Sterilization of sterile tanks

Emma Wärlinge

Department of Chemical Engineering, Lund University, P. O. Box 124, SE-221 00 Lund, Sweden

March 2007

Abstract

In the product portfolio of Tetra Pak, Tetra Alsafe is a system, including a buffer tank and auxiliary equipment for supply and removal of steam and air, respectively, used in aseptic applications. The pre-sterilization of the tank is conducted with steam. In the first part of the sterilization sequence air is removed in cycles of feeding steam into the tank and then draining a part of the air/steam mixture together with condensate. This study focuses on this process and uses measurements of temperature, pressure and mass of condensate to develop a model that calculates the velocities of the steam, condensation rate and the efficiency of the air evacuation. The results show that the velocities in the valves vary between 100 and 400 m/s both when steam enters and exits the tank. Calculations based on the flow gives that 9 kg out of the 14 kg fed to the tank are still in the tank at the end of the air-removal cycle. All condensate that is formed will exit the tank in the two final draining periods. It is proposed that they are prolonged with ten seconds to drain more condensate and air.

Introduction

In the product portfolio of Tetra Pak, Tetra Alsafe is an intermediate storage tank that is placed in dairies to buffer fluid flow, see Fel! Hittar inte referenskälla.. The tank is of aseptic design and needs to be cleaned and sterilized before the product enters the tank. The sterilization is conducted with steam that condenses and heats the tank. When a standardized temperature is obtained and withheld for a certain duration of time, a sufficient level of microorganism reduction is obtained.¹

The first target of the sterilization process is to remove air from the tank that could restrict the sterilization. This study will look at this process to gain knowledge about the steam velocities in the different parts of the system, condensation rate and air evacuation efficiency. Measurements of pressure, temperature and discharged condensate are the basis for calculating velocities, condensation rate and air evacuation to be able to optimize the sterilization.

Background

Steam is an efficient medium for sterilization which is widely used in the food processing and health care sectors. When steam condenses at a surface latent heat is released and transferred to the material. The presence of air has a big impact on the sterilization and results in an insufficient temperature increase since a given pressure implies a higher temperature than what really is obtained.² Air can also be entrapped in corners which prevent the steam to reach all surfaces. If no condensation occurs on the surface it will not be heated satisfactorily.³

In the system studied here, the steam is introduced as a high velocity flow that mixes with the air in the system. The flow then continues to valves or steam traps that will drain the steam, air and condensate.³ Sterilizing Tetra Alsafe is performed in three cycles of feeding steam into the tank and then part of the mix will be drained. After this the tank will be heated by the steam to a target temperature of 125 °C and kept above this for 30 min.

Flow of compressible fluids

Calculations on flow of a compressible fluid, such as steam, are more complicated than those on a non-compressible fluid because the variation of density because of changes in temperature and pressure has to be taken into account.⁴

For a flow through an orifice, or a section of smaller diameter, with the variables stated in Figure 2, an expression for the flow and velocity through a
cross section of the orifice can be derived from the general energy equation.

Figure 2 Tank, orifice and variables

For a non-isothermal flow the relation between pressure and volume (\(v\)) can be expressed as \(P \cdot v^k = \text{constant}\) where \(k\) depends on the heat transfer between fluid and the surroundings and \(v\) is the specific volume. If the flow can be described as reversible, \(k\) can be approximated to be equal to \(\gamma\) which is the ratio of the specific heats of the gas according to Equation 1.

\[
k \approx \gamma = \frac{C_p}{C_v} \quad \text{Eq. 1}
\]

The discharge velocity is described by Equation 2 and the mass rate of flow by Equation 3 for isentropic conditions. \(C_D\) is a correction factor for friction and \(A_0\) is the area of the smallest passage in the orifice.

\[
u = \sqrt{\frac{2\gamma}{\gamma-1} P_1 \nu_1 \left[ 1 - \left( \frac{P_2}{P_1} \right)^{\gamma-1} \right]} \quad \text{Eq. 2}
\]

\[
Q = C_D A_0 \left( \frac{P_2}{P_1} \right)^{\gamma/2} \sqrt{\frac{2\gamma}{\gamma-1} P_1 \nu_1 \left[ 1 - \left( \frac{P_2}{P_1} \right)^{\gamma-1} \right]} \quad \text{Eq. 3}
\]

Material & Method

The volume of the tank used in the measurements is 12 m³. In the first step of the sterilization sequence the steam and product inlet pipers are drained from old condensate with steam. Then the air removal cycles begin. In P1, P2 and P3 (see Table 1) 2.7 barg steam enters the tank through the valve placed in the middle of the tank in Figure 3. This valve splits the flow into the side of the tank and through the CIP pipes that lead to the top of the tank. The flow will continue until the tank has reached the target value in Table 1.

Table 1 Explanation to the abbreviations and target values

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Explanation</th>
<th>Target value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Pressurise 1</td>
<td>1 barg</td>
</tr>
<tr>
<td>D1</td>
<td>Drain 1</td>
<td>60 s</td>
</tr>
<tr>
<td>P2</td>
<td>Pressurise 2</td>
<td>1.8 barg</td>
</tr>
<tr>
<td>D2</td>
<td>Drain 2</td>
<td>20 s</td>
</tr>
<tr>
<td>P3</td>
<td>Pressurise 3</td>
<td>2 barg</td>
</tr>
<tr>
<td>D3</td>
<td>Drain 3</td>
<td>10s</td>
</tr>
</tbody>
</table>

After the third draining the tank will be heated to the target temperature 125 °C indicated by three transmitters. This is done by feeding steam in the same way as before for 55 s of every minute. The remaining 5 s the tank is drained from condensate.

At the top of the tank an outlet is leads steam through an air filter to sterilize it and then through a valve with a 1.5 mm hole. The flow is divided before the filter and it also passes a valve with a 3.5 mm opening which relieves the pressure on the filter and drains condensate. This can be seen in Figure 3 and 4 as black lines going from the top right hand of the tank.

Condensate will be discharged through 3 discharge pipes during the sterilization cycle. The amount of condensate was measured at three locations with the condensate trap and silencer together. The condensate was collected in vessels and the amount continuously measured. The data was sampled at three different occasions, and the three measuring points with different sample times and units depending on discharge rate and total
amount of condensate. Temperature and pressure curves were recorded from the HMI (Human Machine Interface) and sampled at a rate of one second.

Calculations & modeling
The calculation program Matlab, MathWorks Inc, was used to calculate the flow of steam into and out from the tank. The flow coming from the top of the tank was estimated to only have one point of pressure loss since it passes through two such small openings. The tank system was divided into three parts; steam inlet pipes, outlet pipes and top outlet. For every part each valve that the flow passes was identified and the diameter of the internal passage gave the size of the restriction. Pressure drop was said to only occur in the valves and not in the pipes. In Matlab a series of Equation 3 was set up, one for each valve. The first and final pressures were known as the measured pressure and the constant inlet/outlet pressures. A loop in the calculation program calculated the pressure drop in each valve by changing the flow rate until the final pressure was accurate. The result of the calculations gave the pressure in the pipes between the valves and the flow rate for every measured pressure in the tank (every second).

A mass balance of the air in the tank was also made. For every step where steam was fed to the tank, the mole fraction of the two gases was calculated on the basis of how much air that is drained. In these calculations it was assumed that the air and steam are mixed into a homogenous mixture.

During the periods when steam flows into the tank, the sum of all flows in and out was calculated for every second as the accumulated mass in the tank. The part of the accumulated mass that increases the pressure in the tank was calculated as the differences in density, caused by the pressure change, multiplied by the volume of the tank, see Equation 5. The remaining mass of the flow was assumed to condense. In the draining periods Equation 5 was used as a second method of calculating the flow rate out of the tank at every measured pressure value.

\[ \Delta m = V \cdot (\rho_{P2} - \rho_{P1}) \]  
\[ \text{Eq. 5} \]

Measured data
Figure 5 shows the pressure in the tank during the sterilization cycle in three different test runs. In all three curves the pressure is increasing during P1, P2 and P3 to the preset values and the pressure decreases during D1, D2 and D3. The three curves differ from each other in how fast the set pressure is reached. The reason for the differences probably is that the load on the steam supply in the premises varies.

![Figure 5](image)

Figure 5 Pressure curves measured at three different test runs

The temperatures measured by the three temperature transmitters all vary in time due to the changes in the directions of the steam and condensate flows. In Figure 6 the log of the temperatures in a sterilization cycle is shown during the air evacuation process.

![Figure 6](image)

Figure 6 Temperature curves; the blue; after the filling machines, pink; bottom drain, yellow; sterile filter

Measurements of the accumulated mass of condensate discharged at 10 s intervals result in the data in Figure 7 and the total masses in Table 2. The first 30 s when the steam feed pipes are drained it is mostly old condensate that comes out.

![Figure 7](image)

Figure 7 Condensate discharged at the exit after the filling machines

### Table 2 Mass of condensate discharged after the filling machines, kg

<table>
<thead>
<tr>
<th>Step</th>
<th>Condensate</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>14</td>
</tr>
<tr>
<td>D2</td>
<td>25</td>
</tr>
<tr>
<td>D3</td>
<td>3</td>
</tr>
</tbody>
</table>
Condensate in the pipes at the top of the tank will be able to exit the tank through a silencer and steam trap at the top of the tank at all times. Measurements show that it will take until P2 before condensate will be discharged here, see Figure 8. The total mass of condensate is presented in Table 4.

![Figure 8](image)

**Figure 8** Condensate discharged from the top of the tank, pink; steam trap, blue; silencer

<table>
<thead>
<tr>
<th>Exit</th>
<th>Condensate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam trap</td>
<td>70 g</td>
</tr>
<tr>
<td>Silencer</td>
<td>265 g</td>
</tr>
</tbody>
</table>

### Table 3 Mass of condensate discharged at the top, g

Steam inlet analysis

This is the part of the piping system that begins at the steam entry point at the left below the tank and continues to a split where one part goes into the tank and one part goes down to an outlet point through a steam trap.

The velocities in the valves are based on the measurements of the pressure in the tank and the result can be viewed in Figure 9. The placement of the numbered valves can be seen in Figure 10. During P1, P2 and P3 the flow will pass through several valves that each will result in a pressure drop, hence an increase in velocity. This means that the velocity of steam going into the tank will not only change in time but also in every valve it passes.

![Figure 9](image)

**Figure 9** Velocity in valves involved in P1-P3

The three periods that can be seen in Figure 9 represent the velocities in the valves that the steam flow passes during P1, P2 and P3 on the way into the tank. The first valve that the flow passes is the line with the lowest velocity and the proceeding valves are the corresponding lines going upwards in the picture. In time the velocity in every valve will decrease because the pressure in the tank becomes higher which creates a smaller pressure gradient.

![Figure 10](image)

**Figure 10** Explanations to the valve numbers

In Figure 11 the total flow rate of steam that goes into the tank in P1, P2 and P3 has been plotted together with the part that raises the pressure and the part that condenses. The rate of condensation is quite rapid in the beginning of P1. This might be because the temperature in the tank is still low and the majority of the steam that enters is allowed to condense. In P2 and P3 the condensation follows the same pattern as P1 but the increase is not as high because the tank has a higher temperature. The total masses steam that condenses (integral of the flow) is presented in Table 5.

![Figure 11](image)

**Figure 11** The total flow rate in to the tank (black), the condensation rate (purple) and the pressure increasing (blue)

<table>
<thead>
<tr>
<th>Step</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensate</td>
<td>14.2</td>
<td>33.9</td>
<td>6.1</td>
</tr>
</tbody>
</table>

### Table 5 Mass of condensate formed in P1-P3, kg

The maximum flow rate into the tank will occur in the beginning of P1 and P2 because the pressure in the tank is the lowest here. The maximum flow rate is 0.25 kg/s (900 kg/h).

The pressure measurements show that the boiler that delivers steam to the tank has a big impact on how long the sterilization takes. A steam supply that does not provide a sufficient flow rate of steam will slow down the pressure dependent steps (P1, P2 and P3).
Steam outlet analysis

This is the part of the tank system that starts at the bottom of the tank and goes past the filling machines to the valves after the filling machines. The flow here includes steam, air and condensate.

The results of the first method of calculating the flow rate are showed in Figure 12. When the flow passes the first valve (orange line) the pressure is reduced which gives a higher discharge velocity. Then the flow passes the next valve and the same thing occurs and in the last valve the pressure is reduces to atmospheric pressure and here the highest velocity reached. The velocities in P2 and P3 are higher than in P1 because the pressure in the tank is higher which gives a larger driving force for the flow out.

In D1, D2 and D3 steam and condensate will be drained past the filling machines. Since the pressure in the tank gets lower when it is being drained the velocity of the steam will decrease in time. In D1 the temperature will increase when the flow passes but in D2 and D3 the temperatures are so high after the preceding P2 and P3 that the condensate that passes will have a cooling effect. The temperature fluctuations in P3 probably depend on shifts between steam and condensate.

![Figure 12 Velocity in valves involved in D1-D3](image)

The total mass of steam going out of the tank during D1, D2 and D3, see *Fel! Hittar inte referenskälla.*

<table>
<thead>
<tr>
<th>Step</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam</td>
<td>6.2</td>
<td>4.4</td>
<td>2.5</td>
</tr>
</tbody>
</table>

In the second method of calculating the flow rate out of the tank, the density differences at the different pressures was used. In Table 7 the total mass of steam (integral of the flow) is given for the two ways of calculating.

<table>
<thead>
<tr>
<th>Step</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation based</td>
<td>6.2</td>
<td>4.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Measurement based</td>
<td>5.1</td>
<td>1.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The two results do not coincide and it can be due to the flow calculations that may give too high results, which can depend on too low pressure drop in the valves that the flow passes. It can also be due to the fact that the steam flow has to push condensate out of the tank to which no consideration has been taken. The condensate could be a restraint to the flow when it has to be pushed through the valves. The results of the comparison show that the difference of the two methods is the largest in D2 where the most condensate is to be pushed out in a short period of time. Another reason to why the calculations show that too much steam exits the tank could be that condensate, which could be left in the tank, might start to boil when the pressure is decreasing.

The total measured mass of condensate that comes out in D1, D2 and D3 is shown in Table 8. Since the draining steps are time dependent there is no guarantee that all condensate formed will be discharged. When comparing the mass condensed in P1 and the mass discharged in D1, Table 8, it is seen like all the condensate will have enough time to be drained. In D2 and D3 on the other hand it looks as the time is not enough to drain all the condensate from P2 and P3. If the flow in D2 should maintain the flow rate of 0.8 kg/s condensate, as it is at the last measuring point, for another 10 s the total mass of condensate discharged would be 25 +0.8*10 = 33 kg. This would mean that almost all condensate that is calculated to be formed in P2 would be drained in D2. The same thing applies to D3.

<table>
<thead>
<tr>
<th>Step</th>
<th>P1</th>
<th>D1</th>
<th>P2</th>
<th>D2</th>
<th>P3</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensate formed</td>
<td>14.2</td>
<td>33.9</td>
<td>6.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condensate discharged</td>
<td>14</td>
<td>25</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The calculation of the steam flow that leaves the tank through the bottom also includes air that is to be drained from the tank. In a mass balance of air and steam the measurement based values of the mass of steam/air that leaves the tank are used. At the start there is approximately 14 kg of air in the 12 m³. When the air-removal cycle is over, the tank will approximately contain 16.4 kg steam and 9.4 kg air according to the calculations. A summarize of the composition in the tank is given in Table 9.

<table>
<thead>
<tr>
<th>Step</th>
<th>P1</th>
<th>D1</th>
<th>P2</th>
<th>D2</th>
<th>P3</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam</td>
<td>6.7</td>
<td>5.1</td>
<td>15.3</td>
<td>14.2</td>
<td>17.2</td>
<td>16.4</td>
</tr>
<tr>
<td>Air</td>
<td>14</td>
<td>10.5</td>
<td>10.5</td>
<td>9.8</td>
<td>9.8</td>
<td>9.4</td>
</tr>
</tbody>
</table>
The calculations on this part of the system indicate that the time dependent steps D2 and D3 are too short to evacuate any significant amount of air. It is also shown that air in the system will lower the temperature in the tank and makes the heating less efficient. Another thing that would benefit from longer draining periods would be the draining of condensate. As it is now all condensate will be drained in D1 but not in the shorter D2 and D3.

**Top outlet analysis**

The constant flow out from the top of the tank goes through two valves that restrict the flow with holes with the diameters 1.5 mm and 3.5 mm. When calculating this flow, pressure drop was estimated to only occur in these valves because of their small passages. Calculations, according to Equation 2, of the velocity of the steam and air through these valves are the same and can be seen in the plot in Figure 13. In P1 the rising pressure in the tank will give an increasing flow out of the top towards the atmospheric pressure. In D1 the flow will decrease because of the decreasing pressure in the tank.

After 294 s the increase in velocity will stop because the velocity of sound is reached and the flow will stay choked for the rest of the time. The temperature transmitter that reaches 125 °C last is this one which is a result of the small flow of steam that passed through here. The total mass of the flow calculated as the integral of the flow rate is 3 kg of steam and air mixture with varying composition. This means that not a great deal of air will exit the tank here.

![Figure 13 Velocity of steam out through the top of the tank](image)

The results of the flow calculations show that 14.2 kg of steam condenses P1. This is the same amount of condensate that is drained from the tank in D1. In P2/D2 and P3/D3 these amounts are not the same. 33.9 kg condenses in P2 and 25 kg are drained in D2. In P3 6.1 kg condenses and 3 kg are drained in D3. The explanation to why the masses are so different could be that the time for the discharge in D2 and D3 are too short to drain all the condensate that is formed. It is purposed that adding 10 more seconds to both D1 and D2, up to 30 and 20 s respectively, would result in total draining of the condensate.

The calculations on the flow of steam out of the tank in D1, D2 and D3 show that more than the measured pressure increase in the tank admits exits the tank. This is probably due to the condensate that will act as a constriction for the steam which will result in a smaller flow.

On the basis of the flow calculations out of the tank, the mass of air that is left in the tank was estimated. The result is that 9 kg out of the original 14 kg are still in the tank at the end of the air-removal cycle. If the time of D2 and D3 should be prolonged to take out more condensate it would also have the effect that more air would be drained from the tank.

The flow rate at the top of the tank is too small since the temperature by the transmitter after air filter is increasing very slowly. No significant amount of air will be drained from the top.

The complete work and suggestions for future work can be found in the Master thesis report.

**Acknowledgement**

This work was carried out at as a Master work at Tetra Pak with PhD Fredrik Innings as supervisor, who is gratefully acknowledged along with Prof. Anders Axelsson, Dpt of Chemical Engineering LTH, who was examiner.

**Literature cited**


2 Media Box, http://neworbis.tetrapak.com/irj/portal


