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D5.2 – Scalability and manufacturability of single phase change HX material

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[1] Dissemination level security:

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CONTENTS

Summary and Scope

This report reviews the manufacturability and scalability of air-cooled heat exchangers, with GeoHex coatings. The following aspects are reviewed:

1. Current manufacturing routes for air cooled heat exchangers (extended fin);
2. Probable manufacturing routes for finned air-cooled condensers.

In practice, single-phase and phase change heat exchangers have the same or very similar geometries and go through the same manufacturing processes. This applies to both plate heat exchangers and shell-and-tube heat exchangers, and therefore Deliverable 5.1 focuses on shell-and-tube and plate heat exchangers, with no distinction necessary between single-phase and phase change conditions.

This deliverable focusses on air cooled condensers, which are specific phase-change heat exchangers. Manufacturing considerations specific to air cooled condensers with GeoHex materials are also considered in this deliverable.

Objectives Met

The deliverable contributed towards the work package objectives:

1. To identify scalability, manufacturability issues with materials developed for phase change heat transfer application for the geothermal sector.
2. To propose alternate route for manufacturing of HXs, if conventional route does not support.

1. INTRODUCTION

For GeoHex to maximise its impact, it is important to consider the final application at an early stage of the project. The objective is to consider how the coating methods fit into the current manufacturing routes of heat exchangers. Manufacturers are unlikely to radically change their existing manufacturing processes, which can be very costly, unless it gives their product added value or significant advantage over their competitors.

GeoHex utilises five different coating processes methods. Two of these methods, physical vapour deposition (PVD), and suspension plasma spray (SPS), are conventionally line of sight methods while the other three methods, electroless nickel plating (ENP), chemical vapour deposition (CVD) and hydrophobic coatings, are known to be non-line of sight. This difference in the coating processes is important for the manufacturing possibilities and routes of coated heat exchangers, especially for tubes and complex shapes.

2. AIR-COOLED CONDENSERS

2.1 Overview

Condensing the organic liquid is a crucial and necessary step in Organic Rankine Cycle (ORC) systems. After being evaporated and passing through the turbine, the organic working fluid needs to be condensed, before continuing along the closed-loop cycle. Air-cooled condensers (ACC) can fulfil this role, and often do, especially when there is no easy access to cold water close to where the ORC operates. The ACC uses the flow of ambient air to cool down and condense an evaporated working fluid inside finned tubes. Usually, the evaporated fluid is at steam phase and the ambient air flow is either forced or induced. A geothermal ORC power plant with ACC setup is shown in Figure 1.

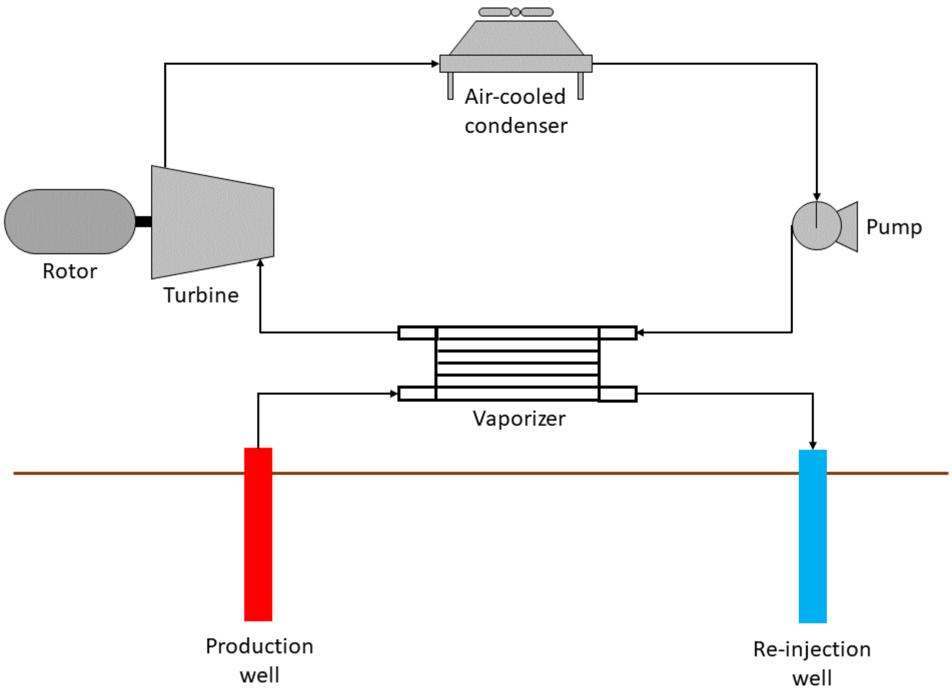

Figure 1: A diagram of a binary geothermal power generation system which utilises an air-cooled condenser for condensing the organic working fluid.

The process set-up of the fluids in the system is shown in Figure 1. The hot geothermal fluid is extracted from underground and used to heat up and evaporate an organic working fluid, which has a boiling temperature lower than water. The organic fluid is often first pre-heated in a single-phase heat exchanger, and then subsequently evaporated in a separate heat exchanger called an evaporator or sometimes vaporiser. Once the fluid is in gas form, it flows towards and through the turbine, generating electricity. Afterwards the fluid passes through an AAC which condenses it. This closes the cycle. The flow of the organic working fluid through the closed cycle is powered using a pump.

The typical air-cooled condenser consists of finned-tube bundles and a fan, along with other necessary components such as a header which brings the organic fluid into the tube bundles. Driver and power transmission are needed to drive the fan unless natural draft is used. A plenum between the fan and bundles is necessary as well using a support structure high enough to allow air to enter beneath the air-cooled condenser at a reasonable rate.

The tube-bundles of the ACC, where cooling and condensation takes place, can be oriented in several ways. The orientation chosen is often a compromise between heat exchange efficiency and usage of ground area. Four different types of orientation are presented in Figure 2.

The most common, especially in larger applications, is for the orientation of the ACC to be horizontal as can be seen in Figure 2 a), where the fan is placed under the tube bundles and thus the draft is forced, or b), where the fan is placed above the tube bundles and thus the draft is induced.

Figure 2 c) shows a horizontal orientation of the ACC. The horizontal orientation takes up the least space while in most cases being the least efficient orientation for heat exchange rate.

Figure 2 d) places the tube bundles at an angle of usually 45-60° to form an “A” shape. The header box which distributes the evaporated fluid into the tube bundles to condense is placed on top of the configuration while the fan is below the tube bundles so that the draft is forced.

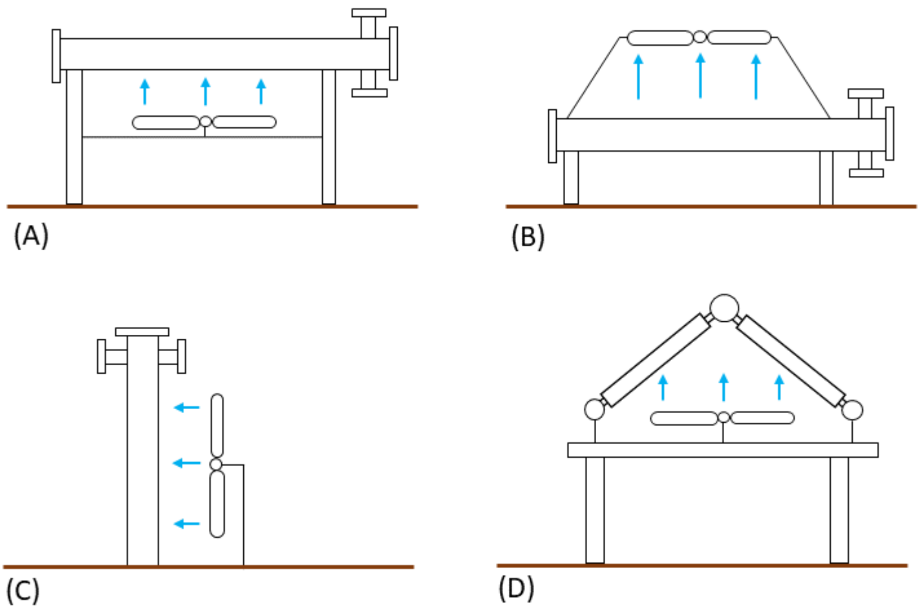

Figure 2: Different orientations of air-cooled condensers.

An alternative and more common way is to orient the tube bundles in a “V” shape, with two header boxes on both top sides of the tube bundles. In that configuration the fan is placed above the tube bundles so that the draft is induced[1]. The “V” shape configuration can be seen in Figure 3. An example of the assembly process for a “V” shaped ACC can be seen in Figure 4.

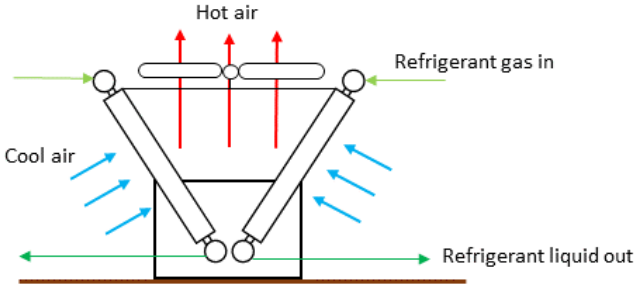

Figure 3: An air-cooled condenser in the "V" configuration.

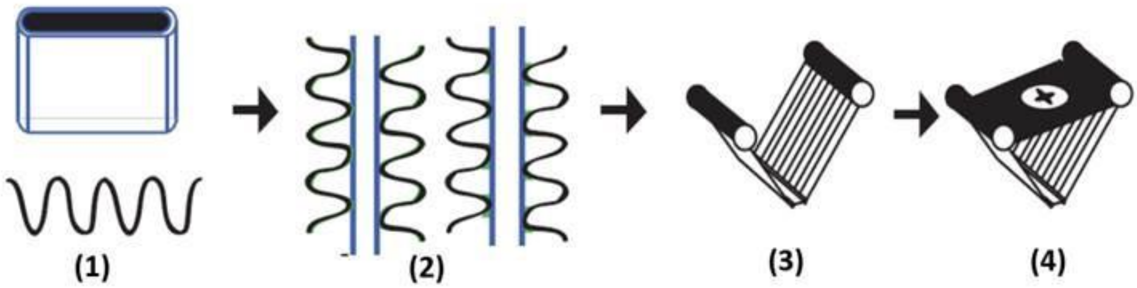

Figure 4: ACC assembly example. (1) Attachment of fins to tubes in a single row by brazing. (2) Tubes assembled into bundles. (3) Two bundles connected to the same header. (4) Fan mounting structure connected between the tubes.

2.2 Finned tube bundles

In ACCs the condensation of the fluid takes place in a tube bundle. These tubes are finned in order to maximise the heat exchange efficiency between the fluid in the tubes and the flowing air outside. Organic fluid vapour, in ORC plants, enters these tubes at low pressure from the inlet header box and travels into the small diameter finned tubes where the condensation takes place (Figure 5). In some configurations there is a venting tube row above the condensing tubes to allow for air extraction. For air-cooled condensers, the main application of coating materials developed in GeoHex is onto the inside of the tubes in the tube bundle, using surface engineered coatings which promote faster drop-wise condensation resulting in lower energy loss within the system.

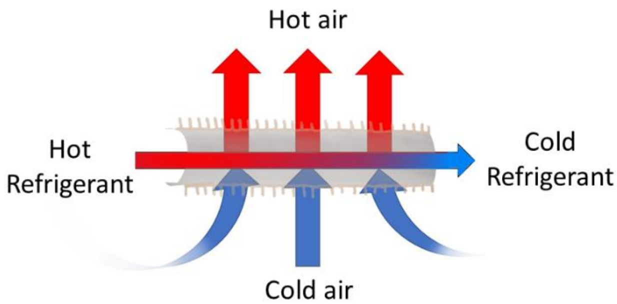

Figure 5: The general principle of the ACC.

An ACC tube bundle is made up of many finned tubes that are placed between two side frames. The tubes are then connected to header boxes on each end. The header boxes can be internally baffled in order for the fluid to take more than one pass through the finned tubes. In horizontal configuration, the inlet and outlet can sometimes be on the same header box but in the case of “V” or “A” configurations, this is not the case, as the condensing fluid moves from the top header down through the finned tube bundle where it condenses and then exits the ACC through the bottom header box[1].

The fins can be made of various metals although aluminium fins are most common. The fins can be solid or serrated and made using welding or tension winding[1]. When the design temperature is lower than 180°C the fin is usually helically wrapped and L-footed while embedded or extruded fins are used when the process temperature is higher. API Standard 661[2] (Air-Cooled Heat Exchangers for General Refinery Service) specification requires cast zinc bands at the ends of the tubes to prevent the unwrapping of the fins when they are helically wrapped.

The tubes themselves are from various materials such as copper, carbon steel, stainless steel, brass or other alloys. Carbon steel or low-alloy steel is most popular, as they can have small diameters, usually from around 1” to 1.5” outer diameters. The wall thicknesses of the tubes vary and are often governed by the pressure and temperature the condenser is designed for. The tubes are generally extruded and often have grooved surfaces. Alternatively, they could be rolled and welded.

Effectively coating the internals of small diameter tubes with 25.4 mm diameter and less is currently only commercially feasible for non-line-of-sight coating processes, as already discussed in consideration to shell and tube heat exchangers in Deliverable 5.1.

2.3 Headers

Headers are boxes at each end of the tube sheets, connected to the tubes, which have the purpose of distributing the fluid to the finned tubes. The tubes are connected to the headers using either welding or expansion. The headers are generally made from carbon steel or stainless steels. The headers themselves are generally welded.

There are many types of header boxes such as plug type, cover plate type, “D” type, completely welded type and manifold type header boxes. The majority of headers are plug type headers. The plug type headers use shoulder plugs at the opposite of each tube which can be easily removed to allow for inspection and, if needed, cleaning of the tubes. The plugs are also used during manufacturing of the tube bundles to access the tube/header joints. Plug type headers are used for low to moderately high conditions[1].

Cover plate headers are often used in processes where fouling or scaling is very severe so that the tube bundle may require frequent cleaning. This type of header has a removable plate on the opposite site of where the tubes connect to it. The cover plate is generally joined to a flange on the header box using bolted connections. Bonnet headers, or “D” type headers, are quite similar to the cover plate type, but instead of the cover plate being removable, the whole header box including the inlet/outlet can be removed[1].

Completely welded header boxes are used for cooling down and condensing clean products and in vacuum conditions. First the tubes are welded into the tube sheets which the header then is welded to. Manifold headers are used in all pressure settings and are quite a popular configuration[1].

2.4 Flat duct air-cooled condensers

An alternative to the fin-tube bundles is the flat duct type of air-cooled condensers. Instead of using finned tubes, they use finned flat ducts as the pathway for the condensing fluid where the heat exchange takes place. These heat exchangers and condensers are generally more compact that the finned-tube version and can be more efficient as well[3].

A flat duct solution, where a header is connected to flat ducts instead of round tubes, is used in Enogia’s ORC equipment with the heat exchangers themselves provided by ThermoKey[4]. The flat ducts are still finned, and the condensation takes place inside channels in the finned tubes. The flat-duct air cooled condensers are assembled via brazing. The header design used is the same as the completely welded header type, although in this case it is brazed.

3. MANUFACTURING OF HEAT EXCHANGERS WITH GEOHEX MATERIALS

3.1 Overview

The manufacturing of heat exchangers with GeoHex materials is discussed in detail in Deliverable 5.1. Specific considerations with regard to air cooled condensers are discussed in this section.

The ACC parts that can possibly have some effect on the application and production of GeoHex coatings inside the ACC tubes are discussed in the Sections 3.2 to 3.5 and summarised in Section 3.6.

3.2 Tube bundle

The tube bundle consists of a series of finned tubes between two side frames or tube sheets, passing between two header boxes at end of each tube bundles. The passing of the cooling medium is circulated via baffles which are connected to the tube bundle on the tube side. Tubes in the tube bundle can be produced in principle via two methods:

1) ***Seamless tube manufacturing.*** The raw steel is first cast into a workable, starting form, ingot. The ingot is then shaped under high pressure into square-shaped billet. The billet is then rolled into a cylindrical shape billet, then put into a furnace where it is heated white-hot. The heat-treated cylindrical billet is then pressed onto a bullet-shaped piercer point that is pushed through the middle of the billet, forming the inner diameter of the pipe. Finally, the billet is rolled in a series of rolling mills and stretched to produce the finished pipe.

2) ***Welded tube*** with (electric flash) welding process (longitudinal or spiral). For a longitudinal welding process (common for a small diameter pipe) a steel sheet is formed into a cylindrical shape. The edges of the sheet are heated until they turn semi-molten, then the edges are forced together and welded to form a continuous joint. Pipes are frequently pickled after the forming and welding process.

For the maximum adhesion and performance on the inner steel surface substrate, surface preparation of the steel must be considered. Cleaning of the surface (remove dust, salts, welding slag etc) and the optimum roughness profile must be considered. Cleaning of a small diameter tube should not be a technical barrier but blasting of the internal surface of the tube to achieve optimum surface roughness could be a technological/cost challenge.

The most common diameter for an air-cooled heat exchanger is 1-inch diameter tube in the tube bundle, which could also be a technological challenge in terms of coating the internal surface of the tubes with the proposed GeoHex coatings. Manufacturing considerations associated with coating the internal surfaces of narrow tubes has been covered in D5.1. The increased diameter of the tubes, more than 1-inch diameter, could mean that it is necessary to make the GeoHex coatings inside the tube surface producible with current manufacturing/coating technology. However, this might not be feasible as heat transfer may be reduced for lager diameter pipes, despite being coated with high performance coatings.

To ensure a leak-free contact between the tubes and the tube sheet, the tubes must either be expanded into the tube sheet (header box) or welded to the tube sheet. During the expansion process, the diameter of the tubes is expanded at the tube-tube sheet joint using inner pressure from a roller which creates plastic deformation in the tube by exerting pressure from the inside[5]. Alternatively, to protect the coated inner surface of the tube, the tube sheet could be subjected to plastic deformation from the outside to form the joint with the tube. The damaging effect on the internal GeoHex coating is probably less for the latter option i.e. by contracting the tube wall by compression from the outside, but the effect of the compression on the integrity of the internal GeoHex coating should not be neglected and coating integrity should be qualified. In the former case, applied heating and pressure on the internal side of the end of the tube can damage the coating if the adhesion is not sufficient or if the coating is brittle. In the case that the tubes are welded to the tube sheet, the heat effect of the welding on the internal GeoHex coating in the low wall thickness tube should be considered.

3.3 Flat ducts

The microchanneled flat ducts are manufactured using extrusion. The channels within the duct are between 25 and 32 mm in width and height. These sorts of channels are well suited to non-line of sight processes, as discussed in Deliverable 5.1. With regards to non-line of sight processes the deposition process is subject to the same considerations as when depositing coatings, internally, on extruded small diameter tubes. Coating considerations related to this were discussed in Deliverable 5.1.

3.4 Fins

The fins are most frequently made of aluminium due to its good thermal conductivity, lightweight and formability. The geometry and production of fins on the tube surface can be through various methods[1]. Extruded fins have typically maximum ability to transfer heat, due to the low contact resistance between fin and the tube. The fins can be brazed, solid, serrated, extruded, tension wound, soldered or welded on the tube surface.

The production of the fins on the tube is considered to have a negligible effect on the GeoHex coating inside the tubes where the formability and workability of the aluminium is good at low temperature. Possible mechanical damage on the internal GeoHex coating is also expected to be negligible during the fin attachment process.

In an environment where SO_2 or H_2S are present, oxidation of sulfuric compounds to sulfuric acid can have a corrosive effect on the aluminium fins. To prevent possible galvanic corrosion between steel tubes and aluminium fins, the fins can be replaced with carbon steel which is galvanised. The zinc coating on galvanised steel is however susceptible to corrosion in an SO_2/H_2S environment, as is also the case for aluminium. In some geothermal areas, these species are present in small quantities in the ambient air and thus can cause corrosion of equipment.

Consideration of diffusion bonding of meshes onto heat exchanger plates for enhanced condensation performance was included in D5.1. Although diffusion bonding has been utilised to produce fin and plate heat exchangers, no references were found related to its usage for the production of finned tubes, let alone finned tubes incorporating mesh structures. Therefore, further development work might be required to allow the manufacture of air-cooled condensers incorporating GeoHex mesh structures.

3.5 Header box

The header box at the end of the tube bundle distributes the process fluid to and from the tubes as described previously. Sometimes the cover plate header includes a removable cover or bonnet if the header is subject to scaling or corrosion of the internal surfaces. However, in ORC applications this issue would not be expected, given the presence of only the working fluid. The cover plate can be welded to the tube sheet plate, fastened with stud bolts, through bolts or installed with a plug depending on the extent of maintenance and nature of the operation.

Heat exchange and condensation mostly takes place within the tube bundles and not the header boxes, the internal coating of header boxes with GeoHex coatings does therefore not need to be considered for ORC applications. However, when used for other applications where the condensed fluid might hold corrosive and/or scaling species, the anti-scaling and anti-fouling GeoHex coatings might prove attractive. For bolted headers, the internal surfaces will be accessible, and therefore coatings could be easily applied. The manufacture of components with GeoHex materials has been covered in detail in Deliverable 5.1.

Detailed design requirements and fabrication of air-cooled heat exchangers are suggested in standard ASTM/API 661[2] (ISO 13706[6]).

3.6 Summary

Key points that should be taken into account for the application of the GeoHex coatings inside ACC tubes and headers are summarised below.

Tubes:

- Tubes with small internal diameters are commonly used in ACCs. These tubes cannot be coated with traditional line-of-sight process without further development, and the design of the tubes, i.e. changes to the internal diameter, might also need to be considered even for non-line of sight processes.
- In the case where tubes are fastened to the tube sheet via tube expansion: For the expansion of tubes into the tube sheet, either reduction of the outer diameter of tubes or expansion of the outer diameter of the tubes can be applied. The damaging effect of the thermal expansion process on the internal GeoHex coatings should be considered. In the case where tubes are fastened to the tube sheet via welding: The heat effect of the welding process on the internal GeoHex coating inside the tube end should be considered.

Header:

- Design of air-cooled condenser with removable headers, coated internally with GeoHex coatings, should be considered to minimise scaling and corrosion effects inside the header box in certain non-ORC applications.

Tubes and Header:

- Surface preparation – cleaning and blasting the internal surface for optimum surface roughness should be considered for the proposed GeoHex coatings in small diameter tubes in air-cooled condensers. The technical and economic viability of such surface preparation requires consideration.

Fins:

- The fin production process is anticipated to have a negligible effect on the GeoHex coatings inside the tubes. Aluminium fins can however be corroded in H_2S containing environments (H_2S can oxidise to sulfuric acid). However, measures can be taken (using scrubbers etc) to control the level of H_2S in the air used to cool the working fluid. Therefore, H_2S corrosion of the fins is unlikely to be of major concern.

4. NON-DESTRUCTIVE EXAMINATION TECHNIQUES APPLICABLE TO GOEHEX MATERIALS

Non-destructive examination techniques applicable to GeoHex materials are discussed in deliverable 5.1.

5. SCALABILITY OF HEAT EXCHANGERS WITH GEOHEX COATINGS

5.1 Scalability of coating and joining processes

All of the joining technologies discussed in this report are already used in production and therefore it is not thought that any scalability challenges will be associated with them for the construction of GeoHex heat exchangers. Similarly, the technologies used for coating delivery are also widely used for production, however the particular coatings will of-course be optimised for application to geothermal heat exchangers. Therefore, aside from the technical challenge associated with production of the high-performance coatings, which is in the scope of GeoHex, it is not thought that any additional scalability challenges will be encountered.

5.2 Scalability of non-destructive testing processes

Scalability of non-destructive testing processes is discussed in Deliverable 5.1.

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