What's so special about high-temp heat exchangers anyways?

Bulk solids-based technology aligns with rising global sustainability goals

The collective pursuit of a more sustainable future for all is opening new doors in the advancement of heat exchange technology. This sprint to sustainability is proliferating a wider application of the more niche bulk solids heat exchangers, also referred to as moving bed or particle heat exchangers, and created a launch pad for what's referred to as high-temperature bulk solids heat exchangers.

Neville Jordison, Chief Executive Officer, Solex Energy Science

Industry, economic and societal drivers such as energy efficiency, renewable energy and the lowering of greenhouse gas emissions are shedding fresh light on the unrealized applications that come with using an indirect heat exchanger to heat or cool bulk materials.

For example, innovations such as high-temperature pillow plates, diffusion-bonded heat exchangers and vertical tube technology have allowed industries to improve heating or cooling efficiencies, economically recover energy and/or reduce their current environmental and plant hygiene management needs.

High-temperature bulk solids heat exchangers have also allowed for the storage and recovery of solar thermal energy and its ultimate conversion into power.

All of this leads to the questions, what are high-temperature bulk solids heat exchangers and what makes them so special?

Defining high temperature

It starts by understanding "high temperature."

High temperature is relative and will be considerably different for different industries.

As a guideline for heat exchangers, however, the equipment design changes when handling bulk solids with temperatures greater than 400°C. Above this temperature, heat fluxes are high, requiring special designs and detailed analysis to keep material stresses below the allowable limits. Another consideration is that, above 400°C, radiation becomes a significant component of the heat transfer mechanism that also needs to be factored into the equipment design.

The challenge with steel is its allowable stresses diminish with temperature. When it gets hotter, the allowable stress that can be designed at drops off. For austenitic, or 316, stainless steel, the maximum operating temperature may be in the low 600°C range, yet its allowable stresses are only a fraction of what it is at ambient conditions. Once in the 500°C to 600°C range, the allowable stress for the material will have dropped off dramatically.

Designing for high temperatures, also impacts the choice of material. The starting point is an austenitic stainless steel such as 316, which is suitable for most high-temperature heat exchangers where the duty is simply to cool the product using water as the cooling fluid. In this case, the average wall temperature will be close to the cooling water temperature, so well within the range of a 316 grade stainless steel.

Model of a diffusion-bonded heat exchanger core that's designed for a particulate material on the solid side and CO_2 on the fluid side. Photo credit: Solex Energy Science

However, that changes when the duty is for energy recovery – for example to recover high-grade heat as an energy source for a gas turbine in a waste-heat to power application. To achieve a high-turbine efficiency, there needs to be maximum fluid side (air) temperatures. As a result, the average wall temperature will be much higher and may require the use of a superalloy such as Inconel 617 or 625. These high nickel alloys can be used up to about 900°C.

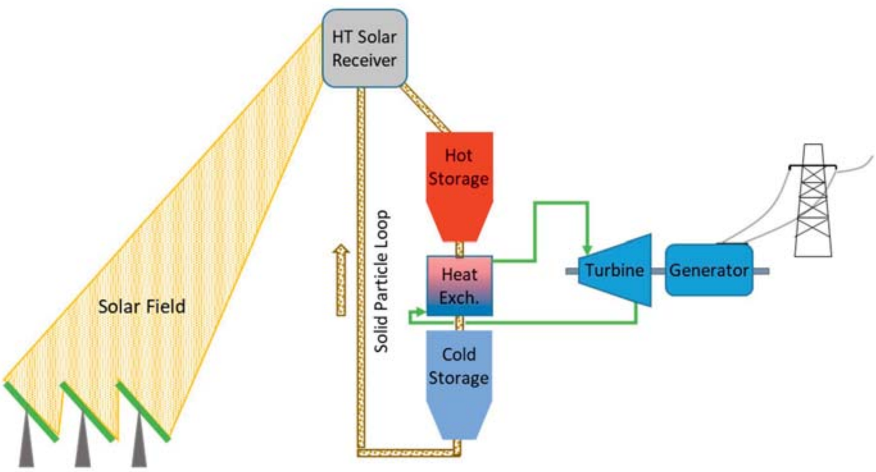
How to handle stress

The next question is, beyond the choice of design material, how do you further mitigate those stresses?

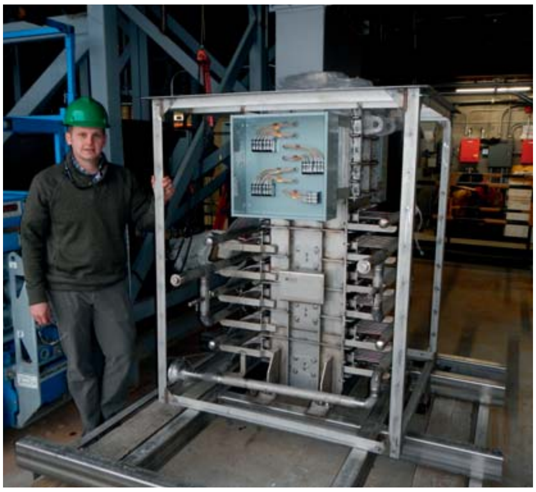
Conventional bulk solids heat transfer technology uses traditional dimple plates with working fluids such as water, thermal oil or even steam. These plates are typically more than one metre wide and one metre high, with, in the case of water or thermal oil, the working fluid flowing counter-current to the solids.
Yet, as noted earlier, above certain operating temperatures, the localized thermal-mechanical stresses on these types of plates can become unacceptably high. To minimize stresses, high-temperature heat exchangers will utilize shorter plates.
The plates themselves also include several patented features that guarantee an even working fluid distribution and high velocities within the plates to accommodate the high rates of heat transfer. The heat exchanger design also needs to be in accordance with pressure vessel codes (e.g. ASME in North America, PED in Europe). A Finite Element Analysis (FEA) of a plate with a solid on the outside and fluid on the inside would then illustrate where extremely high stresses exist at various points at these high temperatures, and allow for further design refinements if necessary.

Evaluating design

Meanwhile, there are additional considerations when designing the mass flow discharge hopper, namely to account for the solids material flow properties that can change at high temperatures. While the solids might still be a long way from their respective melting points, they may start to exhibit different flow properties and drag forces at the solid-wall interface. Therefore the design flow conditions need to be evaluated at those temperatures because the solids will act differently.
To accommodate a change in material flow properties, plate spacing, wall angles in the mass flow hopper and selection of the discharge device (typically a rotary valve) will be tailored to suit flow conditions and meet the requirement for uniform mass flow in the heat exchanger.
Lastly, whereas in a typical bulk solids heat exchanger the product will come into contact with the exterior shell, that's not the case with a high-temperature unit. Instead, the product is contained within a water-cooled envelope.



Process diagram of a concentrated solar plant with solid particle energy storage. Photo credit : Solex Energy Science



A high-temperature heat exchanger with particulate solids and supercritical CO2, which part of a solar power research project carried out by Sandia National Laboratories in the U.S. Photo credit: Solex Energy Science

The reason comes back to differential thermal expansion. If the components in the outer shells are not water cooled, then the differential temperature between the high-temperature bulk solids stream and cold surfaces of these components will lead to extreme fluctuations in the materials. By containing everything within a water-cooled envelope, then you avoid those differentials.
Another benefit of a water-cooled envelope is it decreases the reliance on having to insulate the unit, which can pose challenges when trying to navigate around instrument connections.

No two are alike

No two high-temperature bulk solids heat exchangers are created equal. Each one has to be designed for specific conditions, which are dictated by factors such as the type of product, temperature range and flow rate.
In some cases, high-temperature bulk materials will need to be cooled down to avoid further oxidation at high temperatures. In these cases, the equipment will operate under nitrogen or an inert gas blanket to get it down to those low temperatures where it won't oxidize. When accounting for a purge gas like this, the heat exchangers, in turn, have to be designed with a low positive pressure to avoid air from entering into the unit.
There is also the complex thermal modelling that needs to take place – for example, factoring in the effect of radiation, which, at high temperatures, becomes a significant component of heat transfer.

Applications

Many industries have not traditionally looked at high-temperature bulk solid materials as a potential source of thermal energy that can be either re-used elsewhere in the plant or even converted into electrical power. Instead, those hot solids have often been left on the ground to air cool or be water quenched.
For example, slag that is coming out of a blast furnace is being quenched with water to cool it down, or sometimes just tipped, still in a molten state, and left to air cool. This represents a massive number of gigajoules of energy that's simply dissipating as heat into the atmosphere or being carried away with the quench water. Much of

this energy can be re-used if a technical and economic solution existed.

Consumers and investors today are demanding higher standards of sustainability from companies. A study released by PwC last summer found 65% of investors factored ESG (Environment, Social, Governance) issues when managing investment risks. Meanwhile, a Bank of America survey reported that 92% of Gen Z consumers would switch to a brand that supports ESG issues versus one that does not.

Meanwhile, the renewable energy industry has ushered in additional applications of high-temperature bulk solids heat exchangers – for example, using solid-particle-to-supercritical-CO2 heat exchange technology to power high-efficiency sCO2 turbines.

In addition to the metallurgical industry – which involves slag, ores or metal powders such as those used for the production of batteries – other industries that typically see these high temperatures are ones with carbon-based products or ash such as bio char and mineral powders such as cement.

Interestingly, not all industries are exclusively looking to cool the bulk solids – although most are. Some are looking to indirectly heat a solid – for example, a feed material that's going to a calciner.

Conclusion

Overall, there are a lot of things going on in these high-temperature situations that need to be understood. The heat exchanger modelling is more complicated. There are also changes in the thermal characteristics of these bulk solids, meaning it's important to understand the factors that come into play when designing for mass flow.

That's not to forget that there's a lot of advanced engineering that goes into building this technology, which requires a solid understanding of how to evaluate and analyze thermal-mechanical stresses, as well as certain construction material properties and the fabrication techniques required for a successful design. There's no such thing as a cookie-cutter answer to these types of challenges.

About the author

Neville Jordison is the Chief Executive Office of Solex Energy Science, a Canadian-headquartered company that focuses on developing and applying high-temperature bulk solids heat exchange solutions to green technology solutions such as solar power, waste heat recovery and carbon capture.

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