Economic optimization of heat exchangers for corrosive environments

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Abstract:
Heat exchangers play a key role in power generation and many industrial processes. In various applications, the construction material is however exposed to a corrosive environment. This requires the device to be made from expensive corrosion resistant materials, causing the cost of the heat exchanger to increase significantly. One alternative could be to use more readily available metals (e.g. carbon steel). Although it might have to be replaced several times over its lifetime, the material cost of the heat exchanger would be more economical. In order to investigate if this is a viable alternative, a model was made. This model calculates the total cost of ownership (TCO) of a heat exchanger, taking into account the investment costs, maintenance costs and operational costs. A corrosion model is implemented allowing to specify the behaviour of a certain material in the fluid it is exposed to. Furthermore, the model allows to optimize the design to achieve a minimal TCO for a specific case. As a demonstration, the model is applied to the design and selection of an 5 MW heat exchanger for a binary geothermal power plant in Belgium, where the (corrosive) geothermal brine is used to heat water for a district heating network and an organic Rankine cycle.

Keywords:
Heat exchanger, Corrosion, Cost optimization, Geothermal energy.

1. Introduction

Heat exchangers are devices used to transfer thermal energy from one fluid to another over a heat transfer surface. In many different industries (e.g. the oil and gas industry, the chemical and pharmaceutical sector, petroleum refining and the pulp and paper industry), they are part of the production process [1]. Therefore, a reliable operation is necessary.

In many of these industries, the fluids which the heat exchangers are exposed to, create an aggressive or corrosive environment. A heat exchanger constructed of an inappropriate material will be subject to corrosion. It has been shown that this has and adverse effect on the performance of the heat exchanger [2]. The formed corrosion products create an additional thermal resistance and increase the pressure drop over the device. Consequently, the efficiency of the production process will decrease and the operational costs will increase. Furthermore, if degradation of a heat exchanger advances to an excessive extent, leakage of the fluid (either to the other fluid or to the environment) can occur. In this case, high economic losses will ensue, comprising (but not limited to): replacement of corroded equipment, loss of product, health issues and environmental contamination. In fact, it was calculated in 1998 that corrosion of heat exchangers in the electrical power industry in the USA are responsible for $855 million of losses annually [3].

To prevent corrosion in heat transfer equipment, several solutions are available. When temperatures and pressure are sufficiently low, heat exchangers can be constructed out of polymers (or composites) [4]. A different option is the application of coatings [5]. Coatings are typically classified into three categories: metallic coatings, organic coatings and inorganic coatings. In the case that temperatures and pressures are too high and no coatings are available, an appropriate metal needs to be selected. Metals like titanium or highly-alloyed stainless steel types are then often considered. Because of a higher material cost and a lower machinability, this will however have an impact on the price of the heat exchanger [6].

One alternative approach would be to construct the heat exchanger of a material that could exhibit a relatively high corrosion rate. While this device, made from e.g. carbon steel, might need to be replaced or maintained more often, it would have a considerably lower purchase cost, compared to the same heat exchanger constructed from e.g. titanium. To investigate this approach, a model was developed to calculate the total cost of ownership (TCO) of a heat exchanger. In the current paper, the three main components of this model (i.e. the heat exchanger model, the corrosion model and the cost model) are discussed. Finally the use of the model is demonstrated with a case study involving a heat exchanger for a geothermal power plant.

2. TCO-model

2.1. Heat exchanger model

The goal of the heat exchanger model is to accurately assess the performance of the device when the heat exchanger dimensions and the properties of the flow are given. Since shell-and-tube heat exchangers are common in industry (especially in high pressure and temperature conditions), the model is currently only developed for this type of heat exchangers. To estimate the convective heat transfer coefficient and the pressure drop on the shell-side, the Bell-Delaware method is used [7]. For the tube-side, the correlations proposed by Gnielinski are implemented [8]. The reader is referred to a previous publication for more information about these calculations [9].

2.2. Corrosion model

Several types of corrosion exist and most of these have caused already heat exchanger failure [2]. The types of corrosion can broadly be divided into two categories: uniform corrosion and localized corrosion [5]. Common examples of localized corrosion are pitting corrosion and crevice corrosion. Both uniform and localized corrosion can cause the breakdown of heat transfer equipment. With uniform corrosion, the thickness of the wall will gradually reduce, increasing the leakage probability and posing a danger to the strength of the tube. Pitting corrosion on the other hand, will barely influence the tube thickness, but can locally cause a penetration of the heat transfer surface or to the exterior. Of both types of corrosion, only uniform corrosion is reported to have a significant influence on the heat exchanger performance.

2.2.1. Uniform corrosion

Uniform corrosion is taken into account by a gradual reduction of the tube thickness. In the model, it is assumed that the corrosive fluid flows inside the tubes, which means that the inside diameter of the tubes will gradually increase. The uniform corrosion rate CR, can be a function of temperature T, velocity u_t, pressure P_t, wall roughness e_t and the thickness of the existing corrosion layer t_c. The user of the model should specify this corrosion rate based on experiments. For the case study described in the next chapter, a fixed corrosion rate of 0.3 mm/y was chosen.

$$CR = \mathrm{f}(T_t, u_t, P_t, e_t, t_c) \tag{1}$$

The uniform corrosion process will also result in the formation of corrosion products. These products typically have lower density (and a lower thermal conductivity) than the base metal, which will have a decreasing effect on the inner diameter of the tube. Therefore the behaviour of the inner diameter is depending on the density of both the base metal and the corrosion products and also on the amount of corrosion products that adhere to the wall. If all corrosion products dissolve in the flow, then the inside diameter will be the same as the metallic diameter and increase over time. On the other hand, if a layer of corrosion product (with a thickness t_c) forms, the effective inside diameter $d_{i,e}$ will be smaller than the metallic diameter ($d_{i,e} = d_{i,m} - 2 \cdot t_c$). To characterize the behaviour of the corrosion products and combine the density of the corrosion products and the tendency of the products to form a layer, a relative density factor γ is defined. This factor is defined as the density the corrosion products would need to increase the volume of the corrosion layer with the same volume as with the real density and the real tendency to adhere, assuming all corrosion products contribute to the formation of a corrosion layer, relative to the density of the base metal. As is illustrate in Fig. 1, a relative density of zero, would mean all corrosion products dissolve in the flow and tube thickness only decreases. With $\gamma = 1$, the corroded base metal is replaced by corrosion products, without having an influence on the tube inner diameter and with $\gamma > 1$, the corrosion process would cause the tube inner diameter to decrease over time. Additionally the thickness of the corrosion layer also has an influence on the roughness of the tube inside surface, consequently influencing the heat transfer rate and the pressure drop. To take this into account, the relationships between roughness and friction factor deduced by Moody are used [1].

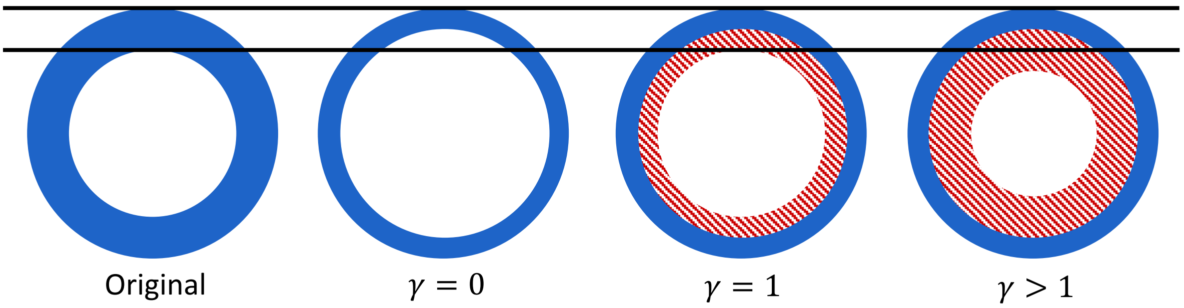

Fig. 1. Illustration of the relative density factor γ (blue = base metal; red = corrosion products).

2.2.2. Pitting corrosion

Although the impact of localized forms of corrosion on the tube diameter, the heat transfer rate and the pressure drop is limited, a pitting model is still implemented to be able to evaluate the TCO of e.g. stainless steel heat exchangers. The results of the pitting model are used to determine when the affected tubes need to be replaced. For this, a statistical model was implemented, based on the publication by Valor et al. [10]. In this paper, equations are proposed to estimate the mean pit depth as a function of time. In the TCO-model, the heat exchanger is replaced as soon as the mean pit depth reaches a predefined threshold. The relevant parameters in this model should be determined by experimental measurements. An example of the probability distribution of the pit depth and of the evolution of the mean pit depth can be seen in Fig. 2.

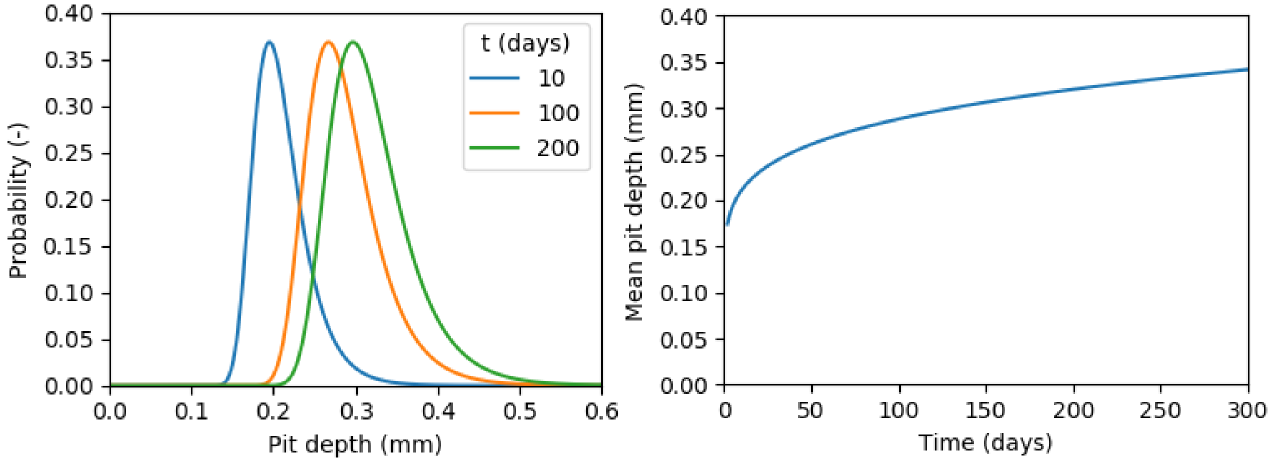

Fig. 2. Pit depth distribution for various times (left) and evolution of the mean pit depth (right).

2.3. Cost model

The model calculates the total cost of ownership (TCO) for the lifetime of the heat exchanger. For each month of this lifetime, the performance and the costs are evaluated and a discounted cost is added to the TCO. This monthly cost is comprised of three components: the investment costs, the operational costs and the maintenance costs.

2.3.1. Investment costs

The method developed by Taal et al. [11], shown in Eq. (2), is applied to determine the investment costs. This cost C_{inv} (€) is dependent on the heat transfer surface area A (m²) and the construction material. For each material, different coefficients C_1, C_2 and C_3 are chosen, listed in Table 1. This investment cost is added to the total cost at the beginning of the simulation and each time the corrosion model determines that the heat exchanger needs to be replaced.

$$C_{inv} = C_1 + C_2 \cdot A^{C_3} \tag{2}$$

Table 1. Coefficients used to calculate the heat exchanger investment costs [11].

Material (shell-tube)	C_1	C_2	C_3
Carbon steel (CS) – CS	7000	360	0.8
CS – Stainless steel	8500	409	0.85
CS – Titanium	14000	614	0.92

2.3.2. Operational costs

As postulated by Eq. (2), a smaller heat exchanger would have a low investment cost. However, the pressure drop of a compact device is typically higher, requiring higher pumping power. This pumping power is translated to an operational cost with Eq. (3). In this equation, ΔP is the pressure drop, V is the volumetric flow rate, η is the efficiency of the pump, c_E is the cost of electricity and T is the considered operational period (in this case, this is one month). The subscripts t and s, respectively, refer to the tube-side and the shell-side. The pressure drop is depending on the state of the heat exchanger (tube diameters, wall roughness, corrosion layer). This state is determined for each time step. After the calculation of the pressure drop and the corresponding C_{op}, the maintenance costs for this time step are determined.

$$C_{op} = \left(\frac{\Delta P_t \cdot V_t}{\eta_t} + \frac{\Delta P_s \cdot V_s}{\eta_s}\right) \cdot c_E \cdot T \tag{3}$$

2.3.3. Maintenance costs

During the lifetime of the heat exchanger, several actions might be required. When, due to uniform corrosion, the heat transfer rate drops below a certain threshold or the pressure drop reaches excessive levels, a cleaning operation is applied. A predefined cleaning cost is then added to the maintenance costs of the corresponding month. It can also occur that the tube thickness is too low (uniform corrosion) or the mean pit depth is too high (localized corrosion). In this case, a cleaning action can no longer solve the problem, so the heat exchanger needs to be replaced. The original investment cost is then discounted and taken into account. The decision if the heat exchanger needs to be replaced (REP, *0* or *1*) or cleaned ($CLEAN$, *0* or *1*), is depending on the tube (metallic) wall thickness t_m, the tube-side velocity u_t, the pressure drop ΔP_t and the heat transfer rate Q. Their values are depending on the state of the heat exchanger, determined by the corrosion model for each time step. The functions in Eq. (4) and (5), are defined by the user of the model. They can be as simple as e.g. $t_m < 1mm$. After the cleaning or replacement, C_{maint} is added to the total cost and the model advances to the next time step, where the corrosion continues.

$$REP = \mathrm{f}(t_m) \tag{4}$$

$$CLEAN = \mathrm{f}(REP, u_t, \Delta P_t, Q) \tag{5}$$

$$C_{maint} = C_{rep} \cdot REP + C_{clean} \cdot CLEAN \tag{6}$$

3. Case study

One example of an application of heat exchangers in a corrosive environment, are geothermal power plants. In Belgium, VITO has recently drilled several wells of approx. 3.5 km deep [12]. At these wells, a geothermal brine is present at a temperature of 128°C. With this brine, a district heating network can be supplied or electricity can be produced. This brine has, however, a salinity of around 165 g/l (about four times the salinity of seawater) and high gas content (mainly carbon dioxide) [12].

Below, it is demonstrated how the model can be used to design a 5MW heat exchanger for this geothermal plant. The brine (43.5 kg/s) is used to heat water with a return temperature of 70°C (38.0 kg/s). In all presented results, it is assumed that the equipment should operate for a period of 20 years. There is a yearly interest rate of 10% and the cost of electricity is fixed at 5c€/kWh.

3.1. Corrosion model demonstration

Firstly, only carbon steel is considered. For the simulations, a uniform corrosion rate of 0.3 mm/year is assumed [13]. A relative density factor $\gamma = 1$ is used and the heat exchanger is cleaned when the heat transfer rate decreases with 30% or the pressure drop increases with 50%. As soon as the tube thickness drops below 1mm, the heat exchanger is replaced with a new device.

In Fig. 3, the evolution of the TCO of two different heat exchanger designs can be seen. Some design data of both devices is listed in Table 2. As can be observed, their purchase cost and the TCO are approximately the same. There are, however, some differences in the evolution and composition of the TCO, caused by e.g. the different tube diameter d_o. The smaller diameter (and consequently smaller tube thickness) of heat exchanger A, leads to higher operational costs (higher pressure drop) and a higher investment cost (the tubes need to be replaced more often). But since the tubes are replaced more often, the need for cleaning is less frequent, which is translated to a lower maintenance cost.

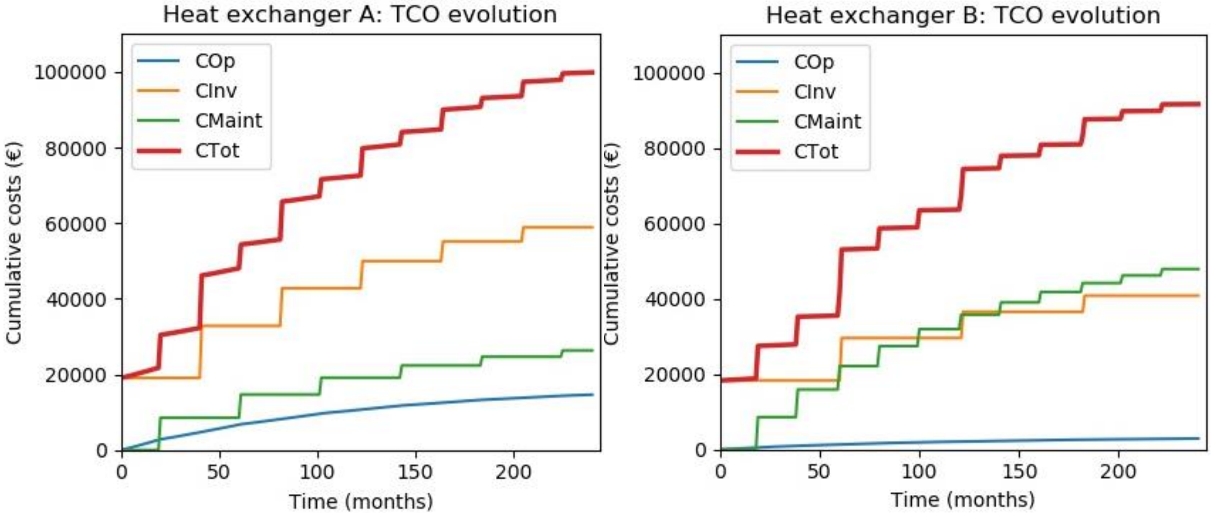

Fig. 3. Evolution of the TCO of two heat exchangers delivering the same heat duty (COp: operational costs; CInv: investment costs; CMaint: maintenance costs; CTot: total TCO).

Table 2. Dimensional data of the simulated heat exchangers.

	D_s *(m)*	d_o *(mm)*	*L (m)*	*B (m)*	N_t *(-)*
HEX A	*0.75*	*20*	*3.1*	*0.38*	*417*
HEX B	*1.0*	*25*	*2.0*	*1.0*	*474*

3.2. Design optimization

In the previous section, two possible designs are compared. However, by varying the geometric parameters over a set of values, a multitude of combinations are possible. By evaluating the TCO of all possibilities, an optimum design can be chosen. In literature, several publications can be found using optimization algorithms (like e.g. genetic algorithms [14]) to find the design with the lowest TCO. A different approach was chosen for this study. Instead of using an optimization algorithm, the entire design space is evaluated. Although the calculation time is increased, the current computers still allow a reasonably fast simulation time. With this method, not only the optimal design is found, but also the relationship between parameters and the TCO can be investigated afterwards. This way, guidelines for making a good design can be proposed to manufacturers. In Fig. 4, for example, the distribution of the TCO for different tube diameters demonstrates that an optimum can be found around shell diameters of 1m.

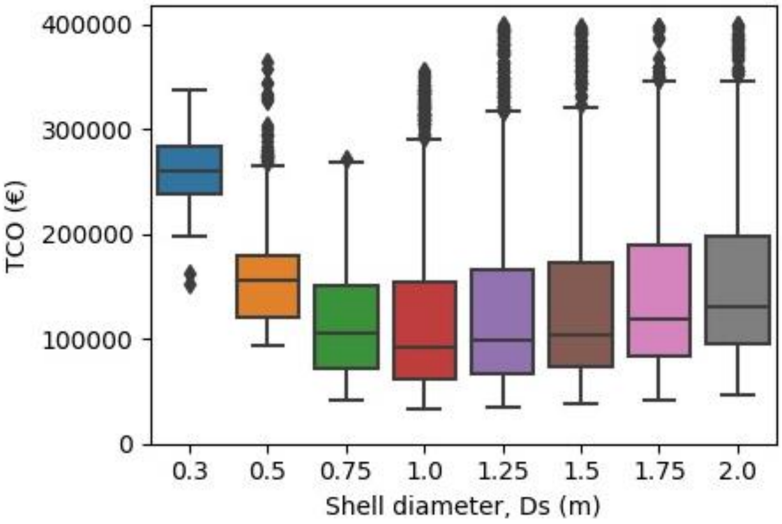

Fig. 4. Distribution of the TCO for different shell diameters.

3.3. Material comparison

Where in the previous example only carbon steel was considered, it is also possible to evaluate the TCO of heat exchangers with other materials. In Fig. 5, the TCO of carbon steel, stainless steel and titanium heat exchangers with the same dimensions are compared. For stainless steel, the pitting model described above is used, where, as soon as the mean pit depth reaches 0.45mm, the heat exchanger is replaced. Also titanium is considered, where it is assumed that no corrosion occurs at all.

It can be observed by the value at 0 months that the carbon steel heat exchanger has the lowest purchase cost, while the titanium heat exchanger is most expensive. However, since the stainless steel device needs to be replaced 5 times over its lifetime, the TCO of a stainless steel heat exchanger is higher than the one of a titanium heat exchanger. The overall most economical option is in this case the carbon steel heat exchanger, even while considering the number of times it needs to be cleaned or replaced.

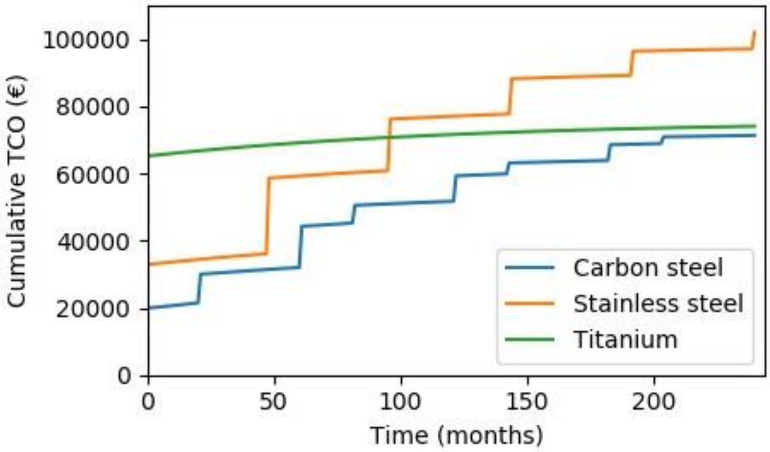

Fig. 5. Comparison of the TCO of a heat exchanger made of carbon steel, stainless steel and titanium.

3. Conclusion

Heat exchangers used in corrosive applications are typically constructed from expensive materials like e.g. titanium. To study if the alternative of using a heat exchanger made of corroding materials which needs to be replaced several times over its lifetime is a viable option, a model was developed.

With this model, the TCO of a heat exchanger can be calculated. The model determines the investment costs, the operational costs and the maintenance costs. The investment costs are estimated based on the heat transfer surface area and the chosen material, while the pressure drop over the heat exchanger is used to calculate the operational costs. To determine the maintenance costs, a corrosion model is implemented which evaluates whether a heat exchanger needs to be cleaned or replaced.

As a case study, the model is used to design a heat exchanger for a geothermal power plant. In the paper, it is demonstrated that the model can be used to optimize the different design parameters. Furthermore, it is shown that it could be beneficial to use a corroding material instead of choosing an expensive, corrosion-resistant material.

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Nomenclature

A	surface area, m^2
B	baffle spacing, m
C	cost, €
c_E	cost of electricity, c€/kWh
CS	carbon steel
d_o	tube outside diameter, m
D_s	shell diameter, m
L	length, m
N_t	number of tubes, -
ΔP	pressure drop, Pa
T	time, months
TCO	total cost of ownership
V	volume flow rate, m^3/s

Greek symbols

η	pump efficiency, -
γ	relative density factor, -

Subscripts and superscripts

inv	investment (cost)
op	operational (cost)
s	shell-side
t	tube-side

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