1- Summary

In this article we take a detailed look at heat exchangers systems for batch operations. In these systems, the mass contained in a vessel is pumped through an external heat exchanger for cooling or heating of the mass. For a correct batch system design, many variables come into place and design mistakes are very easily made. In this article we will review all design parameters needed for correct design and layout guidelines for optimal design. Examples will be given that show how an incorrect system setup can lead to unwanted results and how to rectify this.

2- Introduction

Batch heating or cooling systems are found in many places in modern industry (process, food, pharmaceutical etc). In these systems a vessel is filled with content and needs to be heated or cooled in a predefined time period. We can make a distinction between direct heating of the vessel (jacket or internal coil) or indirect heating using an external heat exchanger and a product recirculation pump. See the figure below.

The advantages of using an external heat exchanger are:

- By choosing the correct product recirculation flow it is possible to design a heat exchanger with sufficient high velocity on the product side. This helps to keep the heat transfer rates high and helps to reduce the negative effects of heat transfer fouling. Should fouling be a problem, a system can be designed with a standby heat exchanger (one for cleaning, one for processing), or even a scraped surface heat exchanger can be chosen.
- It is easier to design a setup with large heat transfer area with an external heat exchanger than with a tank, where the limit is defined by the geometry of the tank.
- Existing tanks without a jacket or coil, can be retrofitted to batch heating or cooling systems by adding a pump, heat exchanger and pipe work.
-3- System definition

The next figure shows a detailed setup of a batch system with external heat exchanger.

**Batch procedure:**

- The vessel is filled with product to the desired level. **Mb** is the total batch mass (kg). **Tbi** is the initial batch temperature (ºC). **Tbe** is the desired batch end temperature (ºC).
- The pump is started and product is recirculated. **Fp** is the product’s flow rate (kg/hr).
- Service fluid is fed to the heat exchanger. **Fs** is the service fluid flow rate (kg/hr). **Tsi** is the service inlet temperature (ºC). **Tso** is the service outlet temperature (ºC).
- Slowly the batch is heated up or cooled down (depending on whether we are dealing with a heating or cooling application.) **Tpi** is the inlet temperature to the heat exchanger (ºC). Tpi is equal to the batch temperature. It is assumed that the agitator assures a good mixing and homogeneous temperature of the complete batch.
- When the **Tbe** is reached, recirculation of product is stopped and the vessel content is emptied.
- Instrumentation placed at key points (flow, temperature and level transmitters, **FT**, **TT**, **LT**) makes it possible to monitor the process parameters and control the process.
- It is possible to work with different types of service fluid: **Isothermal** service fluid means working with a fluid that undergoes a phase change. For example steam used for heating. The energy provided to the system is the latent heat of condensation. The exiting condensed steam has the same temperature as the incoming steam. A **non isothermal** service fluid means working with a fluid that is not changing its phase; for example water for heating or cooling that is not brought to boiling or freezing temperatures. The outlet temperature of the water is different than the inlet temperature.
-4- Design guidelines

When designing a batch heating or cooling system, the problem is usually presented in a case similar to the following example:

**Heating of 1 m³ of water from 20 to 90 ºC using superheated water as service fluid.**

**Batch heating time required: 30 minutes maximum.**

For the design of such a batch system there are many variables to play with: Recirculation flow, service fluid flow, is the service inlet temperature fixed or can this be controlled to a desired temperature? What heat transfer area to design with? What is the expected heat transfer coefficient? What are the pressure drop limits for the product and service fluids? Is there any space limitation for installation of the heat exchanger system? What is the total mass of the system (vessel + pipe work + pump + heat exchanger)? Etc.

We will discuss the most important design parameters involved and provide some basic rules that will help the design engineer to come to the best system solution. The key design rules are highlighted with bold letters in blue for clear identification.

**Total system mass**

In a batch heating or cooling system, the material involved in the vessel, piping, pump and heat exchanger will be a part of the heat transfer process. In the example given above, these materials will heat up from 20 to 90 ºC as well. So part of the heat released by the superheated water is absorbed by the surrounding materials. Normally, this percentage of heat absorbed, is much less then the heat absorbed by the batch mass. To illustrate this with an example:

Batch mass:

1000 kg of water, heated from 20 to 90 ºC, specific heat of water: 1 kcal/kg.ºC.

Heat input needed: 1000 x 1 x (90 – 20) = 70,000 kcal.

System mass:


Heat input needed: 430 x 0.12 x (90-20) = 3.612 kcal => 4.9% of the total heat input needed.

The heat input to the system mass is a small fraction of the total heat input. Still, it must be evaluated beforehand what will be the potential heat input loss to elements other than the vessel’s content. This way, surprises in the observed batch heating times can be avoided.

⇒ The correct way is to calculate/estimate the system mass and specific heat and use this input in the batch heating calculation.

**Product recirculation flow, Fp**

Fp is an important parameter. A change in Fp has a direct influence on the batch time needed. It is recommended that during the batch time required the complete batch mass to be pumped through the heat exchanger several times. Imagine a 1000 litre batch with a 1 hr treatment time and a value for Fp of 1000 litre/hr. On average, each litre of product only passes through the heat exchanger one time, so heat is picked up only once. Changing to a 3000 l/hr flow rate, each litre passes three times. A reduction in product flow
rate will mean more heat transfer area needed to meet the required batch time. We have seen cases where a 50% reduction of Fp required the installation of 30% more heat transfer area. In general, the extra investment for heat transfer area is more than the cost saved for a pump with less capacity. Care should be taken in not selecting values for Fp that are too high. This could lead to increased pumping costs. The capital investment reduces but operational costs can exceed the expectations.

⇒ As a general rule we recommend to start designing with a flow rate that will pump the batch mass approximately three times round during the batch time needed.

Service fluid flow, Fs

For the analysis of the service fluid flow we have to make a distinction first between isothermal and non isothermal service fluids. For isothermal service fluids the batch time does not depend on Fs. When steam heating is used, the amount of steam condensed depends on the heat transfer capacity of the heat exchanger: U x A and the temperature difference between the service and the product flow.

\[ U = \text{heat transfer coefficient (kcal/hr.m}^2\text{.}^{°}\text{C).} \]
\[ A = \text{heat exchanger area (m}^2\text{).} \]

As the system is isothermal on service side, the temperature difference between service and product does not change due to a change in service flow rate.

For non isothermal service fluids the case is different. A reduction in Fs can cause a bigger temperature difference between service inlet and outlet temperature. The average temperature difference between service and product will decrease. The heat transfer capacity is affected and the batch time will increase. Also, a reduction in Fs means a reduction in fluid velocity in the heat exchanger. Less fluid velocity means a reduction of the heat transfer coefficient. Again, the batch time needed is affected negatively. To compensate, more heat transfer area must be installed.

Too much service flow means more pumping cost needed, so caution is needed. Also care should be taken to keep fluid velocities within limits in order to avoid tube vibrations in the heat exchanger.

⇒ We recommend starting the design process with values for Fs between two to three times the value of Fp.

Service fluid temperature, Ts

Normally the service fluid temperature is not a parameter that can be changed. Cooling or heating water can be made available from a central system that provides services for various installations in the plant and the temperatures cannot be changed for individual batch system. But a different scenario exists for working with boiler steam for example. Boilers provide steam at pressure of 6 to 8 bar. At the point of steam consumption, the steam temperature can be regulated by installing pressure reduction and or control valves. (6 bar saturated steam has a temperature of 159 °C, reducing it to atmospheric pressure, 1 bar, the steam temperature drops to 100 °C). In general, the higher the steam temperature, the higher the temperature difference between service and product and the shorter the batch times. For a fixed batch heating time, the heat transfer needed for installation can be reduced by increasing the boiler steam pressure/temperature.

But what if the service temperature is so high that overheating of the batch product occurs? At the last moment before reaching the desired batch temperature, the product enters the heat exchanger very close to the end temperature needed and it is very likely that the product exits the heat exchanger at a
temperature that is higher than the desired batch end temperature. This means that part of the batch is over heated and this can lead to dangerous or unwanted situations:

- Product temperatures can exceed boiling point temperatures at the heat exchanger exit.
- Heating above the desired temperature can cause the product to deteriorate.

Similar situations can occur in cooling applications: products can be brought to temperatures below their freezing point. Or the physical properties of the fluid change too much due to temperatures too low. Viscosity can increase rapidly at low temperatures and this will affect pumping cost and heat transfer rates.

To illustrate this with an example:

<table>
<thead>
<tr>
<th>Time</th>
<th>Tp in (T batch)</th>
<th>Tp out</th>
<th>Ts in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hr</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>0.000</td>
<td>20.000</td>
<td>83.212</td>
<td>120.000</td>
</tr>
<tr>
<td>0.049</td>
<td>28.756</td>
<td>86.433</td>
<td>120.000</td>
</tr>
<tr>
<td>0.099</td>
<td>36.745</td>
<td>89.372</td>
<td>120.000</td>
</tr>
<tr>
<td>0.148</td>
<td>44.034</td>
<td>92.054</td>
<td>120.000</td>
</tr>
<tr>
<td>0.198</td>
<td>50.686</td>
<td>94.501</td>
<td>120.000</td>
</tr>
<tr>
<td>0.247</td>
<td>56.754</td>
<td>96.733</td>
<td>120.000</td>
</tr>
<tr>
<td>0.297</td>
<td>62.292</td>
<td>98.770</td>
<td>120.000</td>
</tr>
<tr>
<td>0.346</td>
<td>67.345</td>
<td>100.629</td>
<td>120.000</td>
</tr>
<tr>
<td>0.396</td>
<td>71.955</td>
<td>102.325</td>
<td>120.000</td>
</tr>
<tr>
<td>0.445</td>
<td>76.162</td>
<td>103.873</td>
<td>120.000</td>
</tr>
<tr>
<td>0.495</td>
<td>80.000</td>
<td>105.285</td>
<td>120.000</td>
</tr>
</tbody>
</table>

The design engineer has come up with a solution that involves a steam temperature of 120 °C and a heat exchanger of 1,5 m² and a heat transfer coefficient of 2000 kcal/hr.m².ºC. He calculates a batch heating time of 29 minutes and 41 seconds. He forgets to calculate the product outlet temperatures at the heat exchanger exit. Would he have done that, then this is the table of temperatures that he would have obtained:

After roughly 18 minutes the product outlet temperatures reach values > 100 °C and water will evaporate (a flash occurs) if the tank is operated under atmospheric conditions.

In case the product is injected in the bottom of the vessel in the batch fluid, then gas bubbles can form as part of the product evaporates. This could lead to problems such as unwanted foaming.
By installing a steam control valve it is possible to lower the steam temperature. If the system would have been designed with a steam temperature of 104 ºC and 2.5 m² of heat transfer area the results would be the following temperatures:

<table>
<thead>
<tr>
<th>Time</th>
<th>Tp in (T batch)</th>
<th>Tp out</th>
<th>Ts in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hr</td>
<td>ºC</td>
<td>ºC</td>
<td>ºC</td>
</tr>
<tr>
<td>0.000</td>
<td>20.000</td>
<td>88.134</td>
<td>104.000</td>
</tr>
<tr>
<td>0.053</td>
<td>29.891</td>
<td>90.003</td>
<td>104.000</td>
</tr>
<tr>
<td>0.105</td>
<td>38.617</td>
<td>91.651</td>
<td>104.000</td>
</tr>
<tr>
<td>0.158</td>
<td>46.316</td>
<td>93.105</td>
<td>104.000</td>
</tr>
<tr>
<td>0.211</td>
<td>53.108</td>
<td>94.388</td>
<td>104.000</td>
</tr>
<tr>
<td>0.264</td>
<td>59.100</td>
<td>95.520</td>
<td>104.000</td>
</tr>
<tr>
<td>0.316</td>
<td>64.387</td>
<td>96.518</td>
<td>104.000</td>
</tr>
<tr>
<td>0.369</td>
<td>69.051</td>
<td>97.399</td>
<td>104.000</td>
</tr>
<tr>
<td>0.422</td>
<td>73.166</td>
<td>98.176</td>
<td>104.000</td>
</tr>
<tr>
<td>0.474</td>
<td>76.797</td>
<td>98.862</td>
<td>104.000</td>
</tr>
<tr>
<td>0.527</td>
<td>80.000</td>
<td>99.467</td>
<td>104.000</td>
</tr>
</tbody>
</table>

The total batch heating time is just a little over 30 minutes but the exit temperature of the product has not exceeded the boiling point.

A better solution to the problem would be to change the pump and work with a higher product recirculation flow rate. By doubling the flow rate to 6000 kg/hr we can lower the heat transfer area to 1,1 m² and still avoid overheating of the product:

<table>
<thead>
<tr>
<th>Time</th>
<th>Tp in (T batch)</th>
<th>Tp out</th>
<th>Ts in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hr</td>
<td>ºC</td>
<td>ºC</td>
<td>ºC</td>
</tr>
<tr>
<td>0.000</td>
<td>20.000</td>
<td>50.696</td>
<td>120.000</td>
</tr>
<tr>
<td>0.051</td>
<td>28.756</td>
<td>56.764</td>
<td>120.000</td>
</tr>
<tr>
<td>0.102</td>
<td>36.745</td>
<td>62.301</td>
<td>120.000</td>
</tr>
<tr>
<td>0.153</td>
<td>44.034</td>
<td>67.353</td>
<td>120.000</td>
</tr>
<tr>
<td>0.204</td>
<td>50.686</td>
<td>71.962</td>
<td>120.000</td>
</tr>
<tr>
<td>0.255</td>
<td>56.754</td>
<td>76.168</td>
<td>120.000</td>
</tr>
<tr>
<td>0.306</td>
<td>62.292</td>
<td>80.006</td>
<td>120.000</td>
</tr>
<tr>
<td>0.357</td>
<td>67.345</td>
<td>83.508</td>
<td>120.000</td>
</tr>
<tr>
<td>0.408</td>
<td>71.955</td>
<td>86.703</td>
<td>120.000</td>
</tr>
<tr>
<td>0.459</td>
<td>76.162</td>
<td>89.618</td>
<td>120.000</td>
</tr>
<tr>
<td>0.509</td>
<td>80.000</td>
<td>92.278</td>
<td>120.000</td>
</tr>
</tbody>
</table>

At 6,000 kg/hr the total batch mass is pumped three times around in the batch period of 30 minutes. This coincides with the recommendation given in the previous analysis of the product recirculation flow.

⇒ We strongly recommend always checking the product’s outlet temperature at the heat exchanger and making sure that it stays below maximum acceptable values.
**Heat transfer coefficient and heat transfer area, U and A**

These two parameters are closely related in the design process. Normally product and service flow rates are defined first and then the heat transfer calculation is performed. This can be a manual calculation or a calculation done by specialized heat transfer software. Based on process conditions and product and service physical properties, the heat transfer coefficient is calculated first. With U known, a value of A is chosen such as to meet with the desired batch treatment time. Values of A that are too high will lead to expensive heat exchangers. The choice can then be made to change the process conditions so that U will increase and A can be reduced. Another way of reducing area can be to change the service temperature to get a bigger difference between service and product. As we have seen in the section before, this can lead to an unwanted situation, so caution is needed.

It is important that the heat transfer coefficient is calculated with the right parameters. Physical properties can change with temperatures.

- For fluids with stable physical properties over the temperature range, a good approximation is to calculate U at the middle temperature of the batch process.
- For liquids with varying values the recommendation is to calculate U for the start and end conditions of the batch process and then calculate the average U value of the two, to be used in the batch time calculation.

Examples of systems with changing U values:

- Batch heaters using steam will show higher heat transfer coefficients at the end of the batch than at the beginning. Steam consumption is higher in the beginning (higher dT between product and service) and the product's viscosity is normally lower when it is cooler. High steam loadings and increased viscosity cause lower heat transfer coefficients.
- Batch cooling application can show big changes in viscosity of the product. This is often seen in food industry application with products such as sauces or honey, the increased viscosity at the end of the batch cooling process not only reduce the heat transfer coefficients. The extra pressure drop will require more pumping power to keep the recirculation flow at the desired flow rate. Special care should be taken in the selection of the pump for these applications.

**Space limitations**

From an investment point of view, tubular heat exchangers for batch processes are best designed long with less shell diameter then short and with bigger shell diameter.

- If there are no space limitations then aim for tubular heat exchangers with longer lengths.

For plate heat exchangers the situation is different as these are very compact by nature and can be designed in much smaller spaces. However, certain applications require tubular heat exchangers. If space is limited then there are alternative solutions:

- **Multi pass heat exchanger**: For example, two passes of three meters length instead of one pass with six meters length: Three meters of space is saved. Four passes of one and half meter of length would save four and a half meter of floor space. Multi pass design is often the right choice with isothermal service fluids. For these systems the temperature profiles do not cross (in a heating application this means that the product outlet temperature is always less than the service outlet temperature). For non isothermal system caution is needed. Often, for heating applications, the product outlet
temperature is higher than the service outlet temperature and we have a temperature cross situation. Multi pass units with a temperature cross are far less efficient than a single pass heat exchanger for the same temperature profiles. To avoid temperature crosses we can choose to work with higher product and service flow rates. This will reduce the temperature increase of both product and service as the flow through the heat exchanger.

⇒ Multi pass heat exchangers are a good solution for batch applications with isothermal service fluids.

⇒ For batch systems with non isothermal service fluid, avoid temperature crosses as much as possible.

- If multi pass units are not an option, then a design can be laid out with various single pass heat exchanger modules in series, joined together with interconnecting bends. This way, the combined setup can provide the total thermal length needed in pure counter current flow in a smaller space. The maximum module length is defined by the space limitations.

⇒ Single pass modules with reduced lengths, connected in series, are a good solution for batch applications with temperature crosses and space limitations.