem that is inherent to laminar flows is time, since we must wait at least five or ten seconds before considering that the flow is almost in steady state.

b – Time constraints : filling every bottle with active chemical product must not exceed 0.7 seconds

One of the objective of the improvement made on the nozzle is to decrease the filling time with the sterilizing product. The sterilizing chemical product must stay then a specific amount of time in the container to destroy all the bacteria or other micro-organisms. Despite the fact the stream goes straight forward to the neck of the bottle as we can see on the axial velocity contours on the picture above, waiting for the steady state of the flow shall take a lot of time. At Reynolds number around 2200 in the nozzle, the speed of hydrogen peroxide steam is around 0.25 m/s in the middle bottle, but only around 0.1 m/s to go backward on the edges.

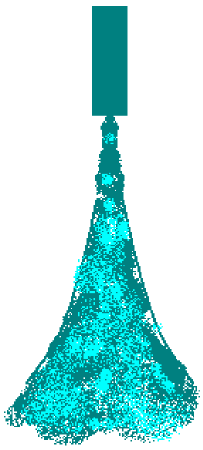
Of course, this case is a little bit critical, since such a high Reynolds number for a laminar flow in the nozzle also means that the jet becomes slightly turbulent in the bottle, since there is roughly an increase in the characteristic length of the flow by two.

The steady state requires also some time to be established and, with these values of speed, it will certainly take more than a second. This is not something that we can consider for industrial purpose. Increasing speed is neither the solution. In this simulation, Reynolds number equal to 688 in the nozzle means that the local Reynolds number is around 1600 downstream, with the shape of the nozzle we use in our experiments.
But the result is quite the same : at high Reynolds number, the recirculation zone and the vorticity linked to turbulence will make the flow unable to reach the neck of the bottle, and the sterile area will decrease.

4 – The former studies : when someone heard about vortices and their ability to propagate far from their "creation point".

a) Blooming jets and vortices studies in the scientific literature : a lot of qualitative work or strictly quantitative description which were hard to understand or to measure with industrial means

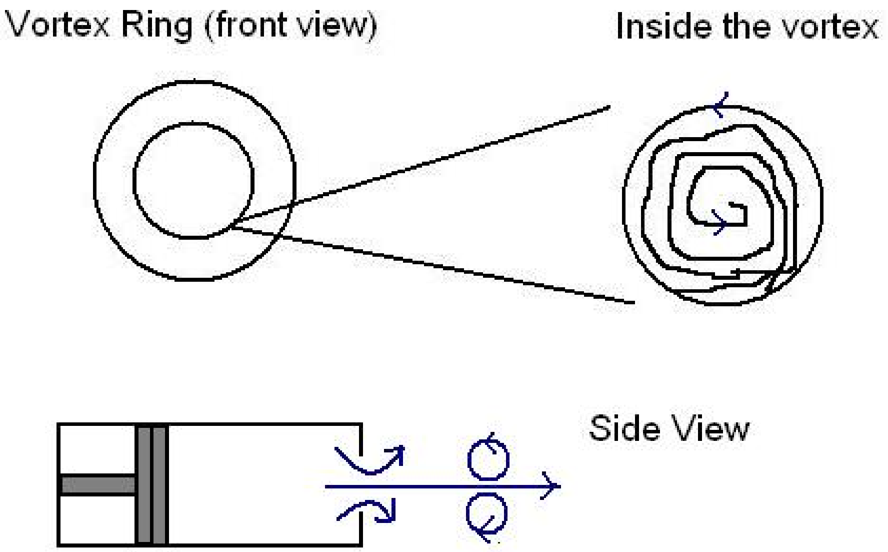
One way to get rid of this kind of problems is to use vortex flows or blooming jets. This kind of streams creates a lot of unsteady structures that go broadening and can fill a wide area. With a simple cylindrical chamber and a piston, torus shaped vortices can be generated and are able to propagate on a good distance before vanishing, because of mixing with air and dissipative work of the viscous forces.



Picture 6 : An example of blooming jet without boundary conditions constraints, the sterile zone grows exponentially depending on the axial distance from the nozzle

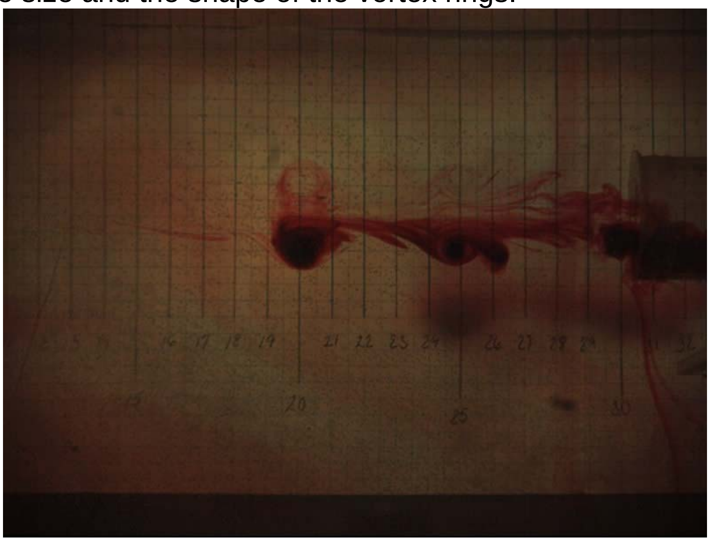
Unfortunately, blooming jets are hard to make, except in conditions of an experiments, and need quite a complex motion of an uneven piston which should have both translational and rotational component of velocity. A blooming jet is also composed of several vortex rings, each of them being sent with a different angle from the central line or the axis of symmetry of the bottle.

Vortices are a kind of motion where each particle takes the place of its close neighbours, and, in our study, have the shape of a ring. All the layers of fluid inside the vortex are rotating around a low pressure point. That also means that the closer a particle gets from the center, the quicker it is. So inside the ring, one may not imagine a hollow structure or circular streamlines but something which looks like a coil :



Picture 7 : Simplified drawing of the structure of a vortex

A picture taken with a high speed camera from our experiments performed underwater can also show better the size and the shape of the vortex rings.



Picture 8 : Two vortex rings made with coloured water. Only half of the vortex is visible here, due to an inhomogeneous concentration of potassium permanganate that was used

The creation and the propagation of the ring will be described in part III and IV of this present report, but the main idea was that it was possible to apply this kind of jet to the machine. Some good scientific articles were already written about the ring speed or the ring size, and there were at the base of all the study.[1]

The great advantage of the vortex rings is that they do not need a sophisticated material to be created. Even a hollow cylinder is sufficient to generate a small ring provided that the speed of a steam which is blown in is high enough. With their ability to propagate on some meters and their size about three or four centimetres, they were the perfect candidates to become the next improvement of the active nozzle which is used today in Tetra Pak.

Of course, after having read some articles of American scientists that have worked on the topic, we knew at the beginning of the study that in order to obtain bigger and steadier rings, it was better to work with :

- A piston chamber that have a ratio between its length and its diameter about 4.1, even if no theoretical explanation had been found.
- A circular section rather than an elliptical section for the piston chamber.
- An outlet diameter that was a little bit smaller than the body of the piston chamber, with an edge that was perpendicular to the axial speed of the flow inside the piston chamber.
- A broadening outlet diameter, so as to encourage the creation of the vortex. Some scientists seemed to use a kind of mechanical opening which was almost closed at the beginning of the motion and that was getting wider to let more fluid go through the exit.

→ As a result, we decided right from the beginning to work with a piston chamber with a perpendicular edge at one end to reduce the opening of the nozzle. The free diameter allowed for the flow was around 3.1 cm, which was more or less also the diameter for the future vortex rings.

→ Another team of master thesis student had already worked before us on the topic. We decided in a first time to work with the same velocity profile for the piston stroke for making our first rings.

b – Some assumptions that were chosen : description of the ring as a torus, use of the incompressible Navier-Stokes equations.

In terms of computational fluid mechanics, some important parameters were also to know, so as to choose in the better way some set of equations or the method of resolution for numerical simulations run with Fluent.

[1] See the bibliography.

Reynolds Number

Very quickly, we realized that we will have to work with a fluid in turbulent mode. Even with experiments that we realized under the water we needed to be at least at Reynolds number between 12 000 for the lowest number and 50 000 for the test that we did with the highest speed as possible with the experimental vortex rings generator.

If we take the Reynolds number that we really need, in simulations or for an industrial machine, we can have a good idea if we take more or less the properties of water vapor that composes around 65 % of the hydrogen peroxide that is used in Tetra Pak and the dimensions of the flow into a bottle.

$$RE = \frac{V \rho D}{\mu}$$

In simulations, for a certain type of nozzle, we obtained very often this kind of array :

	Speed	Reynolds
In the nozzle	4 m/s	5800
In the main part of bottle	14 m/s	78 800

This has been obtained with a density of product equal to 1.208 kg/m3 and an average diameter of the bottle of 6.2 cm. However, the rings are also diluted at 50% – more or less – in ambient air, so their total average real temperature is probably around 320 K rather than 340 K if they are injected at 343 K. Their density can be also a little bit lower, around 1.1 kg/m3. This value can vary a lot, depending on the operating conditions for the machine or the initialization of the numerical parameters. With the same geometry we can have :

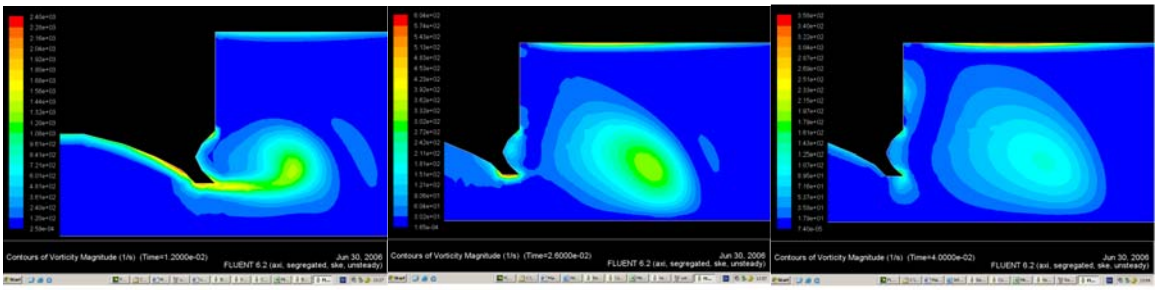
	Speed	Reynolds
In the nozzle	4 m/s	5500
In the main part of bottle	14 m/s	75 100

→ It is obvious that in that case, we must take the effects of turbulence into account.

Unfortunately, for the numerical simulations that had to be run with Fluent, the only simple known model of turbulence that was suitable for this case was the k-ε model. The problem of this method is mainly :

- To estimate quite precisely the turbulent viscosity
- To work with the good boundary conditions in k and ε that Fluent needs to run properly the simulations.

The first simulations in turbulent regime were a disaster since, even if the solution was converged for a second order upwind solving in space. The only evidence was that the default turbulent model of Fluent was not able to predict correctly the propagation of the ring. The first milliseconds of the life time were almost what we expected, but a few moments afterwards, the model overestimated the viscous dissipative work and the virtual vortex rings collapsed much sooner than the real ones, as shown below in 2D-axisymmetric view.



Picture 9 : Fluent screenshots of the ring vorticity, taken at 12 ms, 24 ms, and 40 ms. The results obtained latterly are even worse in turbulent simulation for a ring speed of 1.5 m/s at the outlet of the nozzle. Increasing speed did not bring better simulations.

In terms of computer processing time, turbulent simulations are also very greedy and take very often hours to foresee the evolution of the ring on only 100 ms, what is only 15% of the time of our domain of study. More sophisticated models were also available in the databank of Fluent, such as the Reynolds shear stress, but with so many unknown that their efficiency might have been doubtful.

Assumption of a local laminar structure of a turbulent flow

A good alternative in that case is unexpectedly to come back to a laminar solver, refining the mesh of the grid with a node every 0.8 mm, which was sometimes too wide to describe correctly what was occurring near the boundary layers near the edges of the nozzle and those of the bottle. But this grid was nonetheless a good compromise with the time that was taken before getting the first results.

Sometimes the mesh was even fine enough to capture the turbulence and to reveal some small eddies behind the vortex ring whose sizes were around 1 mm to 4 mm. Then, this case of study can be considered as a wrinkled laminar flow more than a real turbulent flow.[1]

If we consider the model of turbulence developed by Richardson and the Kolmogorov's scale of the larger eddies that rule the mixing rate between the hydrogen peroxide steam and ambient air, we can have an idea of the local Reynolds number in the mean flow.

If L is the diameter of each eddy or the average diameter of the vortex we can write that :

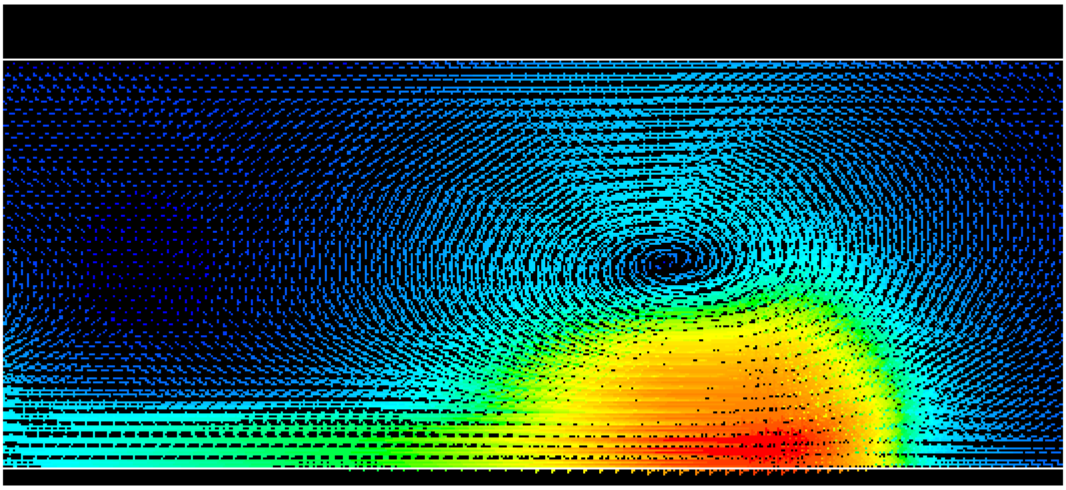
$$RE = \frac{U(L)\,L}{\nu}$$

Where U is the speed of the eddy or the vortex and ν represents its kinetic viscosity.

If we draw a picture of the velocity magnitude in a ring, we obtain more or less this picture, obtain on Fluent. The area coloured in red are around 24 m/s and in blue about 4 or 6 m/s.

---

[1] Courses of MVK 150 Turbulent Combustion at the LTH, chapter 8 about turbulent and the fluid dynamics of the flame, in case of flamelet assumption. Though the Kolmogorov model is accurate to describe the mixing between fuel and air, Richardson model of turbulence based on eddies is suitable for any problem of fluid mechanics with mixing.



Picture 10 : Velocity Magnitude of a vortex ring. 10 ms after its birth in the nozzle, with a piston stroke of 5 m/s during 5 ms, the vortex is the low speed "eye" of the flow.

If we make now an array of the different Reynolds number that can exist, we realize that each vortex ring and its wake can be quite complex, since several zones exist, where the flow is sometimes turbulent and sometimes in transition regime, or even sometimes, in laminar mode.

Location	Heart of the vortex	Wake close to the vortex (<1 cm)	Wake far from the vortex (between 1 and 4 cm)	Smaller Eddies and wake very far from the vortex (>4 cm)
Laminar flow				400 – 2300
Transition regime	2500 – 3000		4000 – 6000	
Turbulent flow		12 000 – 28 000		

Figure 10 : Reynolds number in different parts of the flow generated by a vortex ring

→ As a result, it is now understandable to know why two dimensional simulations have worked so well. They are also very accurate if we compare them to experiments. The flow keeps essentially an almost laminar motion except in the middle of the ring.

→ This explain why the dynamic of the vortex is not three dimensional, because there is not really turbulence inside the vortex. Otherwise, it can make it unsteady. Even if the speed of the flow is around 20-25 m/s in the middle of the stream, the real speed of the fluid is only 8 or 11 m/s in the vortex itself and is even lower anywhere else.

→ As it will be developed later, these results also shows that for a range of speeds of impulse that would be too high, the ring might not be created or might be very unsteady because of the effects of turbulence.

Continuity Equation

In Cartesian coordinates, the continuity equation can be written as :

$$\left(\frac{\partial}{\partial t}\rho(t)\right)+\left(\frac{\partial}{\partial x}\mathrm{U}(x)\right)+\left(\frac{\partial}{\partial y}\mathrm{V}(y)\right)+\left(\frac{\partial}{\partial z}\mathrm{W}(z)\right)=0$$

With the assumption of an incompressible viscous flow, because Ma << 0.3, it can be simplified as :

$$\left(\frac{\partial}{\partial x}\mathrm{U}(x)\right)+\left(\frac{\partial}{\partial y}\mathrm{V}(y)\right)+\left(\frac{\partial}{\partial z}\mathrm{W}(z)\right)=0$$

Where U, V and W are the three axial components of the speed. Then, if we choose to work with cylindrical coordinates and if we make the assumption that there is no rotation around the x-axis because of the 2D-axisymmetric nature of the flow, we can then write that :

$$\frac{\frac{\partial}{\partial R}\mathrm{RU}(R)}{R}+\left(\frac{\partial}{\partial y}\mathrm{V}(y)\right)=0$$

Or even that :

$$\mathrm{U}(R, y, t)=-\frac{1}{2}R\left(\frac{\partial}{\partial y}\mathrm{V}(y)\right)$$

Even though this equation is not very explicit, and does not predict completely the behaviour of the rings, it can be useful to understand some phenomena :

- If one ring tends to spread in the radial direction, it will be slowed, which is not good for stability and the required time of sterilization.

- We can consider two radius of the ring which has a torus shape. R is the outer radius which give the specific size or diameter of the ring, and r the inner radius, which give the strength and the thickness of the ring. If R is too big at the creation of the vortex, because of the continuity equation, it will not be able to propagate with a sufficient axial speed.

- That also mean that the nozzle can not be to small compared to the diameter of the bottle, otherwise, the variation of the radial speed will be very quick, according the axial direction y of the bottle.

Incompressible and unsteady Navier-Stokes Equation

Generally, the Navier Stokes can be solved in an exact fashion by mathematics only for very simple case, for steady states for example, or one dimensional flows. Here the phenomena is time dependent, a little turbulent and at least two dimensional. The approached solution which is solved by a software will be calculated from this equation for the axial velocity.

$$\left(\frac{\partial}{\partial t}\mathrm{U}(t)\right) + \rho\,\mathrm{div}(U) = -\mathrm{gradient}(p) + \mu\,\Delta(U) + \rho\,G$$

Which become, in 2D-axisymetric cylindrical coordinates according the y-axis direction :

$$\rho\left[\left(\frac{\partial}{\partial t}\mathrm{U}(t)\right) + \frac{\frac{\partial}{\partial R}\mathrm{RU}(R)}{R} + \left(\frac{\partial}{\partial y}\mathrm{U}(y)\right)\right] =$$
$$-\left(\frac{\partial}{\partial y}\mathrm{p}(y)\right) + \left(\frac{\partial}{\partial y}\tau(yy)(y)\right) + \left(\frac{\partial}{\partial R}\tau(yR)(R)\right) + \rho\,G$$

Where G is the gravity and τ is the shear stress linked two the viscous work. It can be written as below, if cylindrical coordinates are chosen.

$$\tau(yy) = 2\,\mu\left(\frac{\partial}{\partial y}\mathrm{U}(y)\right)$$

$$\tau(yR) = \mu\left[\left(\frac{\partial}{\partial y}\mathrm{U}(y)\right) + \frac{\frac{\partial}{\partial R}\mathrm{RU}(R)}{R}\right]$$

A similar equation can also be found for the radial component of velocity. This case is very often solved by Fluent with a second order upwind method for solving the space dependent and the SIMPLE algorithm for the pressure correction method.[1]

Energy Equation and Transport species equation :

Theoretically, it would be good to study also the mixing rate and the heat transfer between the injected steam and the ambient air. But the equation are not easy to describe and the best way is may be to comment some numerical results. Of course, as air is already heated when the active chemical product comes, the energy equation shall not be so important for describing the flow, if we neglect the viscous heating effects.

---

[1] « Computational fluid dynamics » by John D Anderson Jr. 5th print. The SIMPLE algorithm is not the only one that can be used, but one of the quickest standard methods which can be run with Fuent to obtain converged solutions.

Conclusion of the second part :

To make a short summary of this second part, three main ideas have to be well kept into memory :

- Vortex rings must be considered as ephemeral phenomena that need some speed for their own stability, but can be destroyed by turbulence or a too high amount of energy : a too long or too strong blast in the nozzle will destroy the ring.
- Vortex rings must be studied and used in almost laminar conditions in the worst case. It is very hard to determine the boundary conditions for a turbulent model, and may be completely turbulent rings are not able to propagate on a long distance.
- The geometry of the flow must be as much as 2D-axisymetric as possible. A very light perturbation can sometime change drastically the efficiency of the flow to sterilize properly the container.

III – Understanding why a ring is created or not, and how to create stable and fast vortex rings : the key parameters

1 – A little tornado loop : the best picture we can have to understand well by mind what a vortex ring really is.

a – Vortex rings and tornadoes are organized around a low pressure line which is straight for the tornadoes and circular for the vortex rings :

Picture 11 : The structure of the flow and the pressure fields have many common points between vortex rings, tornadoes and even rings of smoke (middle).

The great advantage of the experiments that were made with Nicolas Lecomte and Anders Sundberg was to take some films of the ring with a high speed camera that took between fifty and three hundred pictures per second, depending on the speed of the ring. With a good focus, we were able to see the stream lines that were inside the vortex.

The great surprise was in the beginning was to see that it was not something quite and nicely in a uniform circular motion. In fact, the shear layers are sliding one on the others at different speeds and all tend to converge in an accelerated motion to the center of rotation of the vortex. This is due to the low pressure area that exist in this tiny zone inside the ring.

This low pressure area has a crucial role to give the ability of being steady and of going forward at a high speed compared to its size. From this point of view, a vortex ring is nothing more than a miniaturized tornado that would not reach the floor and which would make a continuous loop on itself, propagating straight forward instead of having a random path. Fortunately, the size of a vortex is only about 3 cm in diameter.

b – How to create a low pressure point in motion ? The role of vorticity

First, we must have a look to the simplified Navier-Stokes equation. If we consider a very thin area of space we can neglect the dissipative work due to viscosity and write that :

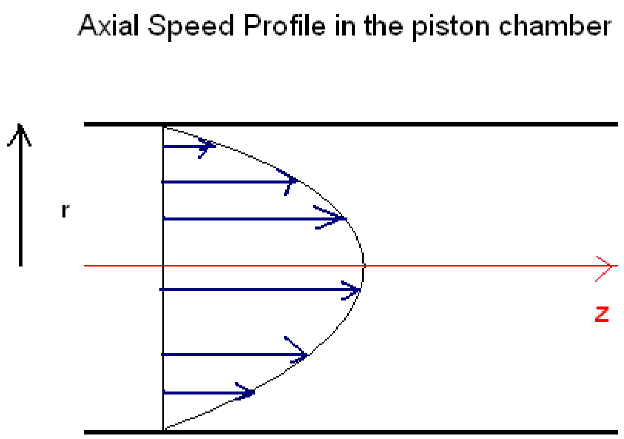
$$\left(\frac{\partial}{\partial t}\mathrm{U}(t)\right)+\frac{\frac{\partial}{\partial R}\mathrm{RU}(R)}{R}+\left(\frac{\partial}{\partial y}\mathrm{U}(y)\right)=-\mathrm{gradient}(p)$$

As a consequence, we can say that the radial derivative of the axial speed is something generally lightly negative since the flow is always slower on the edge than in the middle. All which is important is then that something accelerate the flow and then slow it a little so as to create a pressure loss compensated by a smooth rise of pressure ahead of the future vortex.

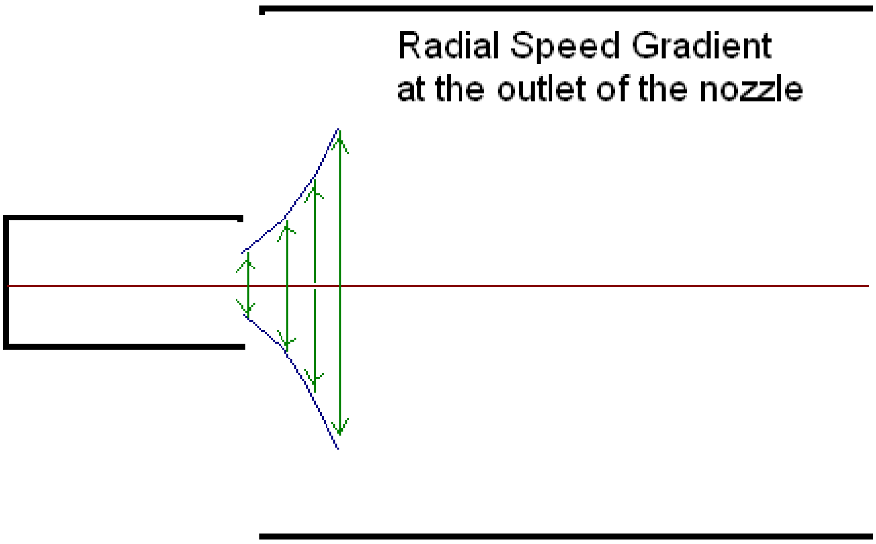
As a result, as the flow is pushed in a first time by a low pressure area, and then a little bit held, the fluid shall be compelled to turn on the sides. It is the point where the vorticity intervenes. Vorticity w is defined as :

$$\omega=\left(\frac{\partial}{\partial R}\mathrm{U}(R)\right)-\left(\frac{\partial}{\partial y}\mathrm{V}(y)\right)$$

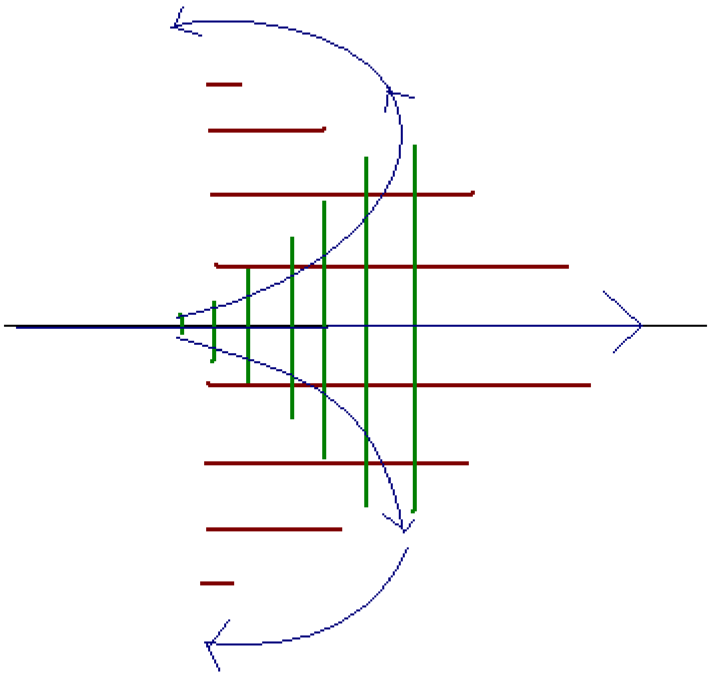
The picture below illustrates the two components of the derivatives that can help the fluid to turn around the low pressure line. This is a view in 2D-axisymmetric :



Picture 12 : du/dR the axial speed profile is always as shown above wether it is in the nozzle or the bottle.



Picture 13 : dV /dy, the radial speed profile is broadening at the exit of the nozzle when the flow is entering the bottle, even if there is no edge at the outlet



Picture 14 : The resultant of the two gradient fields is vorticity and is at the origin of the vortex birth. In red, the axial velocity gradient, and in green, the radial velocity gradient. Three main stream lines has been drawn in blue.

So, it is very important to increase the vorticity of the flow, right from the beginning. Many parameters will depend on this physical value such as :

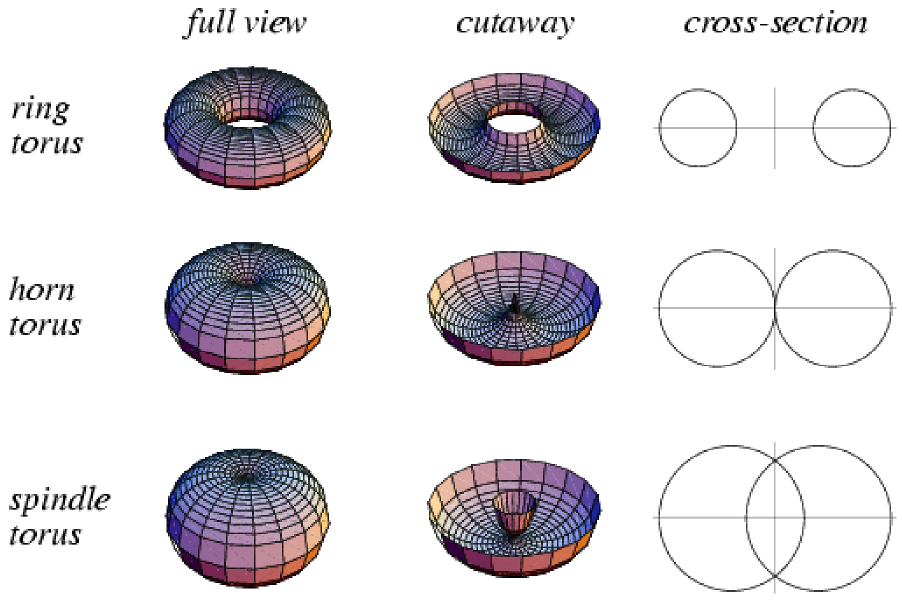
- The thickness of the ring
- The stability of the ring or a kind of robustness.
- The mixing rate with ambient air and the interaction with other rings.

c – More details about the vortex shape and the velocity field near the rings :

One last thing that is to know about the basics of vortex rings is that they are not really like the perfect torus that we can imagine. In fact, if we consider the mathematical formula of the torus volume, we have :

$$Volume = 2\,\pi^2\,R\,r^2$$

Where R is the outer radius or the big one, and r is the inner radius, which give the thickness of the ring. For the vortex rings, we are in the case that strangely, if it was pure mathematics, r would be stronger than R, which correspond to a spindle torus, as described below.



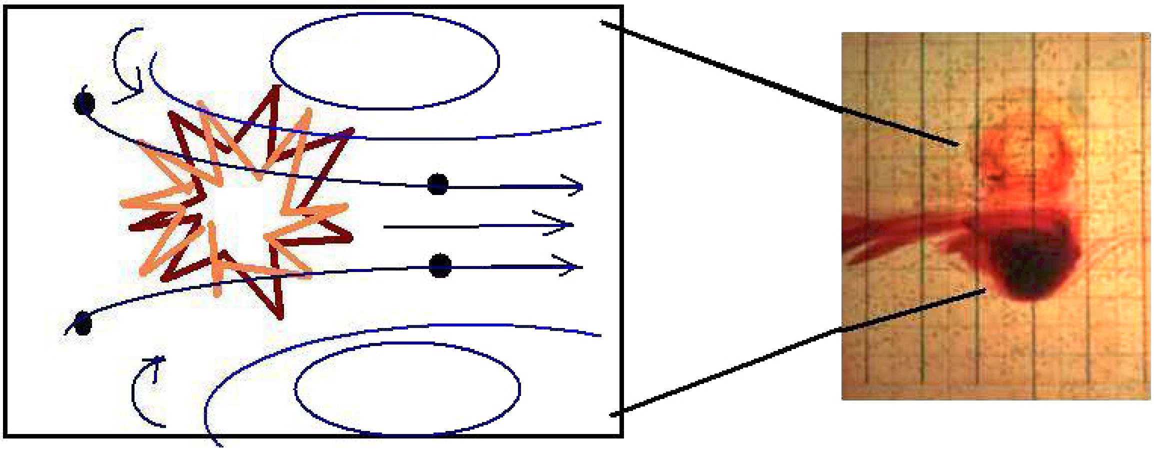
Picture 15 : mathematical view of the three great kinds of torus with circular section

This particular characteristics gives to the stream lines in the middle of the vortex a flattered aspect. In the middle of the colourless part of the ring which correspond to the normal hole of a ring torus, the flow is converging towards a kind a low pressure front and his accelerating. This give to the vortex ring an elliptical shape concerning its thickness.

Picture 16 : Side view of a vortex ring. Even if the shape is circular for the outer radius, the torus has more likely and elliptical section than a circular one for the inner radius.

This particular elliptical shape is probably due to some fluid on the external layers of the vortex that is still rotating around the low pressure circle. When the particles are coming back in the neighbourhood of the ring, they are in the close wake of the ring. The stream lines are converging to the axis of symmetry and attracted by the low pressure line in front of them. They have less and less space to go forward, and in a sense, they are compelled to be accelerated, due to collision between them.

This phenomenon make the viscous layers which are located behind the ring accelerating, and flattering until the flow loses its rotational motion in the heart of the ring. This acceleration is responsible for the deformation of the section of the ring, which becomes elliptical, in the direction of the axial speed.



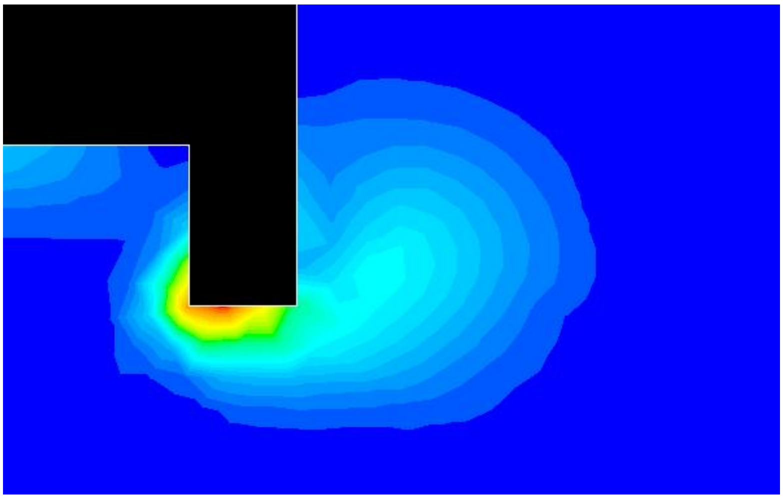
Picture 17 : Mind view of the collision of two symbolic particles with rotating layers behind the ring which compels the fluid to accelerate in the « hole » of the ring which was usually colourless in our experiments with under the water.

2 – Improvements made on the device which was used to generate the vortex rings : from a simple piston chamber to more complex shapes that show the importance of the recirculation zone.

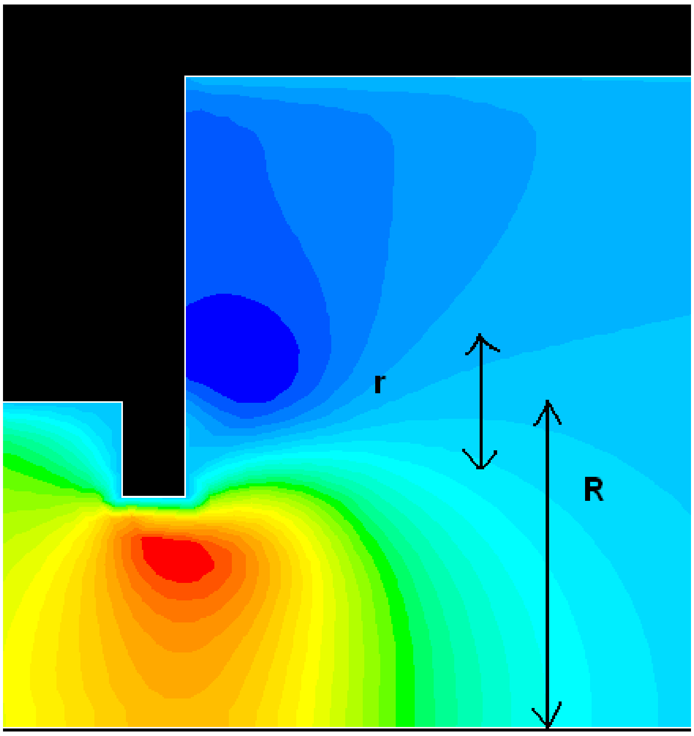
a – The influence of the edge of the outlet : increasing the speed and generating a high vorticity path

Making an edge at the outlet of the piston chamber is something which can be very good for the birth of the vortex, since it will increase both axial and radial velocity gradient of the flow. It is especially the radial speed derivative according the axial direction which will be improved by this way since, there is first a shrinking diameter and then, a brutal increase in the diameter when the hydrogen peroxide is entering the bottle.

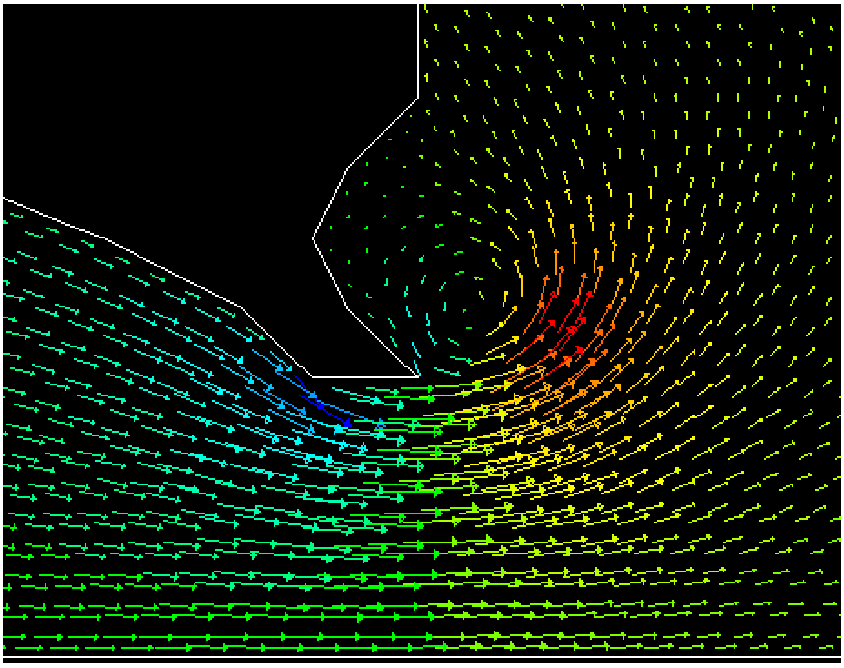
Combined with an axial speed that is a little bit increased at the level of the edge, this already gives a kind of circular motion to the external layers that come out of the outlet. That creates the origin of the circular motion of the ring, though the fluid has more a bubble shape when it is coming out of the nozzle.



Picture 18 : Zoom on the generation of a high vorticity zone which is hooked to the nozzle edge. The colours are purely indicative. The future vortex is on the right part of the picture, coloured in light blue. It is still on its growth phase on this picture.



Picture 19 : Zoom on the axial velocity field near the outlet of the nozzle, the ring is propagating rightward inside the bottle. As some fluid is injected into the bottle, some other is going out (deep blue zone). The vortex is already born . The edge is only 0.3 cm here, but is area of influence on the velocity field is already much bigger than expected : something like 6 cm, twice the visible part. R is equal to 1.5 cm and is the outer radius of the ring. The small r is the inner radius of the torus that we can see with our bare eyes. In fact, its area of influence is felt in the whole width of the bottle.



Picture 20 : Zoom on the radial velocity field near the outlet of another kind of nozzle, the ring is also propagating rightward on this picture. The blue arrows indicate that the fluid is diving toward the axis of symmetry (low edge of the picture), thanks to the shape of the nozzle. Then, the fluid naturally tends to fill all the space that is offered to him, so the red arrows indicate a positive radial velocity which is very strong near the eye of the vortex which is clearly visible in the middle of this screenshot taken from Fluent.

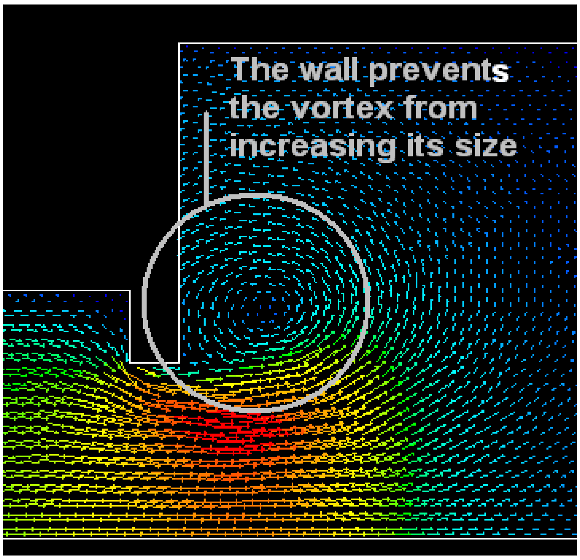
b – The recirculation zone after the outlet of the piston chamber is one of the most important parameter for the growth of the vortex.

As the vortex sends backward a certain amount of fluid right from the beginning, it creates a a recirculation zone which is stuck to the edges of the nozzle. This recirculation zone is an important thing to consider since :

- In a first time, it can be seen as some free space where the vortex is allowed to grow, until it as enough speed and energy to propagate forward.
- Depending on the boundary conditions and the curvature of the solid parts on which the fluid boundary layers are slipping, it will strengthen or weaken the vortex.

To illustrate in a better way this assertion, we can make a zoom on one of the screenshot that has been done with Fluent with a classical nozzle shape. The picture below has been taken just after the 80 milliseconds of life of the vortex, with a maximum local speed of 0.4 meter per second in the middle of the outlet, which correspond to a laminar case.

The point which is very interesting to notice is that the classical shape of nozzle that was used before our work is something which is very bad for the recirculation zone and the growth of the vortex. A straight edge disturb quite a lot the circular geometry of the ring, which cause a loss of vorticity, and more viscous dissipating if the surface is not even. As the no slip condition is enforced at the walls of nozzle, it also means less speed.



Picture 21 : As opposed to an intuitive idea, a straight edge is not something which is optimized for stability and growth of the vortex. The circle is flattered on its back.

Another kind of mistake must also be avoided. It is not so good to increase to its maximum level the length of the perpendicular edge of the nozzle. Simulations and experiments showed that with a little opening of only 0.4 cm of diameter for the outlet, there were no vortex at all.

The explanation is that if the edge is to big, the fluid will accelerate too much in the narrow exit of the piston chamber. Then, there will be a brutal change of geometry, an increase in diameter by almost 15 when the vortex enters in the bottle with this kind of nozzle. It means that the section would be multiplied by almost 220. So, there is a great change of the radial component of the the speed, that tends to stick the fluid to the walls. As a result the vorticity is completely destroyed, by this brutal decrease in axial speed. The recirculation zone is captured in the boundary layer and the fluid then follows the edge of the nozzle due to a kind of Coanda effect, another part of the flow can also make a kind of shapeless cloud in front of the nozzle edge if the piston – or another device – still pushes the fluid forward.

On the contrary, having an opening of only 1.6 cm in diameter is till something possible to obtain very good vortex rings. Even if we do not have studied what was the critical diameter to create a vortex ring. It would not be surprising to find something around 1 cm. On the other hand, making no edge at all or very light edges only give very thin vortices, which is not the aim of this study, since we need them for sterilization and transport of chemical product.

To summarize a little, we can remember that :

- for a nozzle diameter of 3.1 cm and a bottle diameter of 6.1 cm, having a circular edge between 3 mm and 4,5 mm gave the best results, since the outlet that was reduced still had between 1.6 and 2.4 cm to allow the fluid to go through.

- Having a nozzle straight edge is something good on the one hand, since it increases speed and give a circular motion to the fluid to initiate the creation of the ring, but on the other hand, it also troubles the growth of the ring to its full size and gives to it less vorticity than in an optimized case.

3 – The best experimental prototype of nozzles illustrates the main idea : once the vortex ring is created, we must let it free to evolve.

a – A innovating shape of the recirculation zone : no constraint for the vortex which become almost free to increase its width to its maximal value.

The idea came by analysing some intuitive theoretical ideas, pictures taken in experiments or study of the results of numerical simulations. Since the vortex naturally fills a circular volume, it was interesting to try to carve the edge of the nozzle and to see what would happen later.

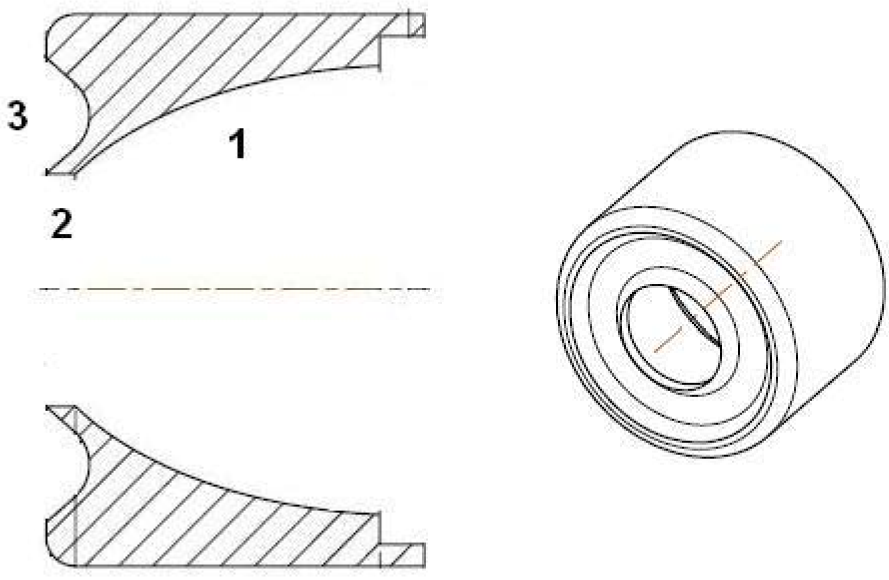
But before founding, that idea, we also had already made a dozen of different kind of nozzles as shown below :

Picture 22 : The first family non-classical models of nozzle

We thought in a first time that our best prototype was one of these ones, which had a converging shape, with a soft slope, which had the same good effects than the straight nozzles, with less disadvantages such as minimizing the speed lost. This kind of nozzle were quite good to send fast and steady rings, but small ones, we felt that something still had to be improved.

So, the idea was to combine the best part of all the shapes that has been formulated before, for designing the new kind of nozzle that we used latterly. In fact there are probably three parts that are to consider on this device, even if it still look pretty simple at a first sight.

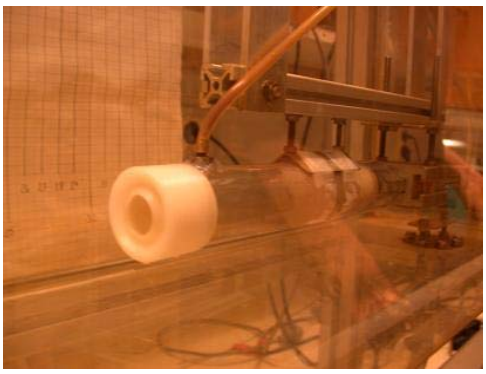
The first zone is made to increase gradually the speed of the flow, and has been drawn according an elliptical curve, whom angle with the horizontal is increasing smoothly, so as to minimize head loss. This first part finishes almost vertical, just like in the straight edge nozzle case. This second part, which is the same that classical models, generate a high vorticity of the flow. The third part allow the vortex to grow freely until reaching the size we want for the process. It also strengthen the 2D-axisymmetric attribute of the flow outside the nozzle and prevent some phenomena such as too much turbulence or swirling to occur. Thus, we can have better control on the path of the vortex and its growth which is crucial for industrial development of this process.



Picture 23 : Our best nozzle shape. Zone 1 for increasing speed, Zone 2 for generating high vorticity, Zone 3 for better controlling stability, growth and direction of the vortex. (From a picture drawn by Henrik Brännmo)

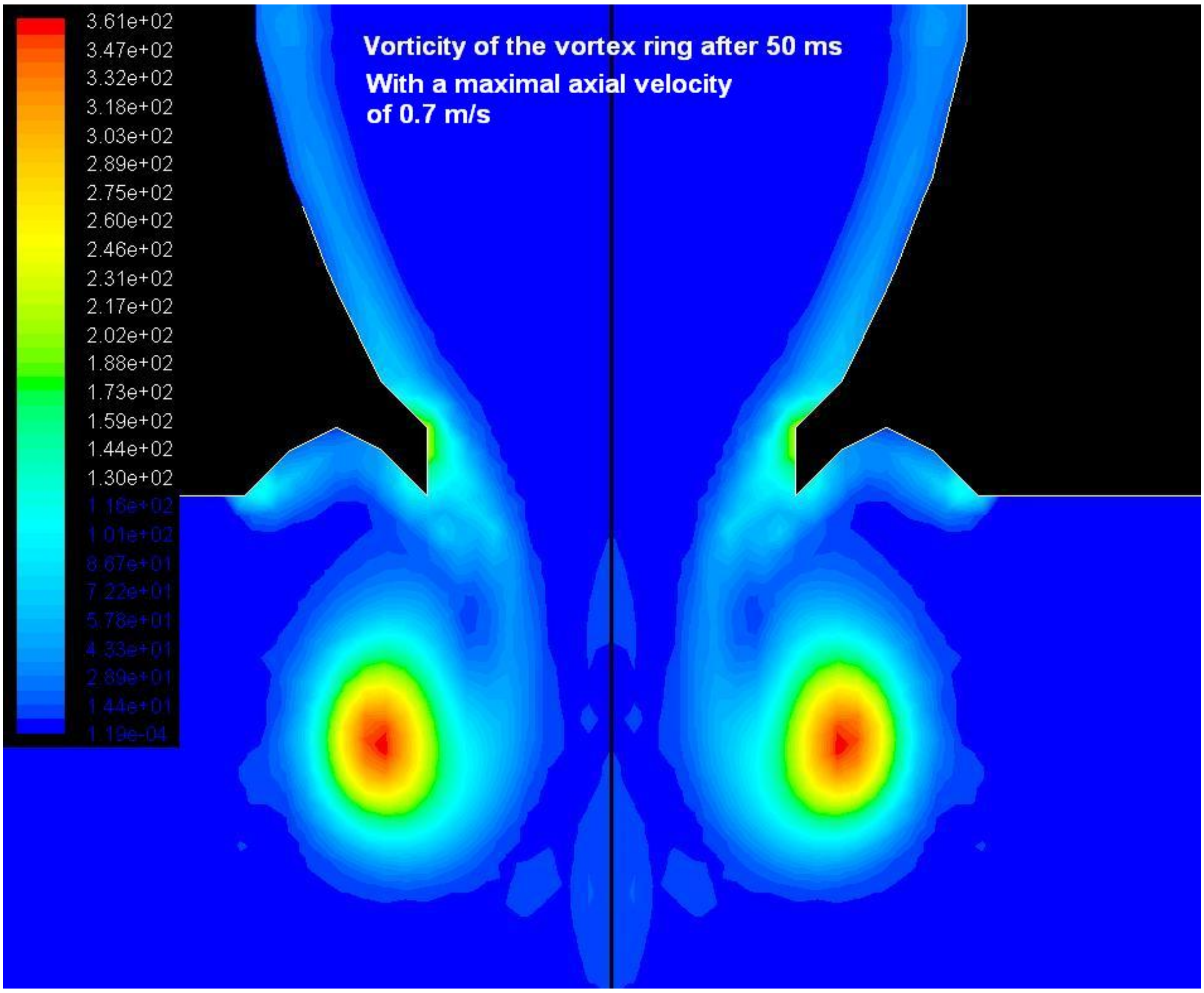
One last detail must be also remembered about the third part of the nozzle. It is not totally circular but lightly elliptic. As the ring tends to accelerate and to be deformed in the axis direction, our idea was also to create the ring in an elliptical cavity that whose greater axis was in the radial direction of the bottle. As a result, it tends to give to the rings a more circular shape in the beginning and helps them to be a little steadier.

Though, quantitative optimisation with mathematical models have not been developed, it can be a good way in the future to improve our pioneer's work.



Picture 24 : Our best nozzle prototype in the tank we used for underwater experiments

b – The new shape of the nozzle allows also some controls on the size, the shape and the ability for the first vortices to reach the neck of the bottle.

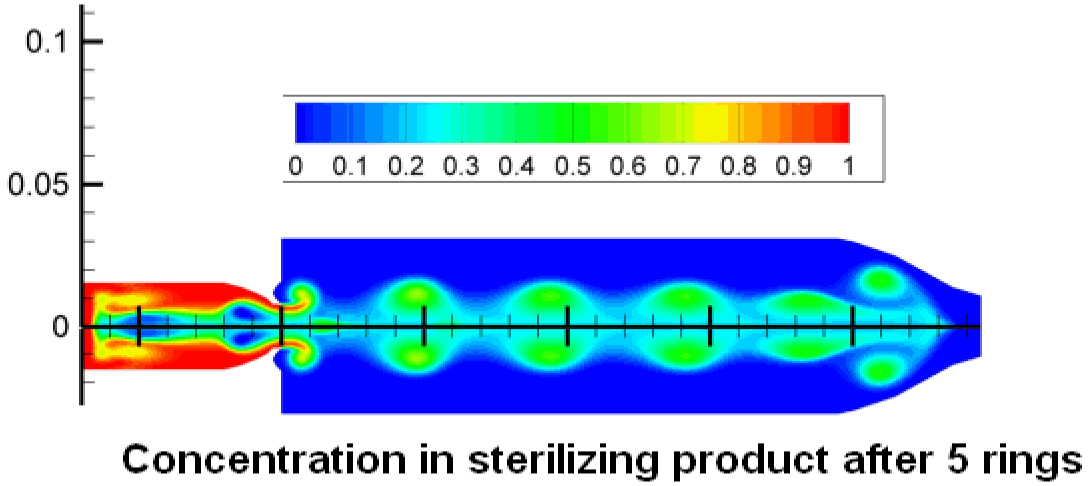


Picture 25: With the new kind of nozzle, seing contours of vorticity is something very good to know where are the boundary of the rings. The high vorticity area is inside the vortex where the fluid moves at more than 340 hz even for a speed of 0.6 m/s at the outlet. The direction is perfectly well aligned with the axis of symmetry of the bottle.

The size of the ring is more or less the size of the hollow elliptical shape which is carved in the walls of the nozzle. It is a very easy way to know more or less what the dimensions of each ring will be. Another advantage is that each ring can be created in the same conditions thanks to that device that minimise the turbulence of the wake which is left behind the ring.

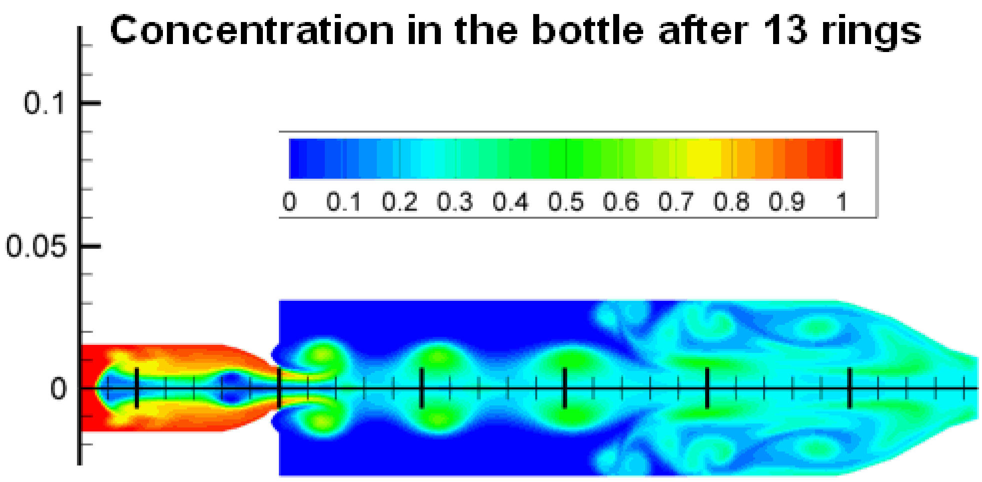
This last point is also good for the last part of this report which deals with interaction between the rings. On this picture, what is clearly shown into evidence is that the visible part of the ring (only what appears in red and yellow) is only the part of the iceberg that is above the sea level. Most of the flow is invisible and here we can see clearly in 2D how the surroundings of the vortex ring are affected.

The most important thing, once the size and direction of the first rings is something certain, is of course to send as many rings as we need to the neck of the bottle. As it is shown on the picture below, this kind of nozzle has a very good ability to send several rings in places that were hard to reach on the devices.



Picture 26 : With this kind of nozzle, each ring can reach the end of its path and even the cup or the neck of the bottle can be well sterilized. Concentration is a function of its original concentration in the nozzle (red color = 1, no dilution, deep blue = 0, air only). This simulation correspond to the worst case of dilution. The bottle is represented horizontally for more convenience.

Of course, what is remarkable with this kind of nozzle is not that the rings can reach the end of their path, but how regular they are in terms of speed and dimensions.



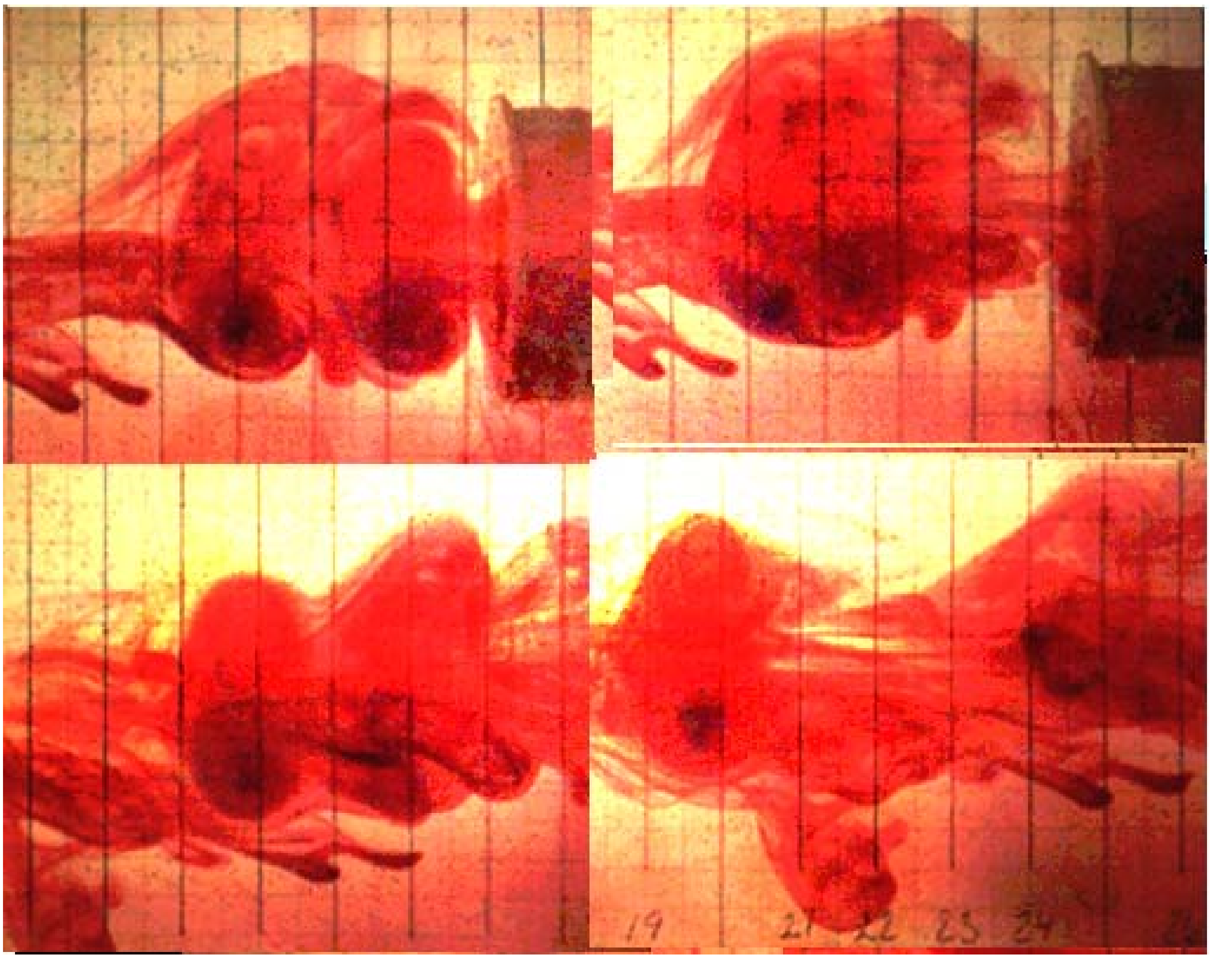
Picture 27 : 13 or 14 rings are enough to sterilize half of the bottle, in the parts where traditional methods are not such efficient in terms of time or injected matter.

IV – Interactions between the rings, a necessary knowledge to determine how often the rings must be sent.

1 – Summary of what has been done before our work

To be very concise, we can say that the former team of master students which have worked on the problem realized that very often, with the same waiting time and the same piston impulse to generate the rings, the second ring was colliding with the first. Once the two rings have destroyed each other, the other rings are very troubled when they go through the turbulent remains of the vortices, and could not propagate very further.

Sometimes, if the two rings have enough vorticity, especially just after their creation, they can also merge in one bigger ring. Otherwise, only the quicker ring can survive to the collision. So, in order to spare some time and hydrogen peroxide, it is good to avoid this kind of problem.

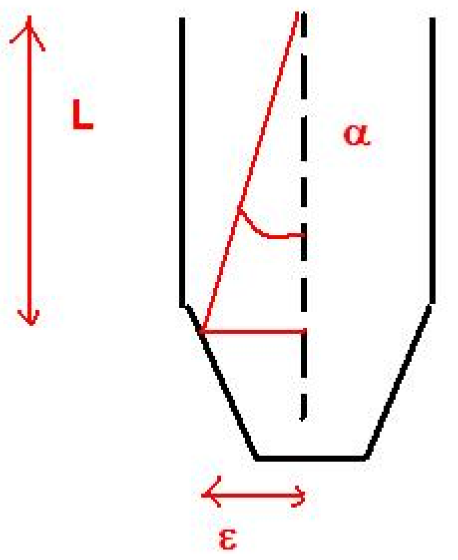


Picture 28 : Collision between two vortex rings. One is lost, the other is bifurcating from the axis of symmetry of the bottle can be less steady than expected.

2 – The directional stability, a critical angle between the nozzle and the bottle must not be reached.

One important parameter that was also revealed from the experiments was that the nozzle and the bottle must be perfectly aligned, to avoid a crash of the ring against the wall of the bottle. But as the bottles will arrived moving on a kind of conveyor, it will be hard to align them, or it will take too much time. So the idea is better to give a range of angle which can be good to respect for deviating from the axis of symmetry.

The calculus is pretty simple and very easy to follow, it is more geometry than fluid mechanics.



Picture 29 : The maximum angle which the ring can be send

For the bottle that we used, or if it was another kind of container, such as a tetrahedron or a brick, L is the axial distance that must be covered by the rings in a satisfactory case. The diameter of the ring is usually around 3 centimeter, and the vortex might be weaken if it comes to close from the walls of the bottle. But the point is that if the ring crashes at a place near the point which is represented above, it can still sterilize the neck of the bottle.

So, we just have to say that :

$$\sin(\alpha) \leq \frac{\varepsilon}{L}$$

And with the characteristics of our experimental device (3 cm for epsilon and 20 cm for the bottle) we can take a maximal angle around 8.5°.

3 – The area of influence : the most important notion to understand in order to avoid ring collisions.

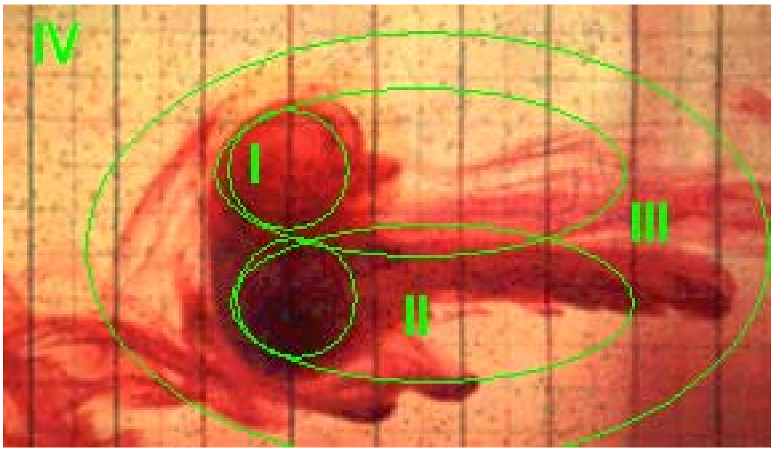
a – Most of the flow is invisible, what we call "area of influence" is the zone of the velocity field where the presence of the vortex can be felt.

One surprising phenomena leaded our attention on some unexplained failure of the rings to propagate if they were to quick or to fast. Everything was going well until a certain extent, and then the ring broke itself.

Of course, that was not expected and this is a serious obstacle for sterilizing quickly a great volume or to heat it if we want to use convective transport instead of heating by radiations. As a result we try to understand why such phenomena occurred quite often, where are the scientists who worked on the vortices did not mentioned this kind of problems.[1]

The only explanation was that the scientist were making vortex but let them evolve and growth freely in a tank of water or a room and not in a bottle. So, we decided to leave away the bottle in our experiments and we had not the problem of a breaking of the rings in the middle of their path.

We had the idea that something else was to consider about vortex rings and we tried to focus on the flow, with maximal zoom on with the high speed camera, and we tried to pay more attention to some detail, like this one, when a ring was spreading the stream lines of the wake of the previous ring that was on its way in front of him :



Picture 30 : the four zones we can consider. I) visible part of the vortex. II), the elliptical part of the flow, were acceleration of the wake can be seen, especially when two rings collide. III) is what we call the area of influence : every thing that is affected by the vortex. IV) is the silent zone which is not really affected by the vortex.

So, the visible part of the flow is not the whole vortex, and it is especially difficult to imagine or try to see the transparent particles of ambient air or water to rotate or to move around the low pressure points. But we understood why a ring which is to big can not propagate inside the bottle.

[1] From "Starting flow through nozzles with temporally exit diameter", O. DABIRI John and GHARIB Morteza, Graduate Aeronautical Laboratories & Bioengineering – California Institute of Technology – USA, June 2004.

The fact is that it is worthless to try to make the rings as big as we can for sterilization purpose in a narrow space such as a bottle. As soon as the boundary layers that should be in motion or rotation are slowed by the friction against the wall of the bottle, the viscous dissipation of energy is transmitted to all the layers of the vortex, which loses its vorticity. Unfortunately, the cohesion of the ring is only due to vorticity, so the ring quickly became a shapeless cloud when its area of influence hits the walls or grows too much and is troubled by the proximity of a solid surface.

As a result, it was something very good to work with smaller rings which were only 0.8 cm if we take the outer radius of the torus model for describing the ring, compared to the first ones which were 1.2 cm in outer radius. The thing is that the ring must be dimensioned for the narrowest space that it has to sterilize. As the cup of our experimental bottle was about 1.1 cm, it was not a surprise to see that the 0.8 cm rings were better, since with their thickness, their external diameter was more something like 1.2 or 1.1 cm. So, they could reach pretty well the neck of the bottle, even if they were growing a little bit on their way.

b – Some parasite effects which are linked to the area of influence can affect the rings interaction quite strongly, changing notoriously their speed.

Avoiding ring collisions thanks to the "Area of influence model"

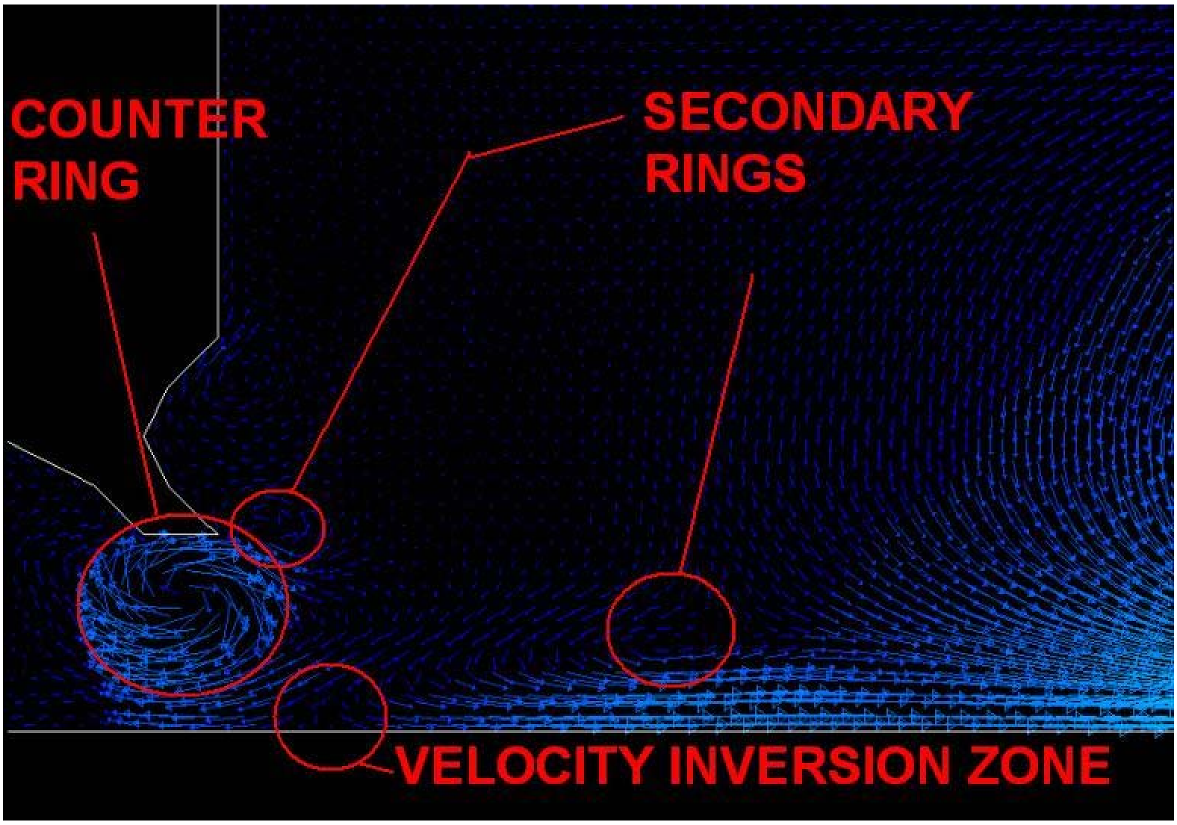
The other great interesting result of our model of area of influence was to analyze why there were so much collision between the rings. The fact is that behind a ring, the zone II which has been drawn on picture 30, is accelerating. So, if the n+1 ring is following too close the n ring, it will be caught in that area and then will be attracted by the low pressure zone of the number n ring, and the n+1 will dive into the its predecessor and then destroy it.

→ In order to avoid this risk of collision, it is good to set a waiting time which is long enough to can consider the rings as almost isolated from all the others.

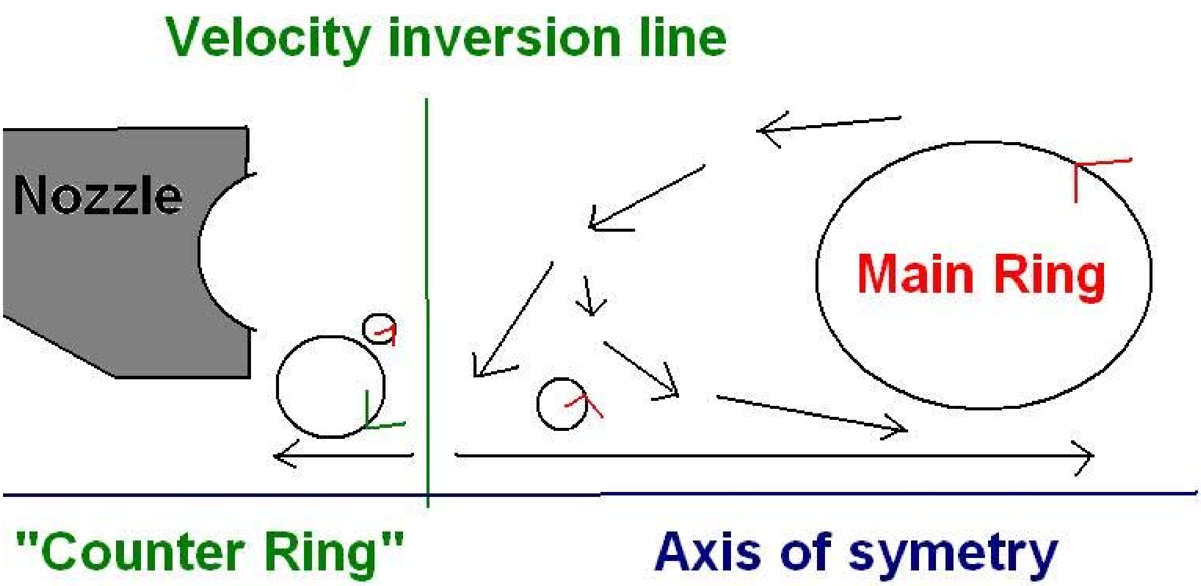
→ Waiting too much is not something to do either, since some parasites phenomena can develop themselves, especially if the time dependence of the excitation of the inlet is not something smooth as a sinus function. A step or triangular signal for the signal is not so good, even if the triangular signal (constant acceleration, linear increase of the piston speed on our devices) gave very good results for the volume and thickness of the rings.

The speed profile of the velocity inlet inside the nozzle has also an influence on the structure of the flow and can generate secondary rings, or even counter-rings :

But on numerical simulations, some even closer zoom revealed some strange turbulence that can happen if the impulse is stopped brutally, for example, if the piston stroke ends too quickly. In other words, the ring must be accompanied by some fluid that will have more or less the same speed than it. Otherwise, if the speed of the fluid which is pushed through the exit of the nozzle falls from 20 m/s to only 4 or 5 m/s in a few milliseconds, this is what can occurs, on pictures 31 and 32 below.



Picture 31 : The wake of the ring can be less quiet than a simple laminar flow



Picture 32 : simplified scheme of picture 31 concerning the stream lines.

Secondary Rings :

Secondary rings are made by the mean flow if the impulse which creates the first ring is too long in terms of time. Once the main ring is sent away from the nozzle, it has more or less a straight wake. Then, if some fluid is still pushed out of the piston chamber, it will make a second ring, or even a third.

But another phenomena which is different can also be at the origin of the birth of a secondary ring. On picture 32, we can see that some fluid which is pulled backward by the vortex make a kind of rotating flow which can become counter-flow. With the different shear layers it can make rotate some fluid, in eddies that are only 3 to 5 mm in diameter that might have a ring shape if the 2D-axisymmetric nature of the flow is preserved.

Counter-rings :

Counter-rings are made when the fluid which is moving backwards and which has not enough vorticity to come back again in the ring or in the wake is diving behind the main wake. If this motion is strong enough, especially if the piston is moving backwards in that moment, it can invert the direction in which is flowing the steam of chemical product. This is what we have called velocity inversion zone. On pictures 31 and 32.

Of course the counter-ring is much stronger than secondary rings and can slow down the speed of the ring which can go just after if the waiting time between two rings is to short. This explains why we had so much problem in the beginning with the second and third rings. The second ring, which was completely slowed by a counter ring born from the wake of the first vortex was caught and destroyed by the third one, where as the former team before us had a collision between the first one and a fast second one since they were using a longer waiting time, but which was not long enough to set the second ring out of the acceleration zone of the wake of the first one. As counter rings can have 10% of the strength of the main rings, and are invisible in experiments, since they are not located in the colour part of the flow, they are not something negligible or easy to deal with.

Velocity inversion zone :

It can be assimilated to a little counter flow that can prevent the ring to reach its maximal speed. Thus, if the ring has to go through a velocity inversion zone, it can be also slowed by 5 or 10%. Combined with a counter-ring, it can reduce even more the speed of one ring. Fortunately, this phenomena dissipates very quickly (some milliseconds) in time.

c – Discovered by chance, a very empiric approximation can foresee more or less what is the extent of the area of influence.

Reading some scientific reviews, we discovered that derive a kind of formula[1] that could foresee roughly a circular shape of the area of influence of the vortex which can be written as

$$Ra = \frac{\sqrt{2}\,\sqrt{\dfrac{y\,Q}{\rho\,(D-2\,\delta)^2\,\omega}}}{\pi}$$

[1] See Appendix II. For complete demonstration.

Where Ra is the radius of the area of influence, y the covered distance in the axial direction, D the mean diameter of the piston chamber, delta the edge put on the outlet and omega is vorticity of the flow.

This parameter is hard to handle but it gave some interesting results. Then if, vortices are sent at the distance r, they will be almost isolated one from the other and will not interact. If they do not interact, they will propagate only a little bit quicker than if they were sent alone, since the first rings will create a kind of remaining flow that will help the following ones to propagate faster.

→ A usual value of distance of safety for avoiding ring collision is around 5 to 6 cm for our device, which is twice the value of Ra to avoid all risk of collision.

d – Knowing correctly the size of the area of influence allows to determine the maximal frequency which the rings can be sent into the bottle without any risk of collision

Being given a certain number N of required rings to be sent for reaching the wished concentration into the bottle, and T the time in which we much inject the chemical product in the bottle for sterilization, we can say that :

The minimal frequency is :

$$fmin = \frac{N}{T}$$

The maximal frequency is :

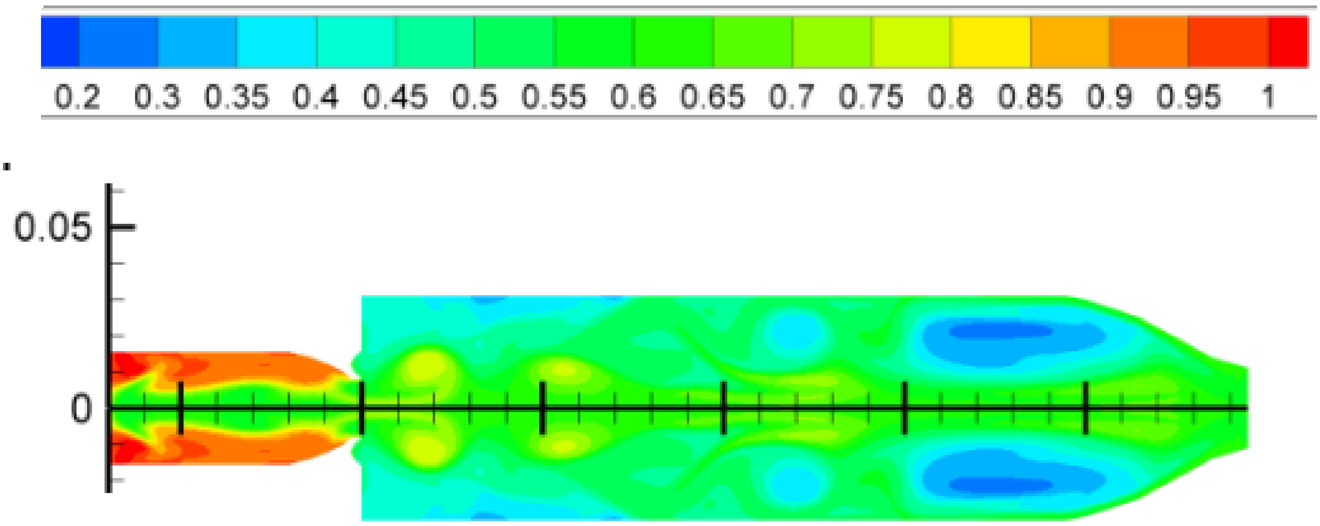
$$fmax = \frac{1}{2}\frac{Vring}{Ra}$$

Where V ring is the average speed of each ring in the axial direction and Ra the area of influence.

4 – Average dilution and number of rings required to fill the bottle in less that 0.7 seconds. 40 rings should be enough.

a – Dilution of the ring : a hard question to solve since the mixing between the active chemical product and ambient air is not homogeneous.

The dilution of active product in the ring is very changing and can vary from 80% on the edge of the ring to only 30% in its heart for the first rings, whereas for the last rings, after 400 ms of sterilization, the dilution is only 40% on the edge of the ring and 20 % in the heart as shown below on the next page.



Picture 33 : Even if the simulation of the flow is less accurate for the last rings (3D phenomena occurs here after 30 rings. The speed of the impulse was governed by the equation v = 1 +4 sin (2 Π * 125 * t) m/s which is one of the best in terms of frequency (125 Hz) and for avoiding turbulence of the wake.

The concentration of the rings is here about 70-80% of its initial value in the nozzle. The low concentrate stationary ring does not exist in real conditions or experiments. The neck of the bottle is full of product in all our tests.

Of course, the concentration of the rings can be even better if instead of mixing with air they could be mixing with active chemical product in a kind of chamber of the same diameter than the bottle which can be located between the nozzle and the bottle.

b – Volume of the ring and ability of each ring to transport some reactant to sterilize the bottle.

The volume of an elliptical torus ring is :

$$Volume = 2\,\pi^2\,R\,(a+b)^2$$

Where a and b are the axis of the elliptical section and R the outer radius. With the perfect gas law and the properties of the sterilizing product which are closed to water vapour it gives at 70°C, it gives the mass of pure active product that each ring can carry :

$$m = 2\,\frac{purity\;p\;\pi^2\;Rring\;(a+b)^2\;M}{R\;T}$$

The mass that we found is very small, something like 1.34*10-6 kg of pure product per ring, that also impossible to heat a bottle by this way with hot air.

Once we have the mass per ring and the concentration in kilo per meter in the bottle, we deduce N, the number of rings that we must send into the bottle.

$$N = \frac{c\ Vol}{m}$$

Where c is the required concentration in kg/m3, Vol the volume of the bottle and m the mass of active product per ring.

If we take 2.5*10-5 kg of active product that is required in the standard bottle we have worked with, and an average dilution of 50% and an initial purity in active chemical part of the steam, we obtain a number of rings that is around 40 with a security margin.

c – Intermediate conclusion about the great advantages of using this methods and last details to be known about the maximal speed.

Of course, increasing speed shall allow to increase maximal frequency. But this idea might by wrong. There is may be for each kind of nozzle shape, a maximal velocity that must not be reached, otherwise the flow is :

- either too turbulent and the rings are not steady.
- Or the flow does not turn enough to make a complete loop in the recirculation zone and create a true vortex, and then, we have the same situation as in a turbulent jet, which is not such efficient.
- For our device, a speed of 8 m/s in the piston chamber is already too much to make good vortex rings. At least, the simulations showed that there was no point in increasing the speed over 6 m/s, but their model is may be not so accurate.

Of course the main idea of using vortex rings is to save :

- time for injecting product
- in the case where the chemical product is hydrogen peroxide, wasting less hydrogen peroxide than in the case of a turbulent and continuous jet.
- Saving energy the fluid has to be injected at 5 m/s maximum or 6 m/s and not 60 m/s, the power which is required is far smaller for putting the fluid into motion.

CONCLUSION

After four months of work, of team work, we have focused mainly our research on understanding how the vortex was created and why they could propagate well or not. We discovered that it was possible to give the nozzle another kind of shape to improve the stability and the size of the vortex. Now, the experimental device has been improved and has given some encouraging results.

But the main point to remember is that a further optimisation of our work must take into account that many physical values are bounded together. The shape of the nozzle can give a range of speed which is suitable for the vortex, and this will put many conditions on the volume of chemical product that each ring and the maximal frequency at which the ring be sent. Of course, this further research can also try to know how this numerical impulse that we found (sinus time dependence for the speed profile at the inlet for example) can be made for real or implemented onto the machine. An other axis of research can be also how to avoid too much dilution of the first vortices, with a kind of steam of chemical product on the side of the bottle, though it may disturb the vortices.

BIBLIOGRAPHY

Scientific Articles

"Fluid entrainment by isolated vortex rings", O. DABIRI John and GHARIB Morteza, Graduate Aeronautical Laboratories & Bioengineering – California Institute of Technology – USA, December 2003. 20 pages.

"Delay of vortex ring pinchoff by an imposed bulk counterflow", O. DABIRI John and GHARIB Morteza, Graduate Aeronautical Laboratories & Bioengineering – California Institute of Technology – USA, March 2004. 3 pages.

"Vortex drive", Pam FROST GORDER, 5 pages. New Scientist, 23 October 2004 (No2470), p30.

"Starting flow through nozzles with temporally exit diameter", O. DABIRI John and GHARIB Morteza, Graduate Aeronautical Laboratories & Bioengineering – California Institute of Technology – USA, June 2004. 26 pages.

"Bifurcating and blooming jets", Reynolds W.C., Parekh D.E., Juvet P.J.D. and LEE M.J.D., Annual Review of Fluid Mechanics, 2003 (volume 35). 21 pages.

→ These articles helped us to understand what type of work has been made before and what was interesting so start with vortex ring. It has also allowed us to get more familiar with vortices, which is not something intuitive. And last point, they were determining to look right from the beginning in the right direction.

Courses

"Fluid dynamics – part 1", LOUISNARD Olivier, 2nd year courses, EMAC, ALBI, 2004/2005

"Fluid Dynamics – part 2", SCHMIDT Fabrice, 2nd year courses, EMAC, ALBI, 2004/2005

Notes from the course computational fluid mechanics attended at the LTH (code of the course MVK150 for undergraduate students)

Notes from the course turbulent combustion attended at the LTH (code of the course MVK125 for undergraduate students)

→ All the theoretical background of our study came from here. The turbulent combustion, which is based on the fluid mechanics of the larger eddies in the flow has been the most useful to well understood what can happen with vortex rings

"Computational Fluid Dynamics, the basic applications" by John D. Anderson Jr. 547 pages, fifth print. ISBN : 0-07-113210-4

Online fluent help.

→ Once again, some basic knowledge is compulsory to use solvers as Fluent and to program some advanced function of control of the flow using a kind of special C++ language which adapted to Fluent in order to simulate as best as possible the physics of the flow.

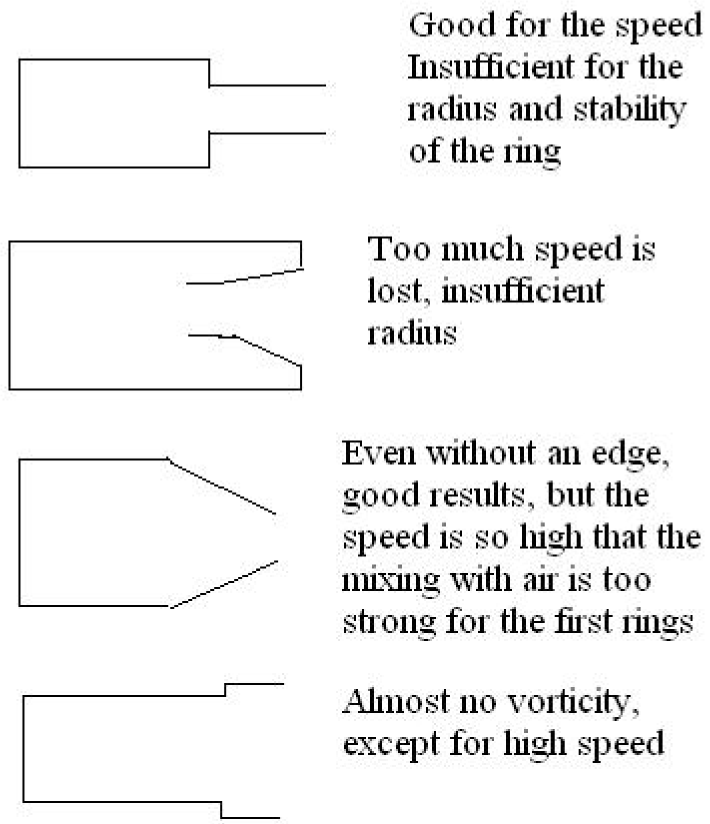
APPENDIXES

I – Some kind of nozzles that was tried before selecting the best one

II – The demonstration about how we found the area of influence of the ring and the minimum distance that must separate two rings.

III – More details about the use of the terms "hydrogen peroxide" or "active chemical product".

I – Some kind of nozzles that was tried before selecting the best one



These kinds of nozzles where tried in the first days we were working on the nozzle shape. Step by step, we picked up the good elements of each to make the most efficient shape at the end. Of course, this picture only shows the four greatest subfamily that we made, some other models were sometime even stranger.

II – The demonstration about how we found the area of influence of the ring and the minimum distance that must separate two rings.

If we consider the circulation Γ of the fluid around the vortex, some scientists have made the assumption that :

$$\frac{d\,.\,\Gamma}{dt} = \frac{1}{2}\,\mathrm{V}(p)^2$$

Where V(p) is the piston speed inside the nozzle. If we integrate this equation, one may obtain :

$$\int_0^T \frac{d\,.\,(\Gamma(t))}{dt}\,dt = \int_0^T \frac{1}{2}\left(\frac{\partial}{\partial t}\,\mathrm{y}(t)\right)^2 dt$$

Where y is the covered distance by the ring in the axial direction of the bottle, and the speed is nothing more than its time derivative. Thus by an integration by part we can write that it implies that :

$$2\int_0^T \frac{d\,.\,(\Gamma(t))}{dt}\,dt = \left[\,y\,\frac{dy}{dt}\,\right] - \int_0^T \frac{1}{2}\,y\left(\frac{\partial}{\partial t}\,\mathrm{V}(t)\right)^2 dt$$

Even if it is a bold approximation we may neglect the last term of the equation, since the acceleration of the ring (in fact the slow down) is not so important compared to its speed, except at the nozzle exit. So this formula is only valid far from the creation point and before the ring reached the end, because otherwise it would foresee an infinite Radius of influence when the travelled distance tends to be big. So this assumption is mainly the weakest point of the approximation and can be contested, or at least, handled with the knowledge of how we calculate things.

So there is only :

$$2\,\Gamma(t) = y\,V$$

Which is left. And to make things even simpler, if we make the assumption that the area of influence is almost circular, we can write that :

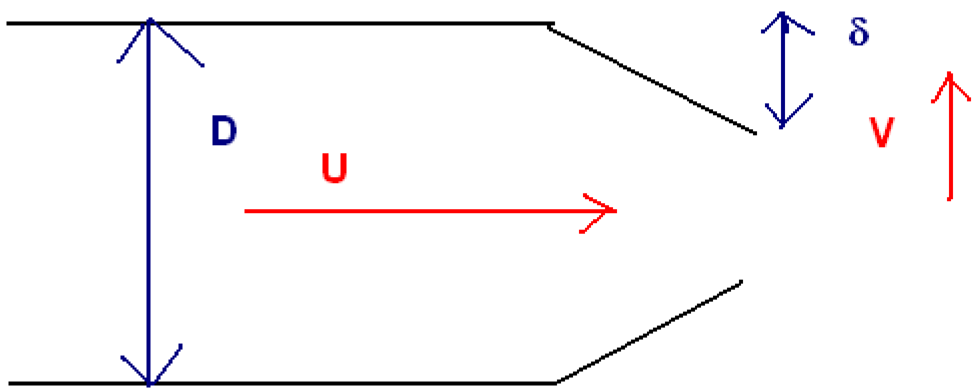
$$\Gamma(t) = \omega\,\pi\,Ra^2$$

$$Ra = \frac{1}{2}\sqrt{2}\,\sqrt{\frac{y\,V(p)}{\omega\,\pi}}$$

Once reach this point we have more or less the theoretical limit of the fluid who should be turning more or less around the vortex, which is affected by vorticity, even if it is not part of the ring itself. Omega is vorticity, and it can be more explicit to write it like that :

$$Ra = \frac{1}{2}\sqrt{2}\,\sqrt{\frac{y\,V(p)}{\left(\left(\frac{\partial}{\partial R}U(R)\right) - \left(\frac{\partial}{\partial y}V(y)\right)\right)\pi}}$$

Where we must not be confused by letter U(y,R,t) is axial velocity according to y, it is not a conventional writing, and V(y,R,t) is the radial speed, perpendicular to the axis of the bottle. V(p) is still the piston speed.



Now, we can say that if there is a mass flow Q and a density ρ of the fluid, we can write that :

$$Q = \frac{1}{4}\rho\,V(p)\,\pi\,D^2$$

$$Q = \frac{1}{4}\rho\,V(p)\,\pi\,(D - \delta)^2$$

If we take into account the convergent nozzle or an edge that reduce the free section that allow the fluid to go forward. The second assumption here that it is a kind of Bernoulli's law with conservation of the mass flow and no head loss.

Then, it can be written that :

$$Ra = \frac{\sqrt{2}\sqrt{\frac{y\,Q}{\rho\,(D-2\,\delta)^2\,\omega}}}{\pi}$$

Or that :

$$Ra = \frac{\sqrt{2}\sqrt{\frac{y\,Q}{\rho\,\pi\,(D-2\,\delta)^2\left(\left(\frac{\partial}{\partial R}\,U(R)\right)-\left(\frac{\partial}{\partial y}\,V(y)\right)\right)}}}{\pi}$$

So if we take the values in SI units :

```
> Ra=sqrt((2*0.00090526*1.34)/(1.2*3.14^(2)*(3.1-1.6)^2*0.1));
```

$$Ra = .03018856937$$

So we find a radius for the area of influence of 3 cm or 0.03 m.

We obtain more or less a radius of the area of influence, which is roughly true. The main critical value here is 0.1 Hz for vorticity. But, as a vortex has a low vorticity on its edge of 10 Hz. So if we want to know the least perturbation that can affect the following vortex, it is 1% of it, so 0.1 Hz.

Of course, if the speed of the ring increases, the lowest vorticity layers will be around 30 or 70 Hz. The point is to take about 1% of this critical velocity for a particle to be inside the visible ring in order to determine the radial length of influence of the ring.

What we call the distance of security is twice Ra so as the two area of influence do not touch themselves. This distance is very often between 4 and 7 cm and is mainly speed dependent.

III – More details about the use of the terms "hydrogen peroxide" or "active chemical product".

In some different cases in the report, the hydrogen peroxide has been mention for playing the role of an active chemical product, that is able to kill bacteria. In fact, the fluid which is used is a mix of hydrogen peroxide, vapour and stabilizers.

Of course, it does not mean that it is the only one. Many other chemical products can be used provided that there are authorized to be used for the same purpose and with a similar efficiency.

But, during this study, the simulations was made considering a future use of hydrogen peroxide for the sterilisations. As a result, the numerical results can change a little for another gas that could be more viscous, for an example. Even if vortices can be applied to many steams, their required number and their properties can be lightly different. So it was only for the case study of hydrogen peroxide simulations that the numerical value can be close from the results that we obtained.

→ So it is perfectly possible to use another gas that hydrogen peroxide provided that the dynamic and chemical properties are almost the same. May be nitrogen can be also suitable, and probably other gases that have not been tested yet.