Experiments and a theoretical analysis explain how to control vortex rings creation in order to optimize a sterilization process in Tetra Pak

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THANKS

I would like to thank Anders Sundberg, my supervisor in Tetra Pak, for his support and his advice. Moreover, the experimental work has been possible thanks to him, since he made the equipment available and some parts of the device prepared. And thank you of course for his help and his ideas.

Thanks also to my tutor at the Ecole des Mines: Olivier Louisnard, teacher and researcher at the Ecole des Mines d’Albi Carmaux, who followed our work during this internship.

Finally, I would like to thank, Christophe Duwig and Johan Revstedt, from Lunds Tekniska Högskola (LTH), who also helped us for this work.
ABSTRACT

Tetra Pak, the famous company of food packaging, wants to use vortex rings to improve a sterilization process. This project, based on experiments, studied several parameters with the aim of controlling vortex rings creation. A piston impulse and the shape of a nozzle modify the speed profile of the fluid and create the vortex structures. Vorticity brings (relative) steadiness to the rings. A high speed of the piston, a medium stroke length and a convergent shape of the nozzle will give fast and quite small rings. Steadiness can be improved by other parameters like the length of the piston chamber or a constant acceleration of the piston. The wait time between two successive impulses of the piston have to be determined for the rings not to collide. The wake of the rings plays a big role in this collision phenomenon. The carried volume and the concentration determine the transport capacity of the rings.

RESUME

Tetra Pak, célèbre entreprise d’emballages alimentaires, envisage d’utiliser des anneaux de vortex afin d’améliorer un procédé de stérilisation. Ce travail, en grande partie expérimental, étudie différents paramètres dans le but de contrôler la création de ces anneaux. Une impulsion donnée par un piston, ainsi que la forme de la buse du dispositif agit sur le profile de vitesse du fluide, créant ainsi ces structures de vortex. La vorticité est ce qui assure la cohésion de l’anneau. Une grande vitesse et une ampltude moyenne du piston, ainsi qu’une forme convergente près de la buse donne des anneaux rapides et relativement petits. La stabilité peut être améliorée en jouant sur d’autres paramètres comme la longueur de la chambre du piston ou un mouvement à accélération constante. Le temps d’attente entre deux impulsions successives devra être déterminé afin que les anneaux ne se détruisent pas mutuellement. La traînée des anneaux joue un rôle important dans ce phénomène de collision. Le volume transporté et la concentration déterminent la capacité d’un anneau à transporter de la matière.
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INTRODUCTION

Tetra Pak is a famous company which provides packaging systems for food processing. In Lund (South of Sweden), the current process for sterilizing a package uses a turbulent peroxide blast. Tetra Pak wants to improve this process by using vortex rings. Indeed, this kind of flow may be more efficient, especially for sterilizing the end of the bottle. This kind of flow could more easily reach the end of the bottle, because vortex rings are steadier and more controllable than classic turbulent jets.

This report explains the experimental part of a work which aims to understand the theory about vortex rings and to start adapting them to the sterilization process in Tetra Pak. As a consequence, some parts of the work will not be found here, but will be explained in the report of Philippe Bécart, another student of the Ecole des Mines d’Albi-Carmaux who also works on this subject and especially on numerical simulations. Moreover, as based on experiments, this report provides especially qualitative results and conclusions. This study is part of the Research and Development work to improve the machines and the processes in Tetra Pak in Lund.

After a quick presentation of Tetra Pak, and of the goals of this work, the device used for the experiments will be described and the first theoretical data will be explained. A second part will present the experiments which aim to understand and control the creation of vortex rings, and their conclusions. In a third part, other phenomena which need to be taken into account will be explained: transport of matter by the rings, interactions between the rings will be studied. At the end of this last part, we will explain what remains to be done for adapting vortex rings to the sterilization process.
I. A PROJECT BASED ON EXPERIMENTS WHICH TAKES PART IN THE RESEARCH AND DEVELOPMENT WORK

A. Background and previous study

1. The Company Tetra Pak and the Research and Development department

Tetra Pak began in Lund, Sweden, in 1951 and is today one of the largest suppliers for food packaging systems. First the company produced liquid milk packages, and it has now extended to fruit juices, drinks and many other products in food manufacturing. In 2004 Tetra Pak had 20 900 employees over the world and its net sales amounted to € 7,525 million.\(^1\) Approximately 2 500 people are now working in the facilities site in Lund. Tetra Pak sells packages or lends machines which produce, prepare and fill these packages. So the company is developing the carton, is conceiving the packages, and is responsible of the service and maintaining of the machines even after placed at the customer’s factory.

The latest years, customers care more and more about image and lifestyle, which makes Tetra Pak work more on conception and which increases the need of flexibility, for example concerning the machines.

This work is part of the Research and Development work to optimize the machines and the processes in the industrial unit of Lund. Approximately two hundred people are working in this Research and Development department.

2. This work aims to prepare an improvement of a sterilization process

Currently, the process of sterilizing a package in Tetra Pak in Lund uses a turbulent air blast which is put downwards in a vertical bottle. The spread of the blast lasts 0,7s. Before this, the bottle was previously heated to 70°C. This process uses a lot of matter and energy, and so has a low efficiency. Peroxide is difficult and expensive to transport, so it would be very interesting to reduce its consumption. Moreover, if less peroxide is used, less energy is required to send it in the bottles.

Tetra Pak wants to improve the current sterilization process by using vortex rings.

As vortex rings are not used yet for this kind of process, the goal of this work is to understand the theory and to think of how such rings could be used to sterilize a package.

Concerning sterilization in Tetra Pak, the data for the process are:
- Tetra Pak uses a solution of peroxide in water, which contains 35% of peroxide.
- The sterilization is going to happen in gaseous phase (all the products have to be gases). Because of this and to avoid condensation, the temperature of the entire system and the products must be 70°C.

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\(^1\) Source: HENRIKSON (C.), How to create a modular system for packaging machines, Thesis for the degree of Master of Science in Product Innovation and Development, September 2005
- For the sterilization process, the quantity of peroxide concentration has to be 5 kg of the 35% H₂O₂ solution for 110 Nm³ (0.045455 kg/Nm³ of the solution, because we work at 70°C).
- The goal of such a sterilization process is to sterilize a bottle in 0.7s.
- The volume of a bottle is up to 1.25 Litre (1 L of juice, but the bottle need to be a bit bigger of course)

![Scheme of an example of sterilization process using vortex rings](image1.png)

**Picture 1 - Scheme of an example of sterilization process using vortex rings**

3. **A previous study built a device which creates vortex rings**

The easiest and most common way to generate vortex ring is to use a piston moving with a translational motion in a hollow cylinder. An impulse of the piston will produce a vortex ring. This happened in whatever fluid (water, air…).

![Picture of the water tank at the beginning of our study](image2.png)

**Picture 2 - Picture of the water tank at the beginning of our study**

A previous study had been made in Tetra Pak about vortex rings, especially the practical and experimental points.

During this study, an apparatus for generating vortex rings in water has been built. It is made of a plastic cylinder piston, which can move in a plastic hollow cylinder. The piston’s motion is controlled by a LinMot Ps 01-23x80 motor, which is driven by the LM1R3R12 LinMot software. This software allows us to create our own curves for the piston’s motion.
This entire device is fixed on a metal plaque (see picture 3). A water tank (a plastic transparent box of roughly 10L) had also been built during this study (see picture 2).

Picture 3 - The apparatus (motor + piston + hollow cylinder) at the beginning of our study

B. A first experimental work provides the basis on vortex rings

1. Experiments can be carried out in water even if the process will work in gas

For the experiments, this device will be used in water. But the sterilization process will work in the air (with the peroxide in gaseous phase). To understand and predict what happens in gaseous phase, we can make an analogy using the Reynolds number: for these two cases, the Reynolds number is the same.

\[ \text{Re} = \frac{\rho_{\text{air}} V_{\text{air}} L_{\text{air}}}{\eta_{\text{air}}} = \frac{\rho_{\text{eau}} V_{\text{eau}} L_{\text{eau}}}{\eta_{\text{eau}}} \]

If the geometry is the same, \( L_{\text{air}} = L_{\text{eau}} \)

So we can link the two velocities:

\[ V_{\text{air}} = \frac{\rho_{\text{eau}}}{\rho_{\text{air}}} \frac{\eta_{\text{air}}}{\eta_{\text{eau}}} V_{\text{eau}} \]

With:

\[ \rho_{\text{air}} = 0,933 \text{ kg.m}^{-3}, \text{ at } 70^\circ \text{C and } 1 \text{ atm}^1 \quad \rho_{\text{eau}} = 998,68 \text{ kg.m}^{-3}, \text{ at } 18^\circ \text{C and } 1 \text{ atm}^3 \]

\[ \eta_{\text{air}} = 0,0000204 \text{ Pa.s}, \text{ at } 70^\circ \text{C and } 1 \text{ atm}^2 \quad \eta_{\text{eau}} = 0,001054 \text{ Pa.s}, \text{ at } 18^\circ \text{C and } 1 \text{ atm}^4 \]

---

1 Source: [http://www.thermexcel.com/french/tables/massair.htm](http://www.thermexcel.com/french/tables/massair.htm), with 80% of humidity, 10/07/06

2 Calculated thanks to the expression: \( \eta = 1,458 \cdot 10^{-6} \cdot \frac{3}{2} \left(110,4 + T\right) \) for a pressure equal to atmospheric pressure, \( T \) in K (100 < \( T < 2000 \) K) and \( \eta \) in Pa.s. Source : [http://linpc3.epfl.ch/e-lin/Ryhming/documents/chapters/documents_published/doc8/node316.html](http://linpc3.epfl.ch/e-lin/Ryhming/documents/chapters/documents_published/doc8/node316.html), 10/07/06

3 Source: [http://www.thermexcel.com/english/tables/eau_atm.htm](http://www.thermexcel.com/english/tables/eau_atm.htm), 10/07/06

4 Source: [http://www.thermexcel.com/english/tables/eau_atm.htm](http://www.thermexcel.com/english/tables/eau_atm.htm), 10/07/06
We find:

\[ V_{\text{air}} = 20.7 V_{\text{c}} \]

As a consequence, the velocity of the rings will be approximately twenty times higher in the air than in the water. It means that, in the experiments (in the water), we need to fill the bottle in \( 0.7 \times 20.7 = 14.49 \text{ s} \).

2. First tries with the apparatus

The coordinates system used is a cylindrical system, as it suits very well to the apparatus. We assume that the whole system is axisymmetrical.

A first try was made with the apparatus described in A.3., in water. Some colour was introduced into the cylinder (thanks to a syringe) and then the motor is switched on. The colour is a pink solution of MnO$_4$\(^{-}\).

The length of the piston’s chamber is \( L_{\text{ch}} = 50 \text{ mm} \). The stroke of the piston (which is in fact the amplitude of the piston’s motion) is \( S = 10 \text{ mm} \). The average speed of the piston during an impulse (forward motion) is \( V_p = 0.14 \text{ m/s} \). The hole’s diameter (or nozzle* diameter) is \( D_n = 22 \text{ mm} \). The inner diameter of the chamber is \( D_{i\text{ch}} = 31 \text{ mm} \) and the outer diameter is \( D_{e\text{ch}} = 34 \text{ mm} \). The length of the piston is \( L_p = 30 \text{ mm} \), and its diameter is \( D_p = 31 \text{ mm} \) (see picture 4).

![Picture 4 - Scheme of the piston and the hollow cylinder used for the experiments](image-url)

We got a toroidal vortex structure, called a vortex ring. The diameter of this ring is closed to the diameter of the hollow cylinder.

3. A vortex ring is an unsteady flow structure

There are two different things which we can speak about, and we have to define and separate them clearly. The coloured area of the fluid moved during the motion can be
different if more or less coloured solution has been put. But the velocity distribution remains
the same (if we assume reproducibility of the experiments). The area where the velocity is
different from the velocity of a piston flow will be called the influence area of the vortex.

The picture 5 shows the vocabulary and notations about vortex rings.

The section of a vortex ring is most of the time elliptic, and we can describe it with the small
axis and the big axis of this ellipse (respectively a and b on picture 5). But if the section is
circular, or is considered circular, r will refer to the radius of this circular section (so in this
case, r=a=b). R is the big radius of the torus.

At the beginning, the colour is all near the axis of symmetry (horizontal on this picture), and
we have a ring which seems very thick (on the left of picture 5). On this shape, we have
roughly \( R \approx a \). Most of the time, few moments later, the ring gradually becomes thinner
because of the colour moving from the axis of symmetry, due to the rotating motions (on the
right on picture 5).

Vorticity is what makes the ring steady. When a ring breaks, it is because vorticity stopped
(because of a decrease of kinetic energy) or because vorticity is killed (by an obstacle).

Vorticity is a vector also called whirl vector. It is defined as: \( \vec{\omega} = \text{rot}(\vec{V}) \)
It can be related to the amount of "circulation" or "rotation" (or more strictly, the local
angular rate of rotation) in a fluid.
As explained in Wikipedia encyclopedia\(^1\), “one way to visualize vorticity is this: consider a
fluid flowing. Imagine that some tiny part of the fluid is instantaneously rendered solid, and
the rest of the flow removed. If that tiny new solid particle would be rotating, rather than just
translating, then there is vorticity in the flow.”

The vorticity is higher in the centre of the vortex (global maximum), as shown on picture 5. Although we did not see it on experiments, sometimes, if the motion is very turbulent, a local maximum of vorticity can appear in front of the other.

4. A pressure gradient creates vorticity and allows the formation of the rings

After several hypothesis and studies on the first experiments, we can explain how the ring is created:

The flow which goes out of the piston (1) has a relatively high velocity. The fluid near the chamber (but not in front of the hole) in (2) has no velocity. So the dynamic pressure (which is equal to $\frac{1}{2} \rho V^2$) in (1) is higher than the dynamic pressure in (2) – see picture 6.

The fluid goes in a way which tends to equilibrate the pressure, so it begins to turn, as shown on picture 7.

Thanks to shear layers, the fluid in (3) (picture 8 and picture 9) is also carried along: so it begins to move in a way shown in the picture 9 (green arrow).
As the fluid which was in (3) has gone, some fluid come to replace it. This fluid can come from the flow coming from the cylinder. This motion of fluid is described by the orange arrows in picture 10.

So, at the end, the motion of the fluid is curling and becomes a (nearly) closed curve. This part of the fluid is rotating in that way (black line, on picture 11) while the flow goes forward (yellow arrow, on picture 11: that is what we call vorticity.*

This process of formation of a ring is very progressive and happens at different scales when the piston moves forward:
This process of formation happens on a little part of colour, which gives a small vortex area (picture 12(a)). As the forward motion of the piston is not finished, this small area turn and follow the same process of formation (picture 12(b)). It gives another vortex area which is a little bit bigger (picture 12(c)). This new vortex area follow the process of formation (picture 12(d)) and so on.

(a) first step

(b) second step

(c) third step

(d) fourth step

Picture 12 - Scheme of the formation of a vortex ring

C. The experimental device has been upgraded

The initial device (see above, part A.3.) has been used for the first tries. Then, thanks to the help of our supervisor in Tetra Pak, some upgrades have been made. The picture of the entire device at the end of our study is shown in Appendix I.

The plastic box was long to empty and not easy to hold, so a new hole was made in the bottom of the box, and some kind of legs, made with metal bars, have been added (see picture of Appendix I).

As the hollow cylinder was fixed on the metal plate thanks to a plastic piece and some glue (see above, picture 3), we tried to use a metal piece to make it stronger by holding the cylinder on the plastic piece. However, this device was not better. Either the metal part is too loose and the cylinder is moving during the motion, or it is too tight and the piston has difficulties to move in the cylinder. Indeed, if the cylinder is too tight or badly fixed on the apparatus, the motion of the piston can differ from the demanded motion, because the motor has not enough strength to fight the frictions. Moreover, a problem of the entire device moving during the motion (because of a high speed of the piston) remained.

That is why the next improvement was to do something which makes the entire device hold on the plastic box. The motor and the bottle are now fixed on metal bars which are put together and which fit together with the plastic box (see picture of Appendix I). The height
and inclination of the bottle can be changed by unscrewing a little bit and by moving the metal bar which holds it. This change was a real improvement. Although now it takes time to remove the hollow cylinder (if you want to change it with a longer or a shorter one for example), the device is now stronger and more stable. After this, a flexible pipe was added on the hollow cylinder. This pipe is linked to a pump and brings coloured solution into the hollow cylinder, which is very handy, because it takes less time than using a syringe, it brings less turbulence, and you can control the flow of colour more easily, thanks to the pump. The last improvement made during this work was to add a flexible pipe at the end of the bottle, on the cap, which allows to put the colour out of the bottle without emptying all the plastic box. This saved a lot of time during the last experiments.
II. THANKS TO THE EXPERIMENTS, SEVERAL PARAMETERS HAVE BEEN STUDIED IN ORDER TO CONTROL VORTEX RINGS CREATION

A. Many data rule the motion of the piston

One of the things to be determined is the motion of the piston. Some experiments were made in order to see the influence of parameters such as the speed, the stroke and the acceleration of the piston. These experiments are presented in this part, and more details and accurate data can be found in Appendix II.

Other parameters have been studied (thanks to other experiments), but their influence is much less important. Some other experiments aimed to find the influence of the length of the wait time or the number of impulses, but these experiments give less interesting results. However, what we can conclude from these experiments is that the wait time is of course for the motor not to be damaged, and that it has no effects on the rings except the space between them. So the wait time will be determined in order to save time (for the process) and to ensure that two following rings will not collide. See part III. A. for more details. Concerning the number of impulses, the most important point is that the second ring (and the fifth, and so on, every second or third ring) has a very different velocity than the others (most of the time the second is slower, but not always). Sometimes, if this difference is too high, two rings collide. See part III. A. for more details. A reason of this difference of velocity for successive rings may lie in the fact that the fluid has already a non-zero speed after the first ring. During the next impulse, the momentum of the fluid will be the momentum given by the piston (during the impulse) and the momentum of the fluid at the beginning of the impulse (which is not zero anymore). Every two or three rings, this momentum of the fluid at the beginning of the impulse will be approximately zero, thanks to fact that the impulses compensate (little by little) the speed of the fluid during the impulses.

1. Influence of the speed of the piston

    a. Principle of this experiment

A motor file provides the demanded position of the piston to the motor depending on the time. To study the influence of the speed of the piston, two motor files which give a single impulse to the piston, with 25 mm amplitude, were created.

The difference between these files is the impulse’s speed (for the same amplitude, so the time of the forward motion is also different). The trend of the motion of the piston is shown on picture 13.

---

1 The actual motion of the piston may differ a very little bit from the demanded motion if the apparatus is not well prepared (if the cylinder is not straight or is too tight). In that case, there will be a lot of irregularities, or even oscillations on the curves. Before each experiment, the similarity between the actual motion of the piston and its demanded motion has been checked (thanks to an oscilloscope in LinMot software).
The apparatus used for this experiment is described in I. A. 3. The data for this experiment are listed in Table 1 (We will always use the same piston and the same hollow cylinder diameter, so these characteristics will not be repeated.)

![Graph](image)

**Picture 13 - Demanded position of the piston for the experiment about speed (two tries: red curve and blue curve)**

The rings produced were filmed with a high-speed camera, which allows us to get video files.

### b. Results

When the velocity of the piston increases, we can see (with the bare eye) that the size (R) of the ring decreases, and its vorticity and velocity increase. It seems that the ring is also more stable.*

### Table 1 - Data for the experiment about the speed of the piston

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_p$</td>
<td>31</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$D_n$</td>
<td>22</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$L_{ch}$</td>
<td>50</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>25</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$D_{i,ch}$</td>
<td>31</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$D_{e,ch}$</td>
<td>34</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$V_p$</td>
<td>0.023 or 0.186</td>
<td>m/s</td>
<td>0.031 or 0.25 without SF</td>
</tr>
</tbody>
</table>

*Remarks:

- $D_p$: Diameter of the piston
- $D_n$: Diameter of the hollow cylinder
- $L_{ch}$: Length of the chamber
- $S$: Length of the piston
- $D_{i,ch}$: Inner diameter of the chamber
- $D_{e,ch}$: External diameter of the chamber
- $V_p$: Velocity of the piston

---

*Footnote: This indicates a note or additional information that is not explicitly shown in the main text but is relevant to the discussion.
Some measurements have been taken on a video file from this experiment. We measured the size of one ring and its speed, at several times. Some curves (graphs) have been made. The graphs of the visible section of a ring and of the speed of a ring depending on the time are shown on Picture 14 and 15.

![Graph showing visible section of a ring depending on the velocity of the piston](image)

*Picture 14 - Visible section of the ring depending on the velocity of the piston*

The graphs of the sections of a ring plot the size of the area of colour which is in the vortex (which follows the rotating motion). This area is sometimes very difficult to see. So the graphs showing the section of the rings are much less accurate than those showing the velocity of the rings. Moreover, it is very difficult to define the limit of the vortex area. Indeed, if we look at the velocity profile, some fluid which is far from the centre of the vortex area follows the rotating motion (thanks to shear layer). So the area of influence of the vortex is much bigger than the area plotted on these graphs. On these graphs, we can see the coloured area, which will give us information about the quantity of matter in the ring, and about whether the ring is loosing matter, whether the colour is diluting, and so on.

Poly. means a polynomial interpolation. When not indicated, it is a 6th order polynomial interpolation. 2 per. Mov. Avg. means a moving average with a period of 2. It means that it plots the graph made of the average between the current value and the previous one. (These notations will be used again below in the report).
c. Conclusions: a big effect on the speed of the rings

The speed of the rings grows from zero to a positive value, and then decreases a little bit while oscillating. For a high speed of the piston, it decreases faster, and the oscillations are quick and have high amplitude. However, for a small velocity of the piston, all these trends are very slow and with slight amplitude.

The section of the rings increases, first quickly, and after slowly, and oscillates a lot. As before, these trends are faster and stronger for a high velocity of the piston.

The faster the piston, the faster the rings. This result, which is not surprising of course, points the fact that, with a high speed of the piston, more kinetic energy is given to the ring.

With a higher speed of the piston, the graph 14 shows that the ring is thicker. This can be explained by the fact that with lower speed it seems that you have less vorticity (the rotating motion of the fluid is a bit slower). Thus more fluid is leaving the ring because it has not enough speed anymore to be kept in the vortex area. The fact that some matter leaves the ring that way can be easily seen on videos, or even sometimes with the naked eye. As some colour has left the vortex area, the core of the ring (the heart of the ring) which is shown on the graph is smaller.

Moreover, with low speed, the diffusive transport may enter into account, which can explain an increase of dilution, and as a consequence, another way for the ring to loose matter. Whereas with high speed, dilution has no time to occur, of course.

Oscillations are due to measurement errors of course, but not only, because their frequency is independent of the frequency of the measurement points (for instance, the curve for a low speed has a frequency of 7 points for the velocity, and of 5 for the section. Especially on the
curve of the section for a low speed, we can see the trend of the oscillations). Oscillations in the size are due to the fact that the ring accept and lose matter at every time, and the fact that the colour is diluted during the motion. These oscillations damp, except for the size of the ring with a high speed. This is probably due to the fact that the ring is still at the beginning of its motion, so it still dilutes and only begins to loose matter.

2. Influence of the amplitude of the piston motion

Increasing the amplitude means increasing the carried volume. So, if big strokes are used for the process, the number of impulses necessary for injecting all the product will be lower. But to study more precisely the influence of this parameter, an experiment has been carried out.

   a. Principle: three motions with different amplitude are compared in this experiment

In order to see the influence of amplitude, rings from different motor files have been compared. The only difference between these files is the amplitude of the impulse. As the average speed is the same for all these files, it means that we compare the time of the impulse.
N.B. In practice, because we want to study more acceleration and speed, the time of the impulse will be determined first, and then we will deduct the amplitude from it.

The picture of the trend of the piston motion can be found in Appendix II – picture 4. The same apparatus as in I. A. 3. has been used.

| Name | Value | Unit | Remarks
<table>
<thead>
<tr>
<th></th>
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<tr>
<td>Lch</td>
<td>58</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>10, 20 or 35</td>
<td>Mm</td>
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</tr>
<tr>
<td>Vp</td>
<td>0,173</td>
<td>m/s</td>
<td>0,23 without SF</td>
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</tbody>
</table>

*Table 2 - Data for the experiment about the stroke of the piston*

The rings produced were also filmed, so we can get video files.

   b. Results

When you see the rings made for this experiment, it seems that increasing the amplitude allows us to have faster, bigger and thicker rings. Concerning vorticity and stability*, it is a bit hard to see, but it seems that there is an optimal magnitude of the stroke of the piston: when the amplitude is low, an increase of this amplitude increases the vorticity (and so the stability). But after a certain value (when the stroke is longer than this value), an increase of the amplitude makes the vorticity fall quickly, especially at the end of the motion of the ring (so the ring becomes unsteady too). This optimal value (where vorticity and stability is the highest) seems to be around 10 or 20 for this device.
When the amplitude is too high, the vorticity is killed, and the rings is destroyed very early. But if the amplitude is very small, the quantity of energy given by the piston to the fluid is too low, so the vorticity is not very high (but it is higher than with a very big stroke).

The measurements on the videos provide the graphs of picture 16 and picture 17.

*Picture 16 - Speed of the ring depending on the stroke of the piston*

*Picture 17 - Visible section of the ring depending on the stroke of the piston*
c. Conclusions: many effects can be linked to a change in the moved volume

The graphs also show that a big stroke bring fast rings up to a certain value of this stroke. If the stroke is higher than this value, bigger stroke brings a bit slower ring (but this is not so significant).

At the beginning of the motion, the size of the rings is approximately the same for each stroke (assuming the errors on measures). At this moment, this size increases slowly. But it is clear that with a shorter stroke, the trend of the size becomes constant earlier, and this size is lower. This is probably due to the fact that, on the videos, the radius of the ring is measured as the radius of the coloured area in the fluid, and with a bigger stroke, you have a higher carried volume, so more colour is entrained into the vortex. We can notice that with a very big stroke, a big wake is created. Indeed, after a certain value of the volume, the ring can not accept matter anymore. It seems that the maximal value of this carried volume depends on the vorticity of the ring.

The rise of the amplitude during the motion is mainly due to the fact that the ring dilutes. On the graphs, we can see that with bigger amplitude, the ring dilute more.

3. Influence of the acceleration of the piston

a. Principle: changing the acceleration profile needs new tools

The curves of the demanded position for the two previous experiments were made by the curve generator of the LinMot* software. But this curve generator allows us to control only the position of the piston. The speeds taken in account were the average speeds, but the speed profile was a bit particular. The speed was never constant during the motion of the piston (see picture 18). In fact, the software always makes a sine's position's profile \(x=a \cdot \sin[b(t-c)]+d\)\(^1\). This allows the software to link every couple of points with a continuous speed (\(dx/dt = a \cdot b \cdot \cos[b(t-c)]\), derivative of \(x\), is continuous). Thanks to the continuous speed, the motor does not suffer from very quick change of speed.

But this trend of the speed (see picture 18) is not necessarily good for creating vortex rings. So I used another software which allows to create curves of the same format as the motor files, but which allows also to control speed and acceleration. This software, called ATMG, belongs to Tetra Pak (it was created in Tetra Pak few years ago). The goal is to determine what is best for the rings: no acceleration, constant positive acceleration… Moreover, maybe the maximum quantity of matter which can be accepted into the ring may be increased by having a positive acceleration during the motion of the piston. Indeed, the matter stops entering into the ring when the velocity of this matter is not high enough for it to be caught in the vortex. So we hope that by increasing the speed at the end of the motion, we can increase the carried volume of the ring. That is what we want to check with this experiment.

\(^1\) \(a \cdot \sin(t)\) extends the curve of \(\sin(t)\) in the ordinate axis (or Y-axis) with a factor \(a\).
\(\sin(b \cdot t)\) extends the curve of \(\sin(t)\) in the abscissa axis (t-axis) with a factor 1/b. (increase of the frequency with a factor b)
\(\sin(t-c)\) translates (so delays) the curve of \(\sin(t)\) of b in the abscissa axis ( t-axis)
\(\sin(t)+c\) translates the curve of \(\sin(t)\) of b in the ordinate axis ( Y-axis).
This experiment was made with the upgraded device and three motor files: one with a constant positive acceleration during 70 ms (picture 19), one with no acceleration (so constant speed) during 60 ms (picture 20), and one with the “usual” speed profile made by the LinMot software (picture 21).

LinMot (“usual acceleration”) gives an acceleration which is low and irregular.
“Constant acceleration” provides an acceleration which is quite low but regular and which last for long.
“Zero acceleration” gives a short but high acceleration at the beginning (and a short but high deceleration at the end) and no acceleration at all elsewhere.

<table>
<thead>
<tr>
<th>Name</th>
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<th>Unit</th>
<th>Remarks</th>
</tr>
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<tr>
<td>Dn</td>
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<td>mm</td>
<td>Special shape of nozzle²</td>
</tr>
<tr>
<td>Lch</td>
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<tr>
<td>Dech</td>
<td>34</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Vp</td>
<td>0.075</td>
<td>m/s</td>
<td>In average. 0.1 without SF</td>
</tr>
</tbody>
</table>

Table 3 - Data for the experiment about the acceleration of the piston

¹ The speed has to go from zero to a positive value (for the piston to move forward). So there has to be acceleration anyway, of course. “Constant acceleration” describes the fact that after a certain period where the movement starts (acceleration), and before a certain period when it stops (deceleration), the acceleration is constant. See pictures for more details.
² The shape of the nozzle used for this experiment is described in II. B. 1. b. i/. This is the good shape which we made after studying the influence of the shape of the nozzle.
Picture 19 - (a) Demanded position, speed and acceleration for the experiment on the acceleration profile and for a constant positive acceleration (motor file made with ATMG)
Picture 20 - (b) Demanded position, speed and acceleration for the experiment on the acceleration profile and for no acceleration (motor file made with ATMG)
Picture 21 - (c) Demanded position, speed and acceleration for the experiment on the acceleration profile and for an "usual" acceleration profile (motor file made with LinMot software)
b. Results

**Picture 22 - Velocity of the ring depending on the acceleration profile**

**Picture 23 - Visible section of the ring depending on the acceleration profile**
c. Conclusions: a good acceleration profile can improve the rings

No acceleration is bad for the speed of the rings, because this file provides the slowest rings. Moreover, this kind of motion brings rings a little bit thinner than with non-zero acceleration profiles, which is also bad.

A motion with constant acceleration provides faster rings than one with the LinMot variable acceleration profile. With a constant acceleration, you have a little bit thicker rings than with the LinMot acceleration profile. It seems that the longer the time of the acceleration the thicker and faster the rings.

For a constant acceleration, the ring is a bit thicker than for the other profiles (see graph of the section of the ring). So it seems that an increase of the speed during the motion indeed allows the ring to carry a little bit more matter. But this difference does not seem to be very significant.

An accelerated motion of the piston provides the desired effect of increasing the ring, but to a small extent. The effect of acceleration on the speed seems to be bigger: an accelerated motion gives faster rings (for a given average velocity of the piston). This is probably due also to the fact that an accelerated motion brings a higher maximal velocity.

The differences on the velocity are a bit bigger than the differences on the size. Anyway, a constant acceleration profile is a bit better for the process, even this is not a very important factor.

B. Thanks to experiments, a better geometry of the device has been found

With the motion of the piston, the geometry of the device is a data which can influence the shape and the propagation of vortex rings.

Indeed, we can see for example that it is much more difficult to create rings if there is no edge on the nozzle.\(^1\)

In this part, we will describe and explain experiments about the shape of the nozzle, the length of the piston’s chamber, and the diameter of the nozzle.

We will not study the influence of the diameter of the hollow cylinder, because we know from previous studies on vortex rings that this is the L/D ratio that matters, where L is \(L_{ch}\), the length of the piston’s chamber, and D is \(D_{ch}\), the diameter of this chamber. This is not hard to understand: an increase of the diameter will have the same effect on the characteristics of the rings as a decrease of the length of the cylinder (in proportion to the size of the device): because these (diameter and length) are the 2 geometric parameters which determine the geometry of the cylinder (because we are in axisymmetric geometry).

\(^1\) During the first tries, it appeared that, if we use a nozzle without edge (\(D_n=D_{ch}\)), it is very hard to create rings, but it is still possible if the velocity of the piston is high enough. (This is what came out after a theoretic analysis, and it has been checked by an experiment).
1. **Influence of the shape of the nozzle**

   a. **Several shapes have been tested**

      i/ Principle and first tests

      This experiment aims to show the influence of the nozzle’s shape. And of course the goal is to determine the best nozzle shape. The motor file used is always the same and its curve is shown in Appendix II.

      We can imagine several shapes, for the nozzle of the piston’s chamber: all the shapes of the scheme below (picture 24) have been tried, but only the #4, 5 and 7 have been filmed and used to take measures (because they were the most interesting ones).

      ![Picture 24 - Shapes of the nozzle tested in this experiment](image.png)

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_n)</td>
<td>22 or other</td>
<td>Mm</td>
<td>Depending on the shape</td>
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<tr>
<td>(L_{ch})</td>
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<td>Mm</td>
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<td>(S)</td>
<td>24</td>
<td>Mm</td>
<td>For the 3 impulses</td>
</tr>
<tr>
<td>(D_{i,ch})</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(D_{e,ch})</td>
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<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(V_p)</td>
<td>0.098</td>
<td>m/s</td>
<td>0.13 without SF</td>
</tr>
</tbody>
</table>

*Table 4 - Data for the first experiment about the shape of the nozzle*
The position profile used for the forward and backward motion is a sine profile made with the LinMot software (the “usual” speed and acceleration profile).

ii/ Results

The shape number #1 and #2 (see picture 24 above) are the usual nozzles, but the hole’s diameter can be more or less big. They give nice rings.

As said before, it is much more difficult to have nice and steady rings with the nozzle #3. Most of the time, a ring is created, but it has nearly no speed and destroys few millimetres after the nozzle.¹

With the shape #5, the rings are thin and have a quite high vorticity. However, they mix very much and lose a lot of matter, which can be explained by the fall of the vorticity during the motion and by the shape of the nozzle: the slow increase of the diameter provides more space to the fluid so the colour can spread a little bit. These rings are small and not very fast.

The shape #6 leads to the same conclusion as the shape #3: very slow rings which destroy very quickly. This kind of “external edge” has no effect on the rings.

The nozzle #8 brings rings which destroy very quickly.

The shape #9 also gives bad results: the rings are very quickly destroyed (even more than in #8). This is due to the increase of the diameter (see above) and to the fact that the curved shape in the hollow cylinder brings turbulence and stagnating fluid (or fluid that can not go out of the chamber).

Rings produced with the shape #4 are quite nice, can move on a long distance and manage to reach the end of the box/aquarium. Yet, they are not as fast as the decrease of the diameter can make us expect, and, at the end they have mixed a lot and are quite slow. A reason of that may lie in the fact that a vortex is already created in the second part of the nozzle (after the quick decrease of diameter), and so, when it comes out, it is not as steady as it was before.

The shape #7 appears to be the best of all (in the scheme of picture 24): It has a decrease of diameter, but not too quick, so the ring is created at the end of the shape, just after being accelerated. So we have nice, quite small and very fast rings, and a fast wake. For a try with the bottle, it is not difficult to make them reach the end of the bottle.

Only the shapes #4, 5 and 7 were filmed and used to take measures. These measures, taken from the video files*, provide the following graphs:

¹ The velocity of the piston in this experiment was too low. Having good rings with this nozzle needs a very high velocity of the piston, and the rings are very big (there is a lot of dilution) and slow. As speed of the piston influences vorticity, a very high speed of the piston brings enough vorticity for the ring to be steady enough. So the nozzle #3 does not create a lot of vorticity at all.
Picture 25 - Speed of the first ring depending on the shape of the nozzle

Picture 26 - Visible section of the first ring depending on the shape of the nozzle
iii/ Conclusion: convergent shapes give nicer rings

An increase of the diameter (or something a bit similar) always produces unsteady rings (in part because it causes a decline of speed, according to conservation of the volume flow $Q=S.V_{moy}=\text{constant}$). This can be seen with shapes #3, 6 and 8. Even on shape #5, it seems that the increase of the diameter at the exit makes vorticity drop a little bit, which is bad for the rings, but this effect on shape #5 is not so big.

The graphs confirm that the shape #7 gives fast rings, but it is a bit surprising that the shape #5, which has an increase of the diameter, provides faster rings than the shape #4 which shows a decrease of the diameter. It seems that the pressure lost in the latter case is very high.

As we saw with the naked eye, the rings made with the shape #5 are very thin. Besides, it appears that the rings made with the shape #4 are very thick.

b. Previous results allows to create a nozzle which enhances vorticity

i/ Explanation of the shape of this “good nozzle”

An interesting thing for the process will be to have steady rings. Indeed, the rings have to reach the end of the bottle. When we see how a ring is created, we can imagine that a curly shape (that follows the flow during the creation of a ring, see picture 27) will help the ring to be created and so maybe the vorticity to be higher. As vorticity determines the steadiness, maybe it will make steadier rings.

The goal is to protect and enhance vorticity

But the good nozzle should also be similar to the shape #7 of the experiment of the shape of the nozzle. This would allow the rings to be faster and a bit thicker (see results from this experiment part II.B.1.a.iii/).

That is why the inner part of this nozzle has this shape (See scheme of the good nozzle on picture 27)

Picture 27 - Scheme of the good nozzle

ii/ Test of this shape of nozzle

Principle

This experiment compares the good nozzle, designed and created in the previous part (II.B.1.b.i/) to the nozzle we were used to have before: a flat edge with a 21 mm diameter hole (shape #1 on picture 24).
<table>
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<td>mm</td>
<td></td>
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<tr>
<td>Dech</td>
<td>34</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Vp</td>
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<td>m/s</td>
<td>In average. 0,1 without SF</td>
</tr>
</tbody>
</table>

Table 5 - Data for the experiment about the shape of the nozzle

The trend of the motion of the piston is shown on Appendix II. picture 19.
The position profile used for the forward and backward motion was made with ATMG* software, in order to have a constant acceleration. (It is the same motor file as for the experiment about acceleration of the piston).

Results

The measures from the video files are plot on the following graphs.

Picture 28 - Velocity of a ring depending on the shape of the nozzle – try with the good nozzle
Conclusions: approval of this shape

The velocity of the ring is higher with the good nozzle, especially at the beginning of the motion. It is like something in the nozzle allows a better impulse, so that the speed reaches a higher value. This trend confirms the result from the shape#7 of the experiments of the shape of the nozzle.

However, the ring is a bit thicker with the good nozzle, and it does not increase a lot, compared to the shape#7. Anyway, this is good for the rings, because it allows them to carry more matter but it does not dilute so much.

Besides, we can see with the naked eye that the rings made with the good nozzle are steadier, especially in direction. The vorticity of these rings seems higher, so even when after been broken by an obstacle, they still move and rotate a little bit. Some tries with the bottle showed that this is very convenient in order to reach the neck of the bottle. As a consequence, this nozzle actually provides nice rings.

2. Influence of the length of the piston chamber
   
   a. Principle

Several cylinders of the same diameter but of different length have been cut and put on the new device.
<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dn</td>
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<td>Mm</td>
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<td>Lch</td>
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<td>L/D= 1,97 ; 3,42 ; and 5</td>
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<td>Di(ch)</td>
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<td>Mm</td>
<td></td>
</tr>
<tr>
<td>De(ch)</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>Vp</td>
<td>0,098</td>
<td>m/s</td>
<td>0,13 without SF</td>
</tr>
</tbody>
</table>

*Table 6- Data for the experiment about the length of the piston’s chamber*

The trend of the motion of the piston is shown on Appendix II. picture 22.

The position profile used for the forward and backward motion is a sine profile made with the LinMot software (the “usual” speed and acceleration profile).

### b. Results

We get three rings for each movement of the piston (because the motor file has three impulses).

With the naked eye, it comes out that a longer chamber brings faster and steadier rings, with a little bit more vorticity. The rings are a little bit bigger and thicker.

*Picture 30 - Velocity of the first ring depending on the length of the chamber*
c. Conclusions: the existence of an optimal L/D ratio has been checked

Assuming the errors in measurement, medium and long chambers provide approximately the same speed. (Even if medium chamber is better at the beginning, and long chamber brings a bit slower rings in average). But it is clear that a short chamber provide slow rings. This is not in contradiction with conclusions from previous studies about vortex rings, especially with the fact that there exists optimal L/D ratio (where L is the length of the piston’s chamber, and D its diameter) for L/D = 4. Indeed, with our hollow cylinder (31 mm diameter), the optimal length will be 124 mm, which is closed to our medium and long cylinder in this experiment.

Concerning the size, a short chamber makes the rings a little bit thinner, and makes the size of the ring change less or less quickly.

3. Influence of the nozzle diameter

a. Principle

The previous experiments have been carried out with a 22 mm nozzle diameter (most of the time). Now this experiment will change this value, in order to see the influence of this parameter.

The trend of the motion of the piston is shown on Appendix II. picture 25. The position profile used for the forward and backward motion was made with ATMG software, in order
to have a constant acceleration. (It is the same motor file as for the experiment about acceleration of the piston).

<table>
<thead>
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<th>Value</th>
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<tr>
<td>Lch</td>
<td>130</td>
<td>mm</td>
<td></td>
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<tr>
<td>S</td>
<td>10</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Di ch</td>
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<tr>
<td>De ch</td>
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<tr>
<td>Vp</td>
<td>0.075</td>
<td>m/s</td>
<td>0.1 without SF</td>
</tr>
</tbody>
</table>

*Table 7- Data for the experiment about the nozzle’s diameter*

b. Results

The last try, with a 5 mm diameter, gives no rings, but a turbulent jet which goes out of the whole with a high speed (see picture 32). The first results of this experiment are that when the diameter increase, the velocity and vorticity of the rings decrease, whereas the size and the section increase a little bit. The rings mix less so they seem a little bit steadier.

*Picture 32 - Shape of the jet for the try*

*Picture 33 - Velocity of the ring depending on the nozzle diameter*
c. Conclusions: for an industrial purpose, there must be an optimal diameter

We can see clearly that the smaller the diameter of the hole the faster the rings (even for the turbulent jet for a 5 mm diameter). This is due to the conservation of the volume flow $Q=S \cdot V_{\text{moy}}=\text{constant}$. When the section decreases (i.e. when the diameter of the hole decreases), the velocity of the fluid increases. Moreover, the faster the rings at the beginning of the motion the more the speed will decrease during the motion.

The section of the ring increases a lot during the motion. The rate of increase seems a little bit smaller when the diameter is bigger. Oscillations come sooner when the rings are faster, and their amplitude is bigger when the rings are faster. At the end of the motion, rings made with a bigger diameter are much thicker.

On the video files, we can see that the rings break a very little bit before if you have a bigger nozzle diameter. This could mean that the rings are a little bit steadier with a smaller diameter (except for the smallest where you have no rings). But with a bigger diameter, the rings are more mixed,. Finally, all things considered, the stability remains approximately the same, even if the time when the rings break is a little bit more important.
C. How to find the best motion and geometry for the sterilization process

1. Experiments with the bottle provides practical points for the process

The length of the bottle which will be used in the process is 264mm, its diameter 64mm, and at the neck, there is a slow decline of this diameter. To study and improve their trajectory, some rings are sent in the bottle.

A lot of tries have been made, so the factors which influence the rings trajectory can be seen.
First, it appears that rings are more slowed down in the bottle than when you have no bottle. And if they become too slow, they are destroyed. So the rings break more easily in the bottle, which means that the parameters which influence the trajectory of the rings in the bottle should be carefully taken in account.

- One of the most important parameter is whether the axis of the bottle and the axis of the hollow cylinder are the same or not. If they are not at all, it is nearly impossible for the rings to reach the end of the bottle, whatever the value of the other parameters. Indeed, if the bottle and the hollow cylinder are not in line, the axisymmetry of the rings is not respected because their vorticity is killed on one size. So these rings begin to deflect and finally they are destroyed on the inner wall of the bottle. (If the length of the bottle is not too high, or if the rings have enough speed, maybe they will break not so far form the neck of the bottle, but they will still deflect a lot).
- If the distance between the exit of the nozzle and the bottle is too high, it is very difficult to have the same axis (the previous parameter is difficult to set), so the rings do not reach the end most of the time. Moreover, the rings are slowed down when they enter into the bottle. As a consequence, the best distance between the bottle and the nozzle is zero.
- Turbulences at the beginning of the bottle have also an influence: if there is too much of it, the rings deflect very much. This has been seen in practice by using the pump which brings the coloured solution into the hollow cylinder (with the upgraded device). As the pipe which brings the colour was very close to the nozzle, when you use the pump at maximal speed, a kind of cloud of colour spreads into this area until the beginning of the bottle and even deeper in the bottle and creates turbulence.
- We can try to make a motion of the piston which allows the ring to have a better trajectory in the bottle. A high speed of the piston is always good, except for the fact that it can make the rings collapse between each other. Indeed, with a fast piston, the rings will be fast, so they will go through the turbulence more easily and they will have more vorticity so more stability. A fast piston will also bring little area of influence of the rings, which will avoid them to break on the walls, and higher stability.
- In theory, high amplitude of the piston brings high speed and quite high stability but makes the rings bigger. So there must be an optimal value for the amplitude. In practice, it is hard to see the optimal value and it seems that, anyway, a big stroke is good for the trajectory of the ring. But it means probably that the tries have been made with a quite low value of the amplitude, so the optimal value is maybe higher.

2. Summary of the key points for adapting vortex rings to the process

The easiest way to sterilize correctly the bottle is to make sure that the first rings (at least the first one) reach the end of the bottle. So the neck of the bottle is sterilized first and then,
with the following rings and thanks to recirculation motions, the rest of the bottle will be sterilized.
To achieve this, the first ring(s) should be not too big, very steady, and must carry enough matter.

- For the process, it is very important that the axis of the bottle is in line with the axis of the nozzle (and of the hollow cylinder)
- Some turbulence can influence the trajectory of the rings. The motion of the bottles which are going to be sterilized and especially the way they stop can bring turbulence, so their magnitude should be carefully controlled.
- A good nozzle has been designed and made and should be used for the process. Thanks to its inner shape (convergent shape) it gives fast rings, and thanks to the curly shape outside, on the edge of the nozzle, it enhances vorticity and makes the rings more stable, especially concerning their direction.
- Experiments checked a result which came out in a lot of studies about vortex rings: the optimal ratio between the length and the diameter of the piston’s chamber is closed to 4. This should be taken into account when designing and sizing the future machines.
- The velocity of the piston should be high, because it brings a lot of advantages (fast, small and thick rings, good stability), but attention should be taken to the fact that it can make the rings crash into each other.
- The amplitude of the piston should take into account the total amount of matter that has to be put into the bottle. Yet, it should not be very high, or else the rings are too big and instable.
- Part II. A. 3. of this report shows that a constant acceleration profile can bring a little bit more to the motion of the piston (Rings a little bit faster, a very little bit thicker and a very little bit more steady).
III. OTHER PHENOMENA NEED TO BE TAKEN IN ACCOUNT, ESPECIALLY IN ORDER TO CONTROL THE RING DISPLACEMENT

A. Rings interaction

1. Observation of a collision between 2 rings

We saw that if the speed of the rings is too high, and/or the time between two impulses is too short, rings can crash into each other. Some experiments with a collision between two rings have been carried out, in order to understand this phenomenon.

Three successive impulses have been made, so we get three rings which are quite close. With a high speed, the second ring is reached by the third which enters into the hole of the second (red arrows in picture 35). This can be explained by the fact that a low pressure area is in the middle of this hole, and that the vorticity entrain the third ring into it (blue arrow on picture 35)

A particular experiment had these parameters:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_n$</td>
<td>22</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$L_{ch}$</td>
<td>53</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>30</td>
<td>Mm</td>
<td>For the 3 impulses</td>
</tr>
<tr>
<td>$D_{i_{ch}}$</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$D_{e_{ch}}$</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$v_p$</td>
<td>0.06 for the 2$^{nd}$; 0.17 else</td>
<td>m/s</td>
<td>0.08 or 0.22 and without SF</td>
</tr>
</tbody>
</table>

Three such rings have been filmed, and measurements on the video files give the graphs of picture 36 and 37. On these graphs, the collision happens between 900 and 1000 ms.

In this experiment, the second ring is destroyed because the third goes through it. And, after its destruction, the second ring becomes a kind of wake of the third ring (with very very low speed). But sometimes, on other experiments, if the second ring has enough vorticity, it can keep its shape and continue its motion.
Picture 36 - Velocity of the three rings for the experiment about the collision between two rings

Picture 37 - Visible section of the three rings for the experiment about the collision between two rings
Conclusions

The speed curves for the first and third rings are the “usual” curves for the speed of a ring, except maybe the facts that the third ring has a high maximal speed and that, after this maximum, the speed decreases quickly. The beginning of the motion of the second ring is also quite usual, but during the collision, its velocity increases. This must be due in part to the fact that it is difficult to see clearly the difference between the two rings during the collision. After the collision, the second ring stops and becomes a kind of wake with nearly no speed.

The curves of the size are quite usual, but they show a lot of oscillations. This is probably because of the turbulence (high Reynolds number), of the difficulty to see clearly the rings (bigger errors in measurements), or of the particular profile of the motion of the piston. We can notice that the size of the ring is slower during the collision, because, as the third rings goes into the hole of the second one, the section of the second one becomes flatter. After the collision, the second ring dilutes, because it has not enough vorticity anymore. That is why we observe an increase of the section on the graph, at the end of the second ring’s motion.

2. Conclusion: three main parameters enter in account for collision

Whether a ring collapse with the previous one depends on 3 parameters:
- the relative velocity between these rings
- the wait time between the impulses of the piston
- the shape of the wake of the previous ring (the speed profile after it)

The first parameter depends on the motion of the piston, especially its velocity. The last parameter can be influenced by initial turbulences, by the carried volume (so, mainly, the amplitude of the piston), and so on…

Picture 38 - Scheme of the flow lines in and around a vortex ring
The flow lines around and behind a ring are shown on picture 38. The global motion of the ring is from right to left (green arrows). We can see that the ring has a big area of influence. Behind the ring, after few centimetres, some turbulence is created. The flow lines in this turbulence area are very schematic. In fact, we have a lot of disordered vorticity. The shapes are random, but we often see a kind of little ring (in black). This turbulence area is much slower than the ring, and when the piston goes backward, it can even go in the other direction (red arrow).

One can easily understand that if a ring is located on the right of the red cross, it will be slowed by the turbulence area. Though, if a ring reaches the area of influence of the previous ring (near the blue arrows), this second ring will be accelerated (because aspired by the low pressure line of the previous vortex ring).

So we understood most of the influence of the wake in the ring collisions. Yet, it is very difficult to evaluate the lengths of the area of influence and of the turbulence area, and of course, their values change depending on the motion and the geometry.

3. How to adapt this to the process

For the process, it is important to send a lot for rings in a short time. The distance between two rings have to be long enough for them not to collapse, but short enough in order not to lose time.

On the motor file created for the experiment, the parameter we can change in order to find the right distance is the wait times (see above). A motor file which gives nice and efficient rings has been changed in order to reach this optimal wait times. This optimal wait time has been found empirically, and the motor file has been renamed, so Tetra Pak can use it during the rest of the study. Details of the comparison between the previous file and the new one are reported in Appendix II. IX.

B. The transport capacity influences the data of the industrial process

1. The ring exchanges matter during its motion

Most of matter which will be in the ring enters in it during its creation, just after the exit of the nozzle. The concentration decreases during the creation process. Afterwards, the ring is also diluted during its motion, because it loses matter and accepts water (or steam).

Indeed, during the motion of the ring, some matter, which was initially in the ring and which is located far from the centre of vorticity, has no speed enough to continue into the vortex, and so goes out of the ring (in the area with blue arrows on picture 38). A big part of this matter becomes the wake. Another part is caught again in the motion (blue arrows) and enters again in the vortex by being aspired by the low pressure area. Some water follows the same motion, and enters into the ring. That is why on the graphs from the experiment, most of the time, the thickness of the ring globally increases (graphs of the section of the ring). So the rings exchange fluid by this process during their motion.
2. Volume and concentration determine the numbers of rings necessary for transporting a given amount of product

The volume of the ring is given by: \( V_r = 2\pi^2 a b R \)

For the bottle to be sterilized, we need to inject 0.045455 kg of the 35% H\(_2\)O\(_2\) solution for 1 m\(^3\) of the bottle, in 0.7s (see data in part I. A. 2.). We can choose either to send few big rings which carry a lot of matter, or to send a lot of quite small rings. As said above, if the rings are too big, they have more chance to break very quickly in the bottle, and so the neck of the bottle will not be sterilized. Therefore, it is better to have small rings. Accordingly, a lot of these rings are needed, and to respect the time constraint, they should be fast.

Let us calculate the estimated number of rings needed, with rings of approximately the same size as those we got in the experiments:
With a radius of the ring equal to 8 mm and a circular section with a 4 mm radius, the volume of a ring is: \( \tau_r = 2.5 \times 10^{-6} m^3 \)

\[ N_r \cdot m_r = m_b \]
with \( m_b \) needed mass of solution in the bottle
\( m_r \) mass of solution in a ring
and \( N_r \) number of rings

\[ N_r \cdot C_r \cdot \tau_r = C_b \cdot \tau_b \]
with \( C_b \) concentration of the solution in a ring
\( C_b = 0.045455 \text{ kg/m}^3 \)
\( \tau_b = 1.5L = 1.5 \times 10^{-3} m^3 \) volume of the bottle

As the volume of fluid that a ring can accept is approximately 40% of its volume at the end of the motion, and given that the density of the 35% solution is 1,2 kg.m\(^{-3}\), the number of rings is:

\[ N_r \approx 38 \text{ rings} \]

We can now calculate a minimal frequency of the piston. Since approximately 38 rings must be sent in 0.7s, it means that one ring is sent every 18ms, which represent a 55 Hz frequency for the motion of the piston.
This value of the frequency and the value of the maximal frequency found by the other student who works on this project give a range for the frequency of the impulses of the piston for the process in Tetra Pak.

3. Tips for the process and ideas of improvement

An order of idea of the number of the rings has been found. This data is helpful for the study, but of course this number will have to be calculated more precisely, when the data of the process are known.
As we can not have very big rings, a lot of small rings will have to be produce for the sterilization of a bottle. As a result, the speed will have to be high.

For the process, it would be interesting to have some peroxide after the exit of the chamber (after the nozzle). So the rings would have more product in them. Indeed, as seen before, the rings accept a lot of fluid during their creation. If peroxide is caught in the rings instead of steam, the rings would be less diluted. But the device and the practical points have to be determined, which will not be done in this report.

C. What remains to be done is mostly finding the technical solution for the process

This study was for understanding the theory about vortex rings and starting to adapt them to the sterilization process. The results of this work will be useful for the firm, since some phenomena of vortex rings and ways to control them have been explained in this report. But, of course, a lot of things are still to discover and to study on this subject.

In Tetra Pak, files and data from this study have been ordered and given to the supervisor who will organize the continuation the study and the adaptation on the sterilization process.

- One thing that has not been studied is the external curve of the good nozzle. Indeed, we do not know if it is better to do a little bit deeper or not, regular or not, circular or elliptic, to use rough material, and so on.
- A motion of the piston with several impulses (with the good characteristics explained in this report) will have to be created. The process will probably need successive impulses instead of a backward motion between each impulse.
- Tetra Pak can also study and try the system with peroxide just after the exit of the nozzle. This may be a good improvement for the creation of the rings for the process.
- And of course, Tetra Pak will have to find the technical solution, in order to use vortex rings in the process. For example, the process will not necessarily use a piston (maybe a valve, a floodgate or a pump). So it will be of course necessary to design and size the machine. Tetra Pak will also have to work about the implementation of this machine in the process.
CONCLUSION

Vortex rings could be used in many industrial processes in order to transport matter. This study showed that vortex rings creation can be controlled in order to optimize their trajectory and their characteristics, even if a process which uses this kind of flow in Tetra Pak has not been precisely designed yet. This work brings interesting explanations about the theory and the first basic points in order to control vortex rings creation, which was the goal of Tetra Pak concerning this internship and which is the first step to the adaptation of this flow structure to the industrial process. At the end of the study, files and data have been given to our supervisor, and a presentation of this work has been made in the company, so that the work can be continued.

Thanks to this internship, a better understanding of the creation and the propagation of vortex rings is now possible. The experimental device and Tetra Pak tools have also been upgraded.

For the process, Tetra Pak should use a lot of small, thick and fast rings. Experiments showed that a way to produce them is to use a piston stroke which has a quite high velocity and a medium amplitude. As we do not want the rings to collide into each other, the wait time between successive impulses should not be too short, but a very long one would waste time in the process. The rings, and especially their steadiness, can be improved by using a convergent shape of nozzle, a constant acceleration motion and an optimal length of the piston chamber.

Concerning the adaptation to the process, it is of course good to have a big volume transported. The number of rings will be determined by this volume and by the concentration. The bottle have to be in line with the nozzle, or else the rings will have a lot of difficulties to reach the end. Experiments showed that turbulence at the beginning of the bottle can seriously disturb the rings, so the process should be designed so that there is not too much turbulence in the bottle, before the first rings. Almost everything can be imagined to generate the motion of the fluid, but, in fact, the only key point is to generate an axial speed flow just before the exit of the nozzle (turbulent at that point would be also bad for the rings).
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GLOSSARY

**ATMG** = name of a software created in Tetra Pak few years ago which allows to create curves thanks to polynomial interpolations.

**LinMot** = brand of the motor used to move the piston in the experimental device used during this work. This is also the brand of the software which drive this motor.

**Motor file** = file with specific format used by the LinMot software in order to move the motor. These files consist approximately in tables of demanded position of the piston depending on the time.

**Nozzle** = also used for “exit of the hollow cylinder”, in the experimental device.

**Peroxide**, or more precisely hydrogen peroxide, is a chemical component with formula $\text{H}_2\text{O}_2$. It is most of the time quite unstable, and so it can be transformed (at least in part) into $\text{H}_2\text{O}$.

**SF = Speed Factor** = a factor we can give to the motor if we want to slow down the motion. Multiply the speed in the motor file by this factor to have the actual velocity. In this report, and in the appendixes, all the data and curves take this Speed factor into account – even for the curves of the demanded position.

**Stability** = Three aspects of stability should be taken into account: the fact that the ring breaks far from the exit of the nozzle or not, the fact that the ring goes in a constant direction or not, and the fact that the ring looses a lot of matter or not.

**Video file** = Some experiments have been filmed with a high speed camera, which allows us to have video files on computers (.avi format)

**Vorticity** can be related to the amount of "circulation" or "rotation" in a fluid. Mathematically, it is a vector also called whirl vector and defined as: $\overrightarrow{\omega} = \text{rot}(V)$. See page 11 for more explanation.

**Wait time** = in a motor file, period when the piston is not moving (flat parts on the curves of the motor files).
NOTATIONS

\( V_p \) velocity (or speed) of the piston [m.s\(^{-1}\)]
\( V \) velocity [m.s\(^{-1}\)]
\( \omega \) vorticity [s\(^{-1}\)]
\( \rho \) density [-]
\( \text{Re} \) Reynolds number [-]
\( \eta \) dynamic viscosity [Pa.s]
\( L \) length [m]
\( D \) diameter [m]
\( D_i \) inner diameter [m]
\( D_e \) outer diameter [m]
\( R \) big radius of the ring (of the torus shape of vortex) [m]
\( r \) little radius of the ring (of the torus shape of vortex) [m]
\( (a,b) \) little and big axis of the ellipse of the ring’s section ([m], [m])
\( S \) stroke of the piston (or amplitude of the motion of the piston) [m]
\( m \) mass [kg]
\( C \) mass concentration [kg.m\(^{-3}\)]
\( \tau \) volume [m\(^3\)]

SF = Speed factor

\( T \) in °C (Celsius degree) is \( T+273,15 \) in K (Kelvin degree)

**Subscripts**
\( p \) piston
\( n \) nozzle
\( r \) ring
\( \text{ch} \) piston’s chamber, so inside the hollow cylinder around the piston
\( b \) bottle
REFERENCES

Articles


“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.


These articles, especially the three first ones, helped me for the understanding of the theory and allowed me to have a preview of studies that had already been made on this subject. I used them especially at the beginning of my internship.

Websites

www.wikipedia.org
I visited this web site a little bit in order to understand some physical phenomena and sometimes to collect some data.

www.linmot.com
This is the website of the motor manufacturer. I visited it in order to learn how to drive this motor and to prepare the experiments.

Courses


Courses from my engineering school provided me some physical and mathematical knowledge for this work.
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APPENDIX I.

PICTURE OF THE EXPERIMENTAL DEVICE AT THE END OF THIS STUDY
APPENDIX II.

DATA AND RESULTS OF THE EXPERIMENTS
I. EXPERIMENT ON THE SPEED OF THE PISTON
In the report: part II. A. 1.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Results used?</th>
<th>Measures in file…</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6605756m.avi</td>
<td>Try3</td>
<td>High speed</td>
<td>Yes</td>
<td>Exp2 speed.xls</td>
<td>200</td>
</tr>
<tr>
<td>6605757m.avi</td>
<td>Try4</td>
<td>Low speed</td>
<td>Yes</td>
<td>Exp2 speed.xls</td>
<td>200</td>
</tr>
<tr>
<td>6605758m.avi</td>
<td>Try4</td>
<td>Low speed</td>
<td>No</td>
<td>-</td>
<td>200</td>
</tr>
</tbody>
</table>

Data in file: "experiment parameters.xls", sheet "Exp2"

*Table 1 - Name and characteristics of the files for the experiment about speed of the piston*

A. Data

*Figure 1 - Demanded position of the piston for the experiment about speed of the piston*

1 “Yes” in the “Results used” column means that some measures have been taken on this video file, and these measures have been used in the graphs below.

“No” means that no measures have been taken on this video file.

“Not here” means that some measures have been taken on this video file, but has not been put on the graphs of this report.
# Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0.25</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>25</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>1</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>1.5</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0.02</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table 2 - Data of the motor file for the high speed (try3)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0.031</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>25</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>1</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0.8</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0.02</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table 3 - Data of the motor file for the low speed (try4)

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_p$</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$D_n$</td>
<td>22</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$L_{ch}$</td>
<td>50</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>25</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$D_{ch}$</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$D_{e,ch}$</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$V_p$</td>
<td>0.023 or 0.186</td>
<td>m/s</td>
<td>0.031 or 0.25 without SF</td>
</tr>
</tbody>
</table>

Table 4 - Data for the experiment about the speed of the piston

For this experiment, a speed factor of 0.75 has been used.

### B. Results

See excel file “Exp2 speed”

---

1 The 1st wait time is between the forward motion and the backward motion.
2 The 2nd wait time is at the end of the file, after the backward motion (and before the forward motion of the following cycle).
**Picture 2 - Visible section of the ring depending on the velocity of the piston**

**Picture 3 - Velocity of the ring depending on the velocity of the piston**
II. EXPERIMENT ON THE LENGTH OF THE PISTON STROKE

In the report: part II. A. 2.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Results used?</th>
<th>Measures in file…</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6622803m.avi</td>
<td>Try27</td>
<td>Long stroke (60)</td>
<td>Yes</td>
<td>Exp16 stroke.xls</td>
<td>300</td>
</tr>
<tr>
<td>6622805m.avi</td>
<td>Try7a</td>
<td>Small stroke (10)</td>
<td>Yes</td>
<td>Exp16 stroke.xls</td>
<td>300</td>
</tr>
<tr>
<td>6622806m.avi</td>
<td>Try5a</td>
<td>Medium stroke (35)</td>
<td>Yes</td>
<td>Exp16 stroke.xls</td>
<td>300</td>
</tr>
<tr>
<td>6622807m.avi</td>
<td>Try5a</td>
<td>Same and air in it</td>
<td>No</td>
<td>-</td>
<td>300</td>
</tr>
</tbody>
</table>

Data in file: "experiment parameters.xls", sheet “Exp16” (new Exp3)

Table 5 - Name and characteristics of the files for the experiment about the amplitude of the piston

A. Data

40
35
30
25
20
15
10
5
0
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000
piston's position (mm)
time (ms)

Picture 4 - Demanded position of the piston for the experiment about the amplitude of the piston

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0.23</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>1.2</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>2.755</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0.02</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table 6 - Data of the motor file for the short stroke (try7a)
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0,23</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>35</td>
<td>mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0,8</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>1,8</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0,02</td>
<td>m/s</td>
</tr>
</tbody>
</table>

*Table 7 - Data of the motor file for the medium stroke (try5a)*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0,23</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>70</td>
<td>mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0,7</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0,7</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0,02</td>
<td>m/s</td>
</tr>
</tbody>
</table>

*Table 8 - Data of the motor file for the long stroke (try27)*

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_p</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_n</td>
<td>22</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>L_ch</td>
<td>50</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>25</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_lch</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_ech</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>V_p</td>
<td>0,023 or 0,186</td>
<td>m/s</td>
<td>0,031 or 0,25 without SF</td>
</tr>
</tbody>
</table>

*Table 9 - Data for the experiment about the amplitude of the piston*

For this experiment, a speed factor of 0,75 has been used.

**B. Results**

See excel file “Exp16 stroke”
**Picture 5 - Speed of the ring depending on the length of the piston stroke**

**Picture 6 - Visible section of the ring depending on the length of the piston stroke**
III. EXPERIMENT ON THE ACCELERATION OF THE PISTON

In the report: part II. A. 3.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Results used?</th>
<th>Measures in file</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6718177m.avi</td>
<td>Try33</td>
<td>Constant acc.</td>
<td>No</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>6718178m.avi</td>
<td>Try33</td>
<td>Idem but later</td>
<td>No</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>6718180m.avi</td>
<td>Try33</td>
<td>Constant acc.</td>
<td>Yes</td>
<td>Exp21bis acceleration.xls</td>
<td>200</td>
</tr>
<tr>
<td>6718181m.avi</td>
<td>Try35</td>
<td>acc.=0</td>
<td>Yes</td>
<td>Exp21bis acceleration.xls</td>
<td>200</td>
</tr>
<tr>
<td>6718182m.avi</td>
<td>Try35</td>
<td>Idem but later</td>
<td>No</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td>6718183m.avi</td>
<td>Try36</td>
<td>LinMot acc.</td>
<td>Yes</td>
<td>Exp21bis acceleration.xls</td>
<td>200</td>
</tr>
<tr>
<td>6718184m.avi</td>
<td>Try36</td>
<td>Idem but later</td>
<td>No</td>
<td>-</td>
<td>200</td>
</tr>
</tbody>
</table>

Data in file: “experiment parameters.xls”, sheet “Exp21bis” (new Exp13, 19 or 21)

Table 10 - Name and characteristics of the files for the experiment about acceleration of the piston

A. Data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0,1</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>10</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0,07</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0,15</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0,03</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table 11 - Data of the motor files (try33, try35 and try36)

For this experiment, the good nozzle, described in part II. B. 1. b. i/ has been used.
Picture 7 - Demanded position, speed and acceleration for the experiment on the acceleration profile and for a constant positive acceleration (motor file made with ATMG)
Picture 8 - Demanded position, speed and acceleration for the experiment on the acceleration profile and for no acceleration (motor file made with ATMG)
VALUE ON THE GRAPHS:
Try33, constant acceleration, acc=1,913, speed.max=0,150, speed.beg\(^1\)=0,015
Try35, zero acceleration, acc.max=7,088, (so) acc.min=-7,088, speed.max=0,092
Try36, LinMot, acc.max=1,875, (so) acc.min=-1,875, speed.max=0,083
(These values take in account the speed factor of the motor, that is why the values for try36 are not the same as in the graphs)

WITHOUT SF (WITH SF=1)
Try33, constant acceleration, acc=2,550, speed.max=0,200, speed.beg\(^1\)=0,020
Try35, zero acceleration, acc.max=9,450, (so) acc.min=-9,450, speed.max=0,123
Try36, LinMot, acc.max=2,5, (so) acc.min=-2,5, speed.max=0,11

\(^1\) = speed at the beginning of the constant acceleration
Picture 10 - Demanded position of the piston for the experiment about the acceleration of the piston

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{p}$</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$D_{n}$</td>
<td>16</td>
<td>Mm</td>
<td>Special shape of nozzle</td>
</tr>
<tr>
<td>$L_{ch}$</td>
<td>130</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>10</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$D_{lch}$</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$D_{ech}$</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>$V_{p}$</td>
<td>0.075</td>
<td>m/s</td>
<td>In average. 0.1 without SF</td>
</tr>
</tbody>
</table>

Table 12 - Data for the experiment about the acceleration of the piston

For this experiment, a speed factor of 0.75 has been used.

B. Results

See excel file “Exp21bis acceleration”

---

1 The shape of the nozzle used for this experiment is described in II. B. 1. b. i/. This is the good shape which we made after studying the influence of the shape of the nozzle.
Picture 11 - Velocity of the ring depending on the acceleration profile

Picture 12 - Visible section of the ring depending on the acceleration profile
Picture 13 - Graph without interpolation for the velocity of the ring depending on the acceleration profile

Picture 14 - Graph without interpolation for the visible section of the ring depending on the acceleration profile
IV. FIRST EXPERIMENT ON THE SHAPE OF THE NOZZLE

In the report: part II. B. 1. a.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Results used?</th>
<th>Measures in file…</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6615778m.avi</td>
<td>Best3 04</td>
<td>Shape#4a</td>
<td>Yes</td>
<td>Exp14 shape nozzle.xls</td>
<td>100</td>
</tr>
<tr>
<td>6615780m.avi</td>
<td>Best3 04</td>
<td>Shape#5</td>
<td>Yes</td>
<td>Exp14 shape nozzle.xls</td>
<td>100</td>
</tr>
<tr>
<td>6615781m.avi</td>
<td>Best3 04</td>
<td>Shape#5, 1st ring</td>
<td>No</td>
<td>Exp14 shape nozzle.xls</td>
<td>100</td>
</tr>
<tr>
<td>6615782m.avi</td>
<td>Best3 04</td>
<td>Shape#9</td>
<td>No</td>
<td>Exp14 shape nozzle.xls</td>
<td>100</td>
</tr>
<tr>
<td>6615783m.avi</td>
<td>Best3 04</td>
<td>Shape#8</td>
<td>No</td>
<td>Exp14 shape nozzle.xls</td>
<td>100</td>
</tr>
<tr>
<td>6615786m.avi</td>
<td>Best3 04</td>
<td>Shape#7a</td>
<td>Yes</td>
<td>Exp14 shape nozzle.xls</td>
<td>300</td>
</tr>
</tbody>
</table>

Data in file: “experiment parameters.xls”, sheet “Exp14” (old Exp17)

Table 13 - Name and characteristics of the files for the experiment about the shape of the nozzle

A. Data

![Graph showing piston position over time](image)

**Table 15 - Demanded position of the piston for the experiment for the shape of the nozzle (best3_04)**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0.13</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>8</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0.6</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0.6</td>
<td>S</td>
</tr>
<tr>
<td>3rd wait time</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>4th wait time</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0.024</td>
<td>m/s</td>
</tr>
</tbody>
</table>

**Table 14 - Data of the motor file (best3_04)**

1 So the total stroke is 24 mm.
2 The three first wait times are the period after each impulse (the 1st, after the 1st impulse, and so on). The 4th wait time is the period when demanded position is 0 after the backward motion.
<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_p)</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(D_n)</td>
<td>22 or other</td>
<td>Mm</td>
<td>Depending on the shape</td>
</tr>
<tr>
<td>(L_{ch})</td>
<td>75</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(S)</td>
<td>24</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(D_{ich})</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(D_{e_{ch}})</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(V_p)</td>
<td>0.098</td>
<td>m/s</td>
<td>0.13 without SF</td>
</tr>
</tbody>
</table>

*Table 15 - Data for the first experiment about the shape of the nozzle*

For this experiment, a speed factor of 0.75 has been used.

![Shapes of the nozzle tested in this experiment](Picture 16 - Shapes of the nozzle tested in this experiment)

**B. Results**

See excel file “Exp14 shape nozzle”
Picture 17 - Speed of the first ring depending on the shape of the nozzle

Picture 18 - Visible section of the first ring depending on the shape of the nozzle
V. EXPERIMENT WITH THE GOOD SHAPE OF THE NOZZLE

In the report: part II. B. 1. b.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Results used?</th>
<th>Measures in file…</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6718180m.avi</td>
<td>Try33</td>
<td>good nozzle</td>
<td>Yes</td>
<td>Exp22 try good nozzle.xls</td>
<td>200</td>
</tr>
<tr>
<td>6718187m.avi</td>
<td>Try33</td>
<td>21mm diameter</td>
<td>Yes</td>
<td>Exp22 try good nozzle.xls</td>
<td>200</td>
</tr>
</tbody>
</table>

Data in file: “experiment parameters.xls”, sheet “Exp22” (taken from Exp11 and exp21bis)

Table 16 - Name and characteristics of the files for the try of the good shape of nozzle

A. Data

![Graph](image.png)

Picture 19 - Demanded position of the piston for the try of the good shape of nozzle (try33)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0,1</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>10</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0,07</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0,15</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0,03</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table 17 - Data of the motor files (try33)
<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_p</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_n</td>
<td>22 or 16 (good nzl)</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>L_ch</td>
<td>130</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>10</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_lch</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_ech</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>V_p</td>
<td>0.075</td>
<td>m/s</td>
<td>In average. 0.1 without SF</td>
</tr>
</tbody>
</table>

Table 18 - Data for the experiment about the shape of the nozzle

For this experiment, a speed factor of 0.75 has been used.

B. Results

See excel file “Exp22 try good nozzle”

![Graph showing velocity of a ring depending on the shape of the nozzle – try with the good nozzle](image)
Picture 21 - Visible section of a ring depending on the shape of the nozzle – try with the good nozzle
VI. EXPERIMENT ON THE LENGTH OF THE PISTON CHAMBER

In the report: part II. B. 2.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Result used?</th>
<th>Measures in file…</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6622809m.avi</td>
<td>Best3_04</td>
<td>Long chber (155)</td>
<td>Yes</td>
<td>Exp18 chb length.xls</td>
<td>100</td>
</tr>
<tr>
<td>6622810m.avi</td>
<td>Best3_04</td>
<td>Medium chber (106)</td>
<td>Yes</td>
<td>Exp18 chb length.xls</td>
<td>100</td>
</tr>
<tr>
<td>6622811m.avi</td>
<td>Best3_04</td>
<td>Short chber (61)</td>
<td>Yes</td>
<td>Exp18 chb length.xls</td>
<td>100</td>
</tr>
<tr>
<td>6609767m.avi</td>
<td>Best3_04</td>
<td>Short chber (54)</td>
<td>No</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>6609768m.avi</td>
<td>Best3_04</td>
<td>Long chber (133)</td>
<td>No</td>
<td>-</td>
<td>100</td>
</tr>
</tbody>
</table>

Data in file: "experiment parameters.xls", sheet “Exp18” (new Exp12)

Table 19 - Name and characteristics of the files for the experiment about the length of the piston chamber

A. Data

![Graph](image)

Picture 22 - Demanded position of the piston for the experiment about the length of the piston chamber (best3_04)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0,13</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>8</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0,6</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0,6</td>
<td>S</td>
</tr>
<tr>
<td>3rd wait time</td>
<td>0,6</td>
<td></td>
</tr>
<tr>
<td>4th wait time</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0,024</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table 20 - Data of the motor file (best3_04)

1 So the total stroke is 24 mm.
2 The three first wait times are the period after each impulse (the 1st, after the 1st impulse, and so on). The 4th wait time is the period when demanded position is 0 after the backward motion.
<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dₚ</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>Dₛ</td>
<td>22</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>Lₐₙ</td>
<td>61, 106 or 155</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>24</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>Dₑₙ</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>Dₑₛ</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>Vₛ</td>
<td>0.098</td>
<td>m/s</td>
<td>0.13 without SF</td>
</tr>
</tbody>
</table>

*Table 21 - Data for the experiment about the length of the piston chamber*

For this experiment, a speed factor of 0.75 has been used.

**B. Results**

See excel file “Exp18 chb length”

*Picture 23 - Velocity of the first ring depending on the length of the chamber*
$R^2 = 0.9755$

$R^2 = 0.965$

$R^2 = 0.9399$

Long chamber: 155 mm

Medium length chamber: 106 mm

Short chamber: 61 mm

Poly. (long chamber: 155 mm)

Poly. (medium length chamber: 106 mm)

Poly. (short chamber: 61 mm)

Picture 24 - Visible section of the first ring depending on the length of the chamber
VII. EXPERIMENT ON THE NOZZLE DIAMETER

In the report: part II. B. 3.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Results used?</th>
<th>Measures in file…</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6718185m.avi</td>
<td>Try33</td>
<td>diameter 15</td>
<td>Yes</td>
<td>Exp11 diaphragm diameter.xls</td>
<td>200</td>
</tr>
<tr>
<td>6718186m.avi</td>
<td>Try33</td>
<td>diameter 25</td>
<td>Yes</td>
<td>Exp11 diaphragm diameter.xls</td>
<td>200</td>
</tr>
<tr>
<td>6718187m.avi</td>
<td>Try33</td>
<td>diameter 21</td>
<td>Yes</td>
<td>Exp11 diaphragm diameter.xls</td>
<td>200</td>
</tr>
<tr>
<td>6718188i.avi</td>
<td>Try33</td>
<td>diameter 5</td>
<td>No</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6718190m.avi</td>
<td>Try33</td>
<td>diameter 5</td>
<td>Yes</td>
<td>Exp11 diaphragm diameter.xls</td>
<td>200</td>
</tr>
</tbody>
</table>

Data in file: “experiment parameters.xls”, sheet “Exp11”

Table 22 - Name and characteristics of the files for the experiment about the diameter of the nozzle

A. Data

![Graph showing demanded position of the piston over time](image)

Picture 25 - Demanded position of the piston for the experiment about the diameter of the nozzle (try33)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0.1 m/s</td>
<td></td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>10 Mm</td>
<td></td>
</tr>
<tr>
<td>1st wait time</td>
<td>0.07 S</td>
<td></td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0.15 S</td>
<td></td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0.03 m/s</td>
<td></td>
</tr>
</tbody>
</table>

Table 23 - Data of the motor files (try33)

This motor file has a constant acceleration during 70 ms, like for the experiment about acceleration of the piston.
For this experiment, a speed factor of 0.75 has been used.

B. Results

See excel file “Exp11 diaphragm diameter”
Picture 27 - Other graph for the velocity of the ring depending on the nozzle diameter

Picture 28 - Visible section of the ring depending on the nozzle diameter
VIII. EXPERIMENT ON THE COLLISION BETWEEN TWO RINGS

In the report, see part III. A. 1.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Re-sults used?</th>
<th>Measures in file…</th>
<th>Frames /s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6605759m.avi</td>
<td>Try33</td>
<td>Can’t see collision</td>
<td>No</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td>6605760m.avi</td>
<td>Try33</td>
<td>Yes</td>
<td>three rings and collision.xls</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

Data in file: “experiment parameters.xls”, sheet “Exp10”

\[ \text{Table 25 - Name and characteristics of the files for the experiment about collision between two rings} \]

A. Data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st and 3rd impulses</td>
<td>0,22</td>
<td>m/s</td>
</tr>
<tr>
<td>Speed of the 2nd impulse</td>
<td>0,08</td>
<td></td>
</tr>
<tr>
<td>Stroke of the each impulse(^1)</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0,2</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0,2</td>
<td>S</td>
</tr>
<tr>
<td>3rd wait time</td>
<td>0,2</td>
<td></td>
</tr>
<tr>
<td>4th wait time(^2)</td>
<td>0,8</td>
<td></td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0,003</td>
<td>m/s</td>
</tr>
</tbody>
</table>

\[ \text{Table 26 - Data of the motor file (try22)} \]

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_p)</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(D_n)</td>
<td>22</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(L_{ch})</td>
<td>53</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(S)</td>
<td>30</td>
<td>Mm</td>
<td>For the 3 impulses</td>
</tr>
<tr>
<td>(D_{ch})</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(D_{ch})</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>(V_p)</td>
<td>0,06 for the 2nd, 0,17 else</td>
<td>m/s</td>
<td>0,08 or 0,22 and without SF</td>
</tr>
</tbody>
</table>

\[ \text{Table 27 - Data for the experiment about the collision between two rings} \]

For this experiment, a speed factor of 0,75 has been used.

B. Results

See excel file “three rings and collision”

\(^1\) So the total stroke is 30 mm.

\(^2\) The three first wait times are the period after each impulse (the 1st, after the 1st impulse, and so on). The 4th wait time is the period when demanded position is 0 after the backward motion.
Collision happens between 900 and 1000 ms.
IX. EXPERIMENT IN ORDER TO IMPROVE THE MOTION OF THE PISTON

In the report: part III. A. 3.

<table>
<thead>
<tr>
<th>Video file</th>
<th>Motor file</th>
<th>Remarks</th>
<th>Results used?</th>
<th>Measures in file…</th>
<th>Frames/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6711832m.avi</td>
<td>Try33</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>60</td>
</tr>
<tr>
<td>6711833m.avi</td>
<td>Try33</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>400</td>
</tr>
<tr>
<td>6711834m.avi</td>
<td>Try33</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>6711839m.avi</td>
<td>Try33bis</td>
<td>Shorter wait time</td>
<td>Yes</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>6711840m.avi</td>
<td>Try33bis</td>
<td>Shorter wait time</td>
<td>No</td>
<td>-</td>
<td>60</td>
</tr>
</tbody>
</table>

Data in file: - (no numeric measures)

Table 28 - Name and characteristics of the files in the experiment for improving the motion

A. Data

![Graph](image)

Picture 31 - Demanded position of the piston for the experiment for improving the motion (two tries)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0.01</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>10</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0.07</td>
<td>s</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0.15</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0.03</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table 29 - Data of the motor files (try33)
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulses</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Speed of the 1st impulse</td>
<td>0.01</td>
<td>m/s</td>
</tr>
<tr>
<td>Stroke of the 1st impulse</td>
<td>10</td>
<td>Mm</td>
</tr>
<tr>
<td>1st wait time</td>
<td>0.07</td>
<td>S</td>
</tr>
<tr>
<td>2nd wait time</td>
<td>0.02</td>
<td>S</td>
</tr>
<tr>
<td>Speed of the backward motion</td>
<td>0.03</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Table_30 - Data of the motor files (try33bis)

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_p</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_n</td>
<td>16 (good nozzle)</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>L_ch</td>
<td>135</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>10</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_lch</td>
<td>31</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>D_Ech</td>
<td>34</td>
<td>Mm</td>
<td></td>
</tr>
<tr>
<td>V_p</td>
<td>0.075</td>
<td>m/s</td>
<td>In average. 0.1 without SF</td>
</tr>
</tbody>
</table>

Table_31 - Data for the experiment about the shape of the nozzle

For this experiment, a speed factor of 0.75 has been used.

B. Results

(No graphs for this experiment).

Thanks to this experiment, it has been checked (with the bare eye) that the rings from the new motor file (try33bis) do not collide and that they manage to reach the end of the bottle. So a new file which allows to have more rings in a given period of time without problems of collisions or stability has been found.
APPENDIX III.

RECAPITULATIVE TABLE OF THE EXPERIMENTS
CONCLUSIONS

Notations
Vp velocity (or speed) of the piston [m.s\(^{-1}\)]
\(\omega\) vorticity [s\(^{-1}\)]
L length [m]
D diameter [m]
Di inner diameter [m]
De outer diameter [m]
R big radius of the ring (of the torus shape of vortex) [m]
r little radius of the ring (of the torus shape of vortex) [m]
S stroke of the piston (or amplitude of the movement of the piston) [m]
<table>
<thead>
<tr>
<th>Action on a parameter</th>
<th>Effects</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_p ) ↑</td>
<td>( R \downarrow )</td>
<td>A little bit (more dilution)</td>
</tr>
<tr>
<td></td>
<td>( r \uparrow )</td>
<td>A little bit</td>
</tr>
<tr>
<td></td>
<td>( V_r \uparrow )</td>
<td>A very little bit</td>
</tr>
<tr>
<td></td>
<td>Stability ↑</td>
<td>A little bit</td>
</tr>
<tr>
<td>( S ) ↑</td>
<td>( R \uparrow )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( r \uparrow )</td>
<td>A little bit</td>
</tr>
<tr>
<td></td>
<td>( V_r \uparrow )</td>
<td>For ( S&lt;35-40 ) mm (optimal value)</td>
</tr>
<tr>
<td></td>
<td>( \omega \uparrow ) then ↓</td>
<td>Optimal value at ( S=10-20 ) mm</td>
</tr>
<tr>
<td></td>
<td>Stability ↑ then ↓</td>
<td>Optimal value at ( S=10-20 ) mm</td>
</tr>
<tr>
<td>( L_{ch} ) ↑</td>
<td>( R \uparrow )</td>
<td>A little bit</td>
</tr>
<tr>
<td></td>
<td>( r \uparrow )</td>
<td>A little bit</td>
</tr>
<tr>
<td></td>
<td>( V_r \uparrow )</td>
<td>Optimal L/D value at L/D≈4</td>
</tr>
<tr>
<td></td>
<td>( \omega \uparrow )</td>
<td>A little bit</td>
</tr>
<tr>
<td></td>
<td>Stability ↑</td>
<td></td>
</tr>
<tr>
<td>( D_n ) ↑</td>
<td>( R \uparrow )</td>
<td>A little bit</td>
</tr>
<tr>
<td></td>
<td>( r \uparrow )</td>
<td>A very little bit</td>
</tr>
<tr>
<td></td>
<td>( V_r \downarrow )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \omega \uparrow )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stability = (( \downarrow ))</td>
<td>Less mixed but breaks a little bit before</td>
</tr>
</tbody>
</table>

Remark: These trends are only available in the studied frames. We are aware that the links between these parameters are not always so simple (especially it is not necessarily linear), but these trends bring a good model which is accurate enough for our industrial application.