Receiver technology in draught power plants with heat accumulator

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The capacity of receiving the thermal flux into a solar, geothermal or nuclear heat exchanger, further called receiver, and transfer it to the working fluids is analyzed, in regard with the design and manufacturing technology for a gravitational draught power plant. The concept of an all-metal design for the receiver is adopted to enhance the heat flux during the radiative and convective heat transfer. Three different interactions: solar light radiation heating, thermal transfer from geothermal, nuclear reactor or electric heater to the on-flowing air and heat accumulation/restitution during normal and cloudy conditions of work in the solar case are under consideration. A thin wall bladed construction is proposed to maximize the heat exchange area of the solar receiver. The heat accumulation problem is considered when a liquid metal working fluid is adopted and a geothermal heating solution by water in the second version. Surface treatment and finishing in regard to the heat transfer coefficients are emphasized. The manufacturing technology enables a thin double-wall shell to be achieved with a convenient level of reliability and repeatability at relatively low cost per operation. The innovative technology proves reliable enough in regard to the medium working conditions regarding the temperature and to the flow instability.

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State-of-the-art in heat receivers

Technological and manufacturing development of large-scale solar power plants had encountered many technological challenges, ending only in a partial success. Beginning in early 80's with the large "*Solar-One*" demonstrator in California, a number of similar installations were further investigated. All existing solar power plants are based on the same principle of water vapor production to drive turbine generators. The solar-water receiver is thus the main element of the scheme, namely the place where the solar infrared radiation is focused on a thin walled heat exchanger, circulated internally by the working water. The only exception to date is the *Solair* European power plant in Spain, where a solar-air receiver is used (Fig. 2), with a second heat exchanger downwind, producing a *double-losses* scheme (Fig. 1). Reserve heat is accumulated sometimes (*Solar-One*) into liquefied nitric salts at about 500-600ºC which are stored into isolated containers and used to reheat the water during cloudy or night periods. A 60% increase of efficiency in electricity generation is thus obtained.

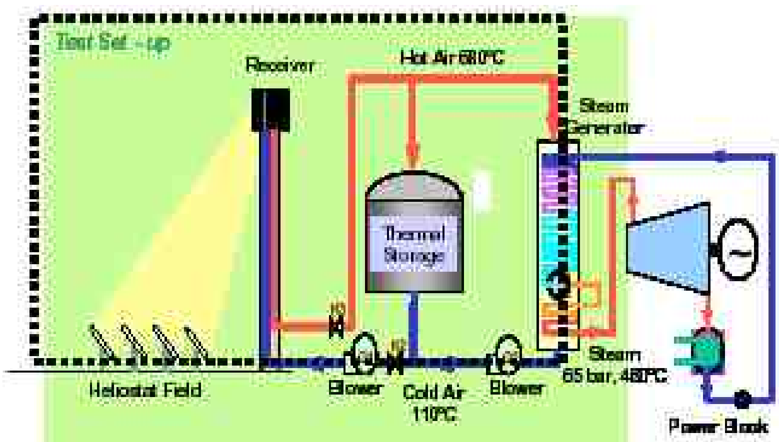


Fig. 1. *Solair* experimental double heat exchanger scheme[8].

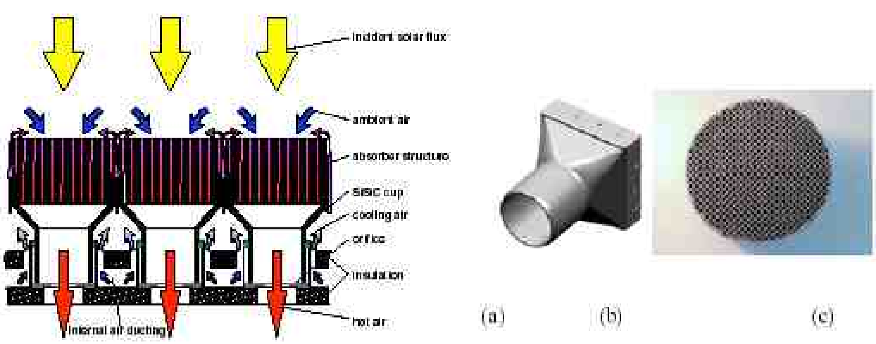


Fig. 2. *Solair* ceramic solar-air heat receiver/exchanger[8].

Dual solar-geothermal operating mode

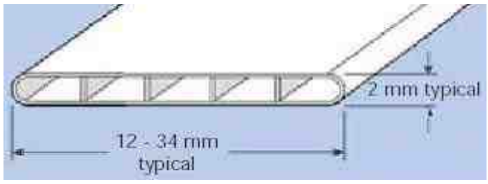
The directly dependent efficiency of solar generators from the insolation behavior is an intrinsic drawback of the solar technology[2] that must be overridden. The extant solution is based on the heat accumulator in the form of a large heat reservoir containing molten salts with high specific heat. These molten nitrates must be kept at temperatures over the melting point (334º*C* for the potassium salt) and their cooling produces icing and blockage of the piping system. Additionally, these salts are extremely hazardous due to their chemical instability and to the high oxygen content. Contaminated with small quantities of organic materials they may detonate with extreme violence. A replacement is thus considered here under the form of a liquefied metal. The role of the accumulator agent is to retrieve its heat content to the working air during sunlit interrupts due to clouds. *Solar Two* power plant in Nevada was the first facility to use molten salts, a combination of 60% *sodium nitrate* and 40% *potassium nitrate*, as an energy storage medium instead of water or oil, as previously used. The molten salts allowed the energy to be stored in large tanks for future use such as at nighttime. *Solar Two* was decommissioned in 1999. Note that it used a steam turbine generator to produce electricity, a not so highly performing solution as seen.

A sensible improvement is introduced now by the all-air, cold high expansion turbines acted by the gravitational draught within the Romanian SEATTLER project, where the air heated by the mirror concentrator is the working fluid itself. The performance is still enhanced through heat accumulation into a liquid metal working fluid, more reliable than the molten nitrates. The receiver had to secure a good heat transfer three-fold: (1) *solar radiation to wall*, (2) *warm liquid to cold wall or warm wall to cold liquid*, (3) *warm wall to the air*. Electric emergency heating is provided for melting of the accumulator metal.

There are three basic equations in the overall heat transfer process: air-side convective heat transfer (between the walls and the working air), heat transfer by conduction (between the walls and tubes) and accumulator-side heat transfer (into the tubes to the refrigerant/coolant). Because the air has a low conductivity, heat capacity and radiative absorption coefficient, overall heat transfer is decided by the air-side part of the equation, a limitation common to both plate-tube and microchannel heat exchangers. Consequently, a great deal of research has been dedicated to improving air-side heat transfer through modification of walls general geometry, surface micro-geometry and surface finishing technology. Such modifications include louvers, lances, rippled edges, sandblasting, eloxation and powder coating. One of the difficulties in regard to the active air circulation into a transfer channel stands in the conflicting effects regarding heat transfer performance on one side and air drag of the channel on the other. Row surfaces enhance the thermal flux while increasing the air drag. Prominences in the local geometry do the same. When infra-red radiation is involved, a direct visibility of the surface requires further a specific optimization of the geometry.

A compromise must be found. The heat conduction part of the energy depends heavily on the bond between the walls and the tube. In fin-tube heat exchangers, that bond is created when hairpins are expanded. If the tubes are loose into the walls, (either from improperly folded panels or splits in the walls material due to over expansion) air gaps between the tubes and the plates reduce the heat transfer. With microchannel heat exchangers, an implicit bond is created by extruding or milling first the channels directly into the plates.

Fig. 3.
Extruded microchannel [19].



At least brazing must be used in all other situations to create a mechanical bond when the two parts come separated. Thus the possibility for air gaps to reduce heat transfer is eliminated.

The accumulator-side heat transfer occurs at the boundary between the coolant/heater and the internal surface area of the receiver, known as the "wetted inner perimeter." In general, as the internal surface area of a tube increases, the accumulator side heat transfer increases. For fin-tube heat exchangers, internal surface area of the receiver can be increased by adding groves to the inside of the tubing. For microchannel heat exchangers, internal surface area is increased by two methods: one, increasing the number of microports in each cross section of the tubes, and two, increasing the number of tubes in each receiver (decreasing the tube spacing). The fin-tube technology has particular challenges when the solar radiation is used. A maximal area of the receiver must be exposed to the direct solar radiation, condition that enters in conflict with the large air-side interface area requirement. A comparison of known solutions is given in figure 4.

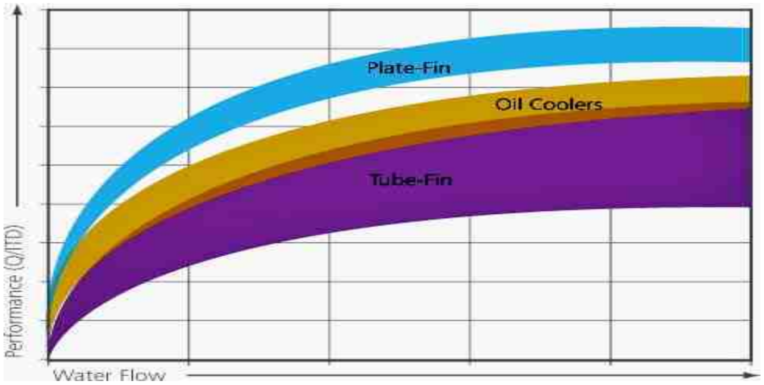


Fig. 4. Comparative efficiencies of different receiver technologies [20].

The geothermal energy will be used as an alternative to heat accumulation, separately or simultaneously with the solar energy. The ADDA receiver design will cover in one piece this dual mode operation. The main thermal parameters considered for establishing the technology of the SEATTLER receiver are:

Nominal speed of air within the heat exchanger $v = 30\ m/s$;

Maximal air temperature at receiver exit $t_a = 200^\circ C$;

Maximal temperature of receiver walls $t_w = 600^\circ C$;

Nominal air pressure level below 1 *atm*.

The nominal thermal and mechanical loads are quite small, which apparently simplifies the technology. The technology must face however a higher emergency temperature in case of failure in the automatic flow control system. It will focus on a good mix of geometry and surface finishing for maximal heat retrieval from the caloric radiation, with a minimized albedo for reduced heat losses. The previous *SolAir* receivers were affected by an efficiency of only 74%, due to large retro-radiation effects at the working temperatures of about 700º *C*. The ADDA low temperature solution profits of black eloxation finishing and powder coating technology to achieve a very low surface albedo.

A nuclear heat source is a possible alternative to the geothermal heating.

Prominent walls heat exchanger

The finned tubing or prominent walls heat exchangers went through minor changes for years, yet a great deal of technological research has been focused on improving their heat transfer performance. In the tower application the receiver has a significant impact on the efficiency of the power plant, under the challenging conditions of the triple heat transfer capacity, mentioned above.

For example, the receiver performance must comply with the 13 SEER standard that went into effect in January. New solutions were introduced for example by York International, Unitary Products Group, York, Pa., using microchannel heat exchangers[9]. They are coils supplied by Delphi Thermal & Interior, Lockport, N.Y. Microchannel heat exchangers have flat, streamlined tubes. Some times one larger tube is split into multiple smaller, parallel ports. The manufacturing technology of finned tubes varies from *brazed* to *welded* or *embedded* or *soldered*. The fins are usually transversal, but in the receiver case the fins are to be longitudinal, for easy airflow considerations, and a specifically designed technology of manufacturing.

Following the history of tubing walls powerful heat exchangers it is observed that the technology of tubular walls was also applied in the extreme case of liquid propellant rocket engines as well[11]. The technology was borrowed from the industrial boilers on its turn. As mentioned, an older Aerojet Corporation engineer observed in early 1947 that the central utility power plant in their research center used that type of construction in their boilers[10].

A demonstrative example of a tubular wall for the very large heat transfer rates in liquid propellant rocket motors is given in figure 5. While in this area the technology required sophisticated precautions due to the complex curved shape of the tubes, for the ADDA receiver with a flat shape the problem is much simpler.

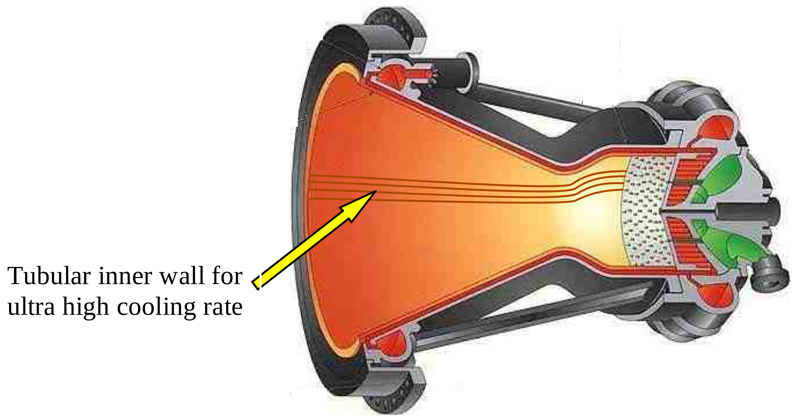


Fig. 5. Ultra high cooling rate tubular wall construction for LRE[14].

In an early Thiokol Chemical Corporation patent[11] it is argued that the aim of the inventions was “to provide an improved wall construction for the combustion chamber and exhaust nozzle side walls, whereby efficient operation of the motor is obtained through the use of higher operating pressures made possible by increased structural strength.

Another object of the patent is to provide a combustion chamber and exhaust nozzle of considerably lighter weight and reduced physical size than has heretofore been possible in motors of equivalent thrust output”. The applicant also simplified the chamber, where the parts were reduced to a minimum. The durability of such an engine in repeated operation was increased, handling and shipping simplified, and ease in which the longitudinal tubular walls could be replaced. Another advantage was the lightweight structure of the burner. Under the disadvantages first must be mentioned that the soldering/brazing used to bond mechanically the tubes along the most loaded lines weakens the part’s resistance.

The patent covered possible construction techniques, like “*solder, weld, or braze each cooling tube to its adjacent tubes in order to seal the gases within the thrust chamber to act as structure to help resist the bursting forces*”. The tubes were to be made of easily formed material of high heat conductivity such as copper or aluminum and are formed by the use of common forming dies with concurrent application of internal pressure to prevent collapse of the tube[13]. This led to the design of "tubular wall" thrust chambers, widely used for the vast majority of US rocket engine applications. These chamber designs have been successfully used for the Thor, Jupiter, Atlas, H-1, J-2, F-1, RS-27 and several other Air Force and NASA rocket engine applications. The primary advantage of the design is its lightweight and the large experience.

Technology of plate-tubes heat exchangers

Far of being so highly loaded, the heat exchangers of the tall tower facilities could better answer the requirements when follow the same reasoning as in the rocket engine case. We refer to a fast response due to the thin wall construction and a very good conductivity of the walls of the receiver itself. Corrosion resistance is important as well. Not only the thermal loading is largely smaller than in rocket engine case, still the mechanical loading is much smaller. It is required however to achieve a given level of stiffness to avoid aeroelastic flutter, in spite of the very low airspeed in the tower. This is due to the large size of the receiver foils in respect to their relatively small thickness (Fig. 4 below). Regarding the level of the temperature and of the other parameters of the heat exchange process, the SEATTLER receiver is more approached to the air-cooling used for electronic components.

The nickel-alloy Inconel X-750 of the liquid rocket motors technology is no longer a need at the low temperatures within the SEATTLER tower and moderately high strength aluminum alloys prove more convenient in these applications. Furnace brazing process remains a good approach, although sometimes avoidable.

The welding technology under neutral atmosphere and flux remains a basic technology for aluminum alloys, especially aluminum-silicon based. Manual torch soldering remains an applicable alternative in case of small size series production. Due to the low melting temperature of aluminum (660.37º*C*) the brazing method could only use zinc, with its lower melting point (419.58º*C*), or a *Zn-Al* alloy similar to the high strength Prestal (78Zn-22Al) alloy, for achieving the braze fillet with good mechanical properties.

The metallurgical tube-to-plate bond must eliminate contact resistance, allowing the plate or wall to transfer heat more efficiently[9]. One of the methods to achieve a metal-to-metal bond is by brazing. Where higher-grade aluminum materials are used, the pressure forming or explosion allows the heat exchanger to be formed in various configurations, even without soldering or brazing. Such technologies are known.

Extruded or brazed microchannel technology should be suitable for any application that uses refrigerant/accumulator and air for heat transfer. This would include residential and commercial condensing units, heat pumps and evaporators, refrigeration systems as well as tower receivers. In addition to the heat exchanger heights and lengths that are normally designed to improve efficiencies, the manifold baffles can be relocated to change the refrigerant-side pressure drop and the split between the "de-superheat" and subcooling portions of the heat exchanger. Contingencies must also be made for condensation removal when the heat exchangers are used in evaporator or heat pump applications.

The commercial feasibility of microchannel technology has been proven for different applications, still additional research should probably be dedicated to optimizing the channel geometry for the various refrigerants used, a task frequently mentioned by different research groups. It is to be mentioned however that, even though the microchannels had dramatically improved the overall heat transfer by increasing the refrigerant-side heat exchange, they are still limited regarding the airside transfer properties. Consequently, additional studies will be necessary to determine the optimum fin or wall geometry to compliment the microchannel geometry. Most current heat exchangers of the large-scale producers are constructed from long and thin aluminum fins with round extruded holes through which the copper hairpins are laced and expanded to provide an interference fit for heat conduction, both of which may have enhancements to improve heat transfer. Circuiting is performed with return bent tubes that are brazed to the open ends of the hairpins.

Parallel flow plate fin technology is a heat exchanger innovation very similar to the tubular chamber of LRMs, designed specifically for the home appliances. The fin differentiates it from conventional micro channel heat exchangers and allows tubes to be oriented vertically or horizontally to function as a condenser or evaporator in refrigeration and air-conditioning applications. Benefits of the plate fin technology include:

- Reduced coil depth that further lowers airside static pressures.
- Reduced face area to cut cabinet costs.
- Reduced internal volume to reduce refrigerant charge.
- Increased design versatility.
- Potential applications include:
- Refrigeration equipment such as ice machines, beverage dispensers, refrigerated display cases and food service refrigeration.
- Air conditioning applications such as residential air conditioners, rooftop air conditioners, chillers, geothermal heat pumps, PTACs and electronic cooling.

In the plate fin concept only the plate size or depth will vary to meet performance needs. The engineers can design cooling solutions around the application, not the heat exchanger technology and in the tower receiver application this is related to the size of the light stream received from the mirror array. That provides for higher system efficiencies and lower system and operating costs. The lowest possible noise operation is implicitly achieved due to the absence of any air driving fans.

A recently introduced plate-on-tube condenser [23] improves the airflow over the condenser surface by using the Coanda effect. The Coanda effect is named for a Romanian researcher, who, prior to World War II, discovered that the air that flows over a curved surface tends to follow that curvature. The technology was first used to improve aerodynamics in warplane designs and even to create the so-called "*lenticular aerodyne* (flying saucer)".

The louvers of traditional tube-on-plate condensers are angled in the same direction to allow air to pass through the condenser. Launched in mid-2005, the Coanda-effect louver design allows air to flow from one side of the plate to the other, and back again, due to a dual-row of fins. It flows much like a wave up through the middle of the condenser, increasing the amount of air that actually passes through the louvers, despite the non-significant pressure drop between the two sides of the condenser.

The technology was designed mainly with upright refrigeration appliances in mind, but can replace any plate-on-tube, and potentially wire-on-tube, condenser.

The company currently has OEM customers in Europe, who purchased the Coanda solution for household refrigerators and upright freezers. The curved design of the heat exchanger fins disrupts the formation of boundary layer on the condenser and creates turbulence, which improves the efficiency of the fins, and in turn, the condenser. Tests have shown a 5%-7% improvement in the heat transfer rate compared to standard plate-on-tube condensers. The development of entirely new products is expected.

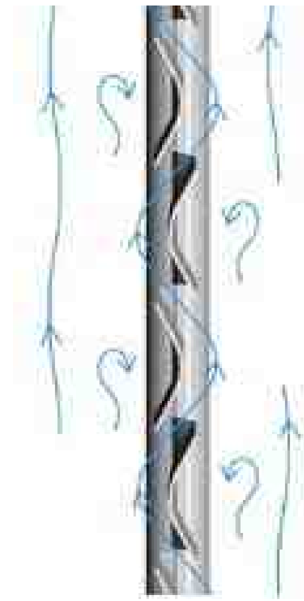


Fig. 6. Coanda effect.

With the tower receiver and its elevated pressure gradient, due to the gravity draught, the solution with Coanda louvers could only be imagined for a slight improvement of the air transfer efficiency, a subject that remains under consideration for future research.

It is seen that no frontier had yet been attained with the technology of heat exchangers. New innovative plastic heat exchanger technologies had been for years developed that offer an interesting alternative to metal heat exchangers. The new designs first entered energy efficient heat exchangers for the automotive industry but had rapidly expanded to HVAC systems for new and retrofit applications. Heat exchanger tubing provides effective energy transfer in most applications (s. figure 7) and producers say that the heat transfer capability of this plastic tubing is comparable to that of copper heat exchangers, and that transfer rate remains high for both heating and cooling. A blunt limitation to 105º*C* appears however.

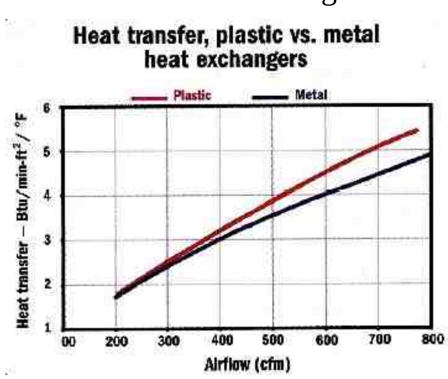


Fig. 7. Plastic vs. metal.

It practically excludes plastics from tower receiver applications their with 200º*C.*

Enhanced solutions for the heat receiver

The main design parameters of the GIGANT heat exchanger and of the equivalent SEATTLER solar receiver[27] with an energy output of 1 *MW* address for the following values that are considered when selecting the material and manufacturing technology of the heat exchanger (figure 8):

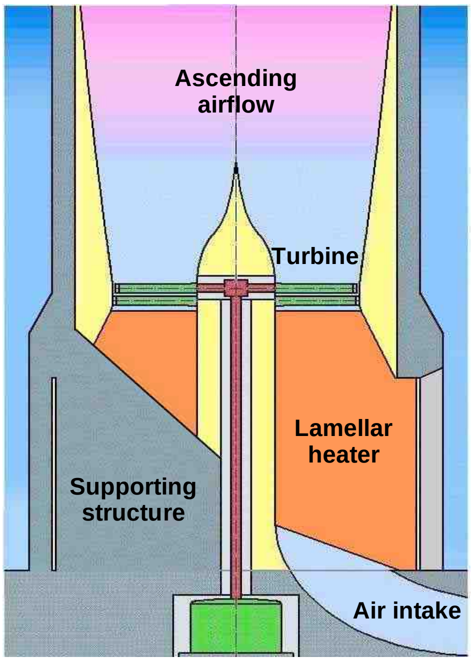


Fig. 8. GIGANT geothermal/nuclear device.

- air temperature at intake	300º*K*
- nominal heater temperature	500º*K*
- maximal heater temperature	900º*K*
- air speed into receiver	30 *m*/*s*
- air pressure at intake	0.95*atm*
- pressure at turbine exit	0.5 *atm*
- air speed at turbine exit	10 *m*/*s*
- inner upper tower diameter	4 *m*
- heater inner diameter	0.5 *m*
- heater outer diameter	4.0 *m*
- heater height	2.0 *m*

The main selection criteria for the material of the heater/receiver are its maximal emergency temperature of 900º*K* and the compatibility with the working fluids, namely the liquid metal in case of the solar receiver with heat accumulator and untreated water in the version by geothermal or nuclear heating. A cooper alloy with brazing by aluminum-titan offers the ultimate choice. The alternative of a double cooper milled plate with electrical soldering, a very used technology for highly loaded LRM, is also considered.

The lamellar structure of the heat exchanger is drawn in detail in figure 9.

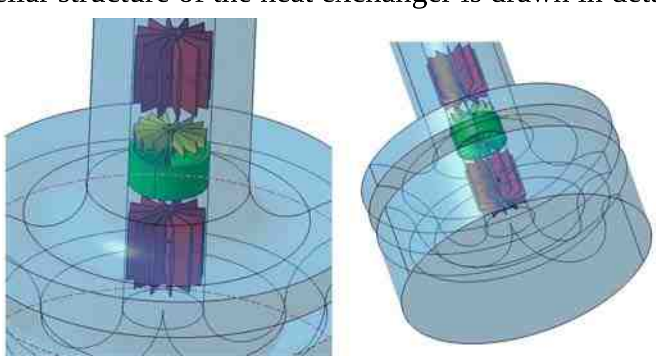


Fig. 9. The open lamellar structure of the SEATTLER solar heat exchanger.

These general conditions are imposed by the safety requirements, prevailing over all other technological aspects of the project. The maximal equilibrium temperature of the receiver walls under solar radiation and zero air transfer is the hardest constraint. This emergency temperature of $600^{o}\ C$ for the brazing material is a challenge that can be answered within the *Al-Ti-Li* alloys.

Shell-tubes brazing receiver technology

Through the first technology the heat exchanger involves a double cooper thin shell with cooper parallel tubing between and the entire bloc brazed with high temperature resistant aluminum-titan alloy (figure 10).

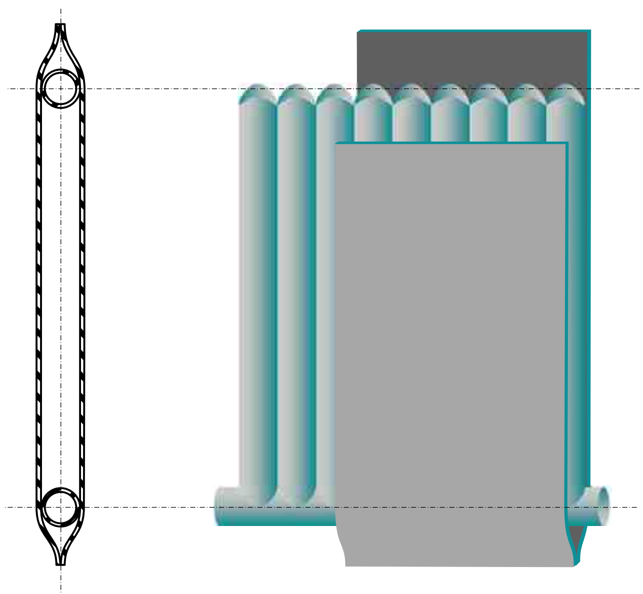


Fig. 10. Shell and tubes receiver solution

Problems that must be solved with a proper choice of technologies are related to the proper positioning of the tubes, a secured fixture during the furnace brazing and the accurate brazing metal and flux layering for best brazing results. To avoid internal brazing, more difficult to control, the tubing is first brazed, finished and tested for leakage and the outer thin shell is brazed at a second session thereafter. This staged process is best achieved when to different brazing fillers are used, with different melting temperatures. This can be permitted by the series of *Al-Ti-Li* alloys, well known for their wide range of melting-softening temperatures. After the second and last stage of brazing the finishing of the cooper tubing structure begins with a passivation process of the entire inner and outer surface, with known procedures. This induces no sensible change in the heat transfer capability of cooper but secures a higher durability and stability of transfer properties by avoiding further oxide or salt deposition on cooper surfaces.

Finishing of the heat exchanger block.

Finishing goes further with powder surface deposition in a very thin layer to obtain a frosted surface with an anisotropic response to radiation and an improved albedo regarding the solar radiation application. The overall manufacturing diagram is given in figure 11. The finishing operation related to cooler/heater liquid channels is important in regard with the surface microgeometry to allow for a maximal heat transfer flux under minimal hydrodynamic drag.

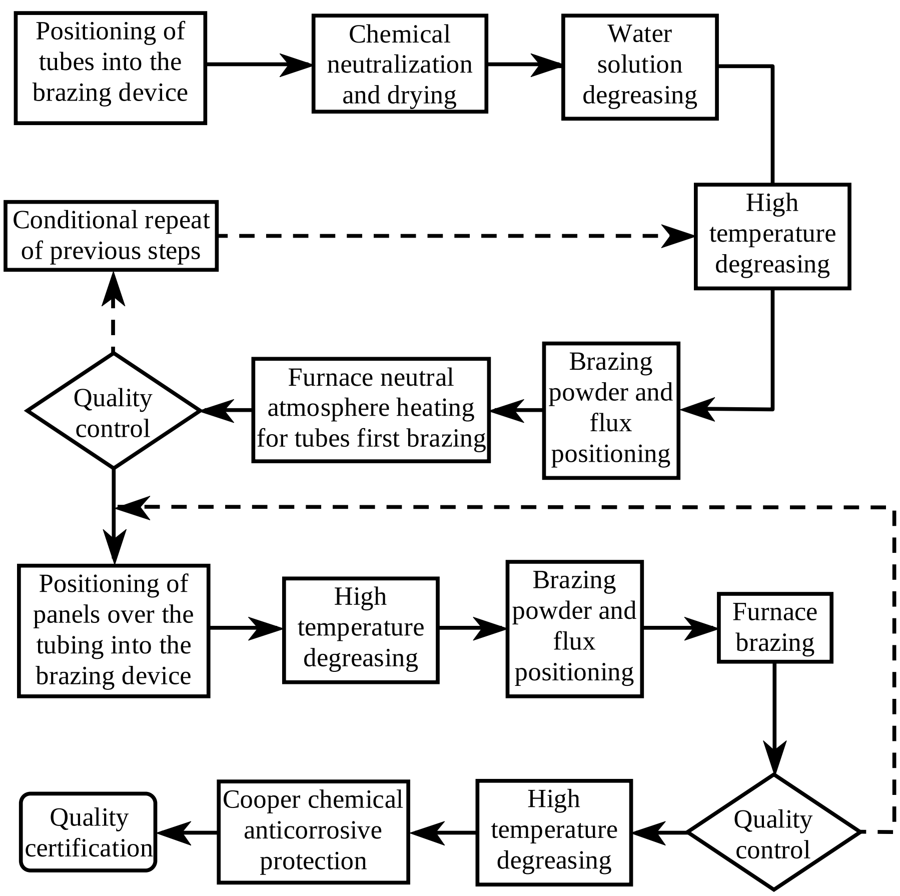


Fig. 11. Manufacturing and finishing plan for the heat exchanger block.

Removing of the brazing process from the technological chain reduces the number of manufacturing operations of the double wall structure of the receiver to better fulfil the different requirements for low mass and thin wall construction, which indirectly improves the heat transfer rate of the structure.

Concluding remarks

The design of the solar receiver for the gravity draught tower faces a number of conflicting requirements that can only be answered by a choice of compromise geometries and manufacturing technologies. The requirement for a large area of visibility from the surrounding area of mirror collectors enters in conflict with the requirement for a dense grid of heating walls, which cover each other and offer a limited surface towards the light source. Also the requirement for a black body property of the surface of the receiver panels enter in conflict with the requirement for a reduced air drag into the channel. A thin structure of the receiver panels to allow a reduced drag property of the channel opposes to the requirement for a large tube diameter for a reduced hydrodynamic drag into the liquid part of the circuit.

A solution was proposed to answer these questions under the form of a modular, tubular structure for the circulation of the accumulating or heating fluid, covered by a aerodynamically profiled double shell with two stage brazing process for achieving a good mechanical and thus thermal bond between the heat transmitting bodies. The basic material for the manufacturing of plate-tubes structure is a cooper alloy with high melting temperature. It was observed that the emergency working temperature of the receiver panels raises to about $600^{o}\,C$. The brazing material within the range of titanium alloys requires further investigation.

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