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Role of heat integration in a sustainable, low-carbon future

How different technologies are playing respective roles in minimising energy consumption and reducing emissions in industrial settings

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The ongoing pursuit of a more efficient, equitable, and environmentally conscious energy future is commonly framed within the sustainability-based concepts of the energy transition and a circular economy. At their core, these discussions focus on reducing carbon footprint, whether through lowering primary energy consumption or minimising waste and pollution.

The global response to climate change has added another layer of complexity. Policymakers worldwide have introduced various mechanisms to influence behaviours and decision-making, aiming to reduce emissions and promote carbon-reducing innovations.

Geopolitical uncertainties and dynamic monetary policies in response to inflation concerns have further intensified volatility in the energy market. Consequently, many industrial operators are proactively implementing risk-mitigation strategies, ranging from deploying financial instruments and hedges to re-evaluating and enhancing physical operations.

Public pressure also plays a significant role. As of November 2023, approximately 145 countries have announced or are considering net zero targets, covering nearly 90% of global emissions. Investors around the world continue to call for increased action, urging companies to improve their sustainability programmes and adopt their own net zero goals.

Financial performance remains a fundamental factor in commercial decision-making, yet its calculation has become increasingly complicated due to emissions pricing and compliance costs in the global market. As a result, many companies are strategically investing in energy efficiency initiatives, as these are considered low risk technically and financially. This approach not only decreases emissions but also improves environmental performance, reduces production costs, and enhances overall financial health.

Enhancing energy recovery and efficiency through heat integration

Implementing heat integration mechanisms into existing operations is highly effective and low risk, and can be a high-return approach for minimising energy consumption in industrial settings.

The concept of heat integration is not novel, but its practical application has, at times, been hindered by factors ranging from high cost of adoption, complexity of integration, and technical restrictions of existing technologies.

Although many industrial processes already incorporate some level of heat integration, difficult-to-handle process streams frequently remain unutilised due to perceived constraints. Tapping into otherwise wasted heat from these previously overlooked streams presents a significant opportunity for operators to incrementally reduce costs and lower emissions.

Heat pipe heat exchangers (HPHE) and moving bed heat exchangers (MBHE) are two heat integration technologies that take very different approaches to improving the energy performance of industrial processes. However, both can play a similar role in optimising energy usage and enhancing sustainability in industrial settings.

Heat pipe heat exchangers

Combustion flue gases hold substantial potential for energy recovery. Extracting energy from these streams has historically

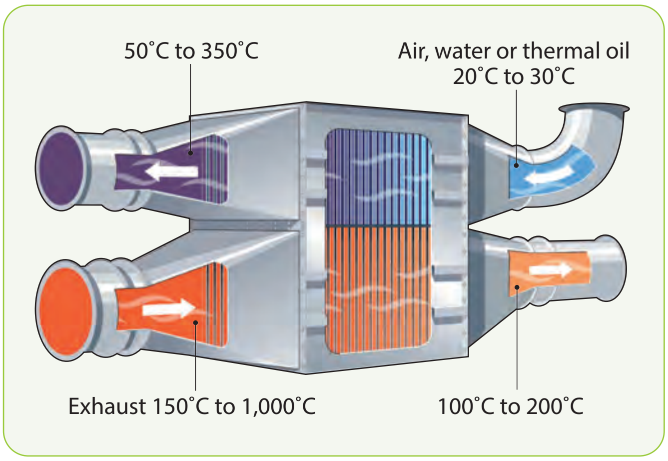

Figure 1 A typical heat pipe heat exchanger arrangement for recovering waste heat from a hot combustion gas stream (*Source: Econotherm*)

proven challenging due to heavy particulate loads, high acidity, and extreme temperature fluctuations, which can cause fouling, corrosion, and mechanical failures, respectively, in conventional heat exchangers (CHE) such as shell and tube or plate and frame varietals. These issues have historically led to higher maintenance, frequent shutdowns and decreased profitability, making it more difficult for operators to justify these investments for energy recovery purposes.

HPHEs offer a proven and reliable solution to these complex heat recovery challenges. The technology acts as an indirect heat transfer device composed of an array of heat pipes, each acting as an individual heat exchanger. A heat pipe is a sealed tube filled with a small amount of working fluid at saturation condition. The latent heat of that working fluid is used for the energy exchange.

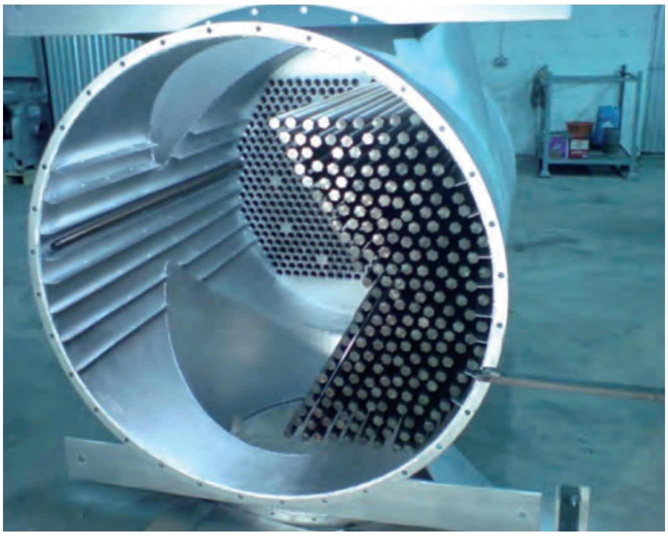

Figure 2 Top-down cross-sectional view of a heat pipe heat exchanger (*Source: Econotherm*)

An HPHE (see **Figures 1** and **2**) is constructed as a cased unit that can receive two process streams. The process streams are isolated using a separation plate that contains affixed heat pipes that contact each process stream:

- On the primary side, also known as the evaporator section, heat pipes contact the hot process stream, causing the liquid working fluid within each heat pipe to boil.
- On the secondary side, or condenser section, each heat pipe contacts a cold process fluid, causing the gaseous working fluid to condense simultaneously. The ends of the heat pipe are free to expand and contract, preventing mechanical stress on the equipment.

HPHEs are highly customisable: the number of pipes, their spacing, dimensions, orientation, material of construction, type of working fluid, and casing dimensions can all be tailored to meet specific application requirements.

Design features for handling particulate-rich gas streams

HPHEs are adept at managing particulate-rich gas streams through:

- Unique internal geometry where process fluids contact only the external surfaces of the heat pipes.
- Smooth heat pipe surface finishes.

As particulate-rich gas flows perpendicular to the heat pipe orientation, particles collide, lose energy, and settle in a dust trap collector, which can be emptied manually or automatically. For particulate-rich wet gas streams, integrated sonic horns or water jets can be activated to keep the heat pipe surfaces clear of build-ups.

HPHEs can also avoid acid condensation conditions as each heat pipe operates isothermally at a predictable intermediate temperature, which can be designed just above the flue gas acid dew point. This allows operators to achieve up to 25% more heat recovery. In contrast, CHEs often develop cold spots that lead to localised acid condensation and corrosion, necessitating operation well above acid condensation temperatures and resulting in suboptimal heat integration.

Lastly, HPHEs are particularly attractive from a total cost of ownership perspective due to their inherent safety redundancies. When conventional CHEs fail, entire systems must be taken offline to avoid contamination or mixing of process streams. Conversely, an HPHE can continue operating safely even in the rare instance that a heat pipe fails since process streams remain isolated. During scheduled maintenance, failed heat pipes can be easily identified, isolated, and replaced without disassembling the whole unit.

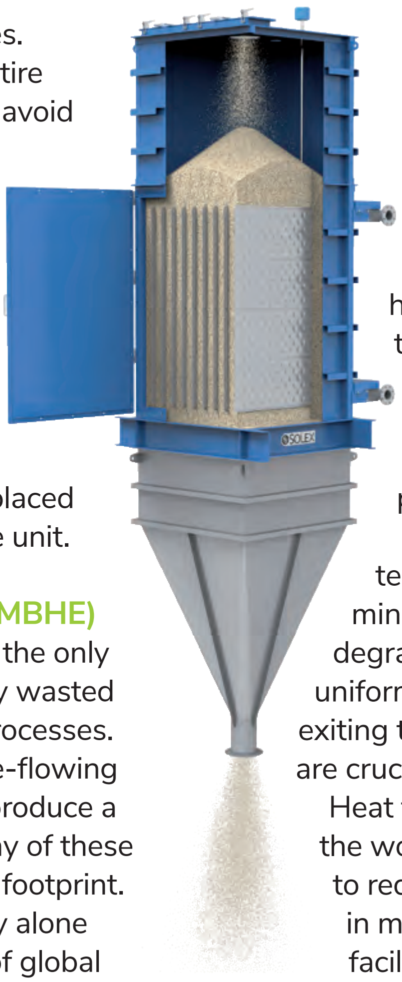

Figure 3 A plate-based MBHE illustrating how the product enters the unit from the top and flows by gravity through vertically orientated banks of stainless steel pillow plates (*Source: Solex Thermal Science*)

Moving bed heat exchangers (MBHE)

Combustion gas streams are not the only source of valuable and potentially wasted heat generated from industrial processes. Every year, vast quantities of free-flowing bulk materials are processed to produce a wide array of products, with many of these processes bearing a high carbon footprint. For example, the cement industry alone accounts for approximately 7% of global greenhouse gas emissions annually.

MBHEs provide another opportunity for heat integration. They efficiently transfer energy to and from free-flowing solid materials with minimal energy requirements and a low environmental impact.

In either a vertical plate or vertical tube orientation, MBHEs exchange heat between granular solids and a heat transfer fluid through conduction. This method differs from convective heat transfer techniques used in less efficient, direct-contact solutions such as fluid beds and rotary drums.

When using plate-based MBHEs, primarily for solid-to-liquid heat transfer, the product enters the unit and flows by gravity through vertically orientated banks of stainless steel pillow plates (see **Figure 3**). A heat transfer fluid passes through the plates, cooling the material as it descends. When using tube-based MBHEs, mainly for solid-to-gas heat transfer, solids flow by gravity through vertically orientated tubes while gas (such as air) flows outside the tubes.

Both types of MBHEs commonly use a counter-current flow arrangement between the product bed and heat transfer fluid, intended to maximise heat transfer efficiency. Both MBHE types are also equipped with a mass flow discharge feeder controlling the flow rate through the unit. Gravity facilitates the slow movement of the product through the heat exchanger.

Beyond heat transfer efficiency, this technology gently handles the product, minimising fugitive dust emissions and degradation while ensuring a consistent and uniform temperature of the granular material exiting the heat exchanger. These advantages are crucial for many downstream processes.

Heat transferred from the granular solids to the working fluid can be utilised elsewhere to reduce overall energy costs. For example, in metal refineries and mineral processing facilities, MBHEs can be used to cool material downstream of kilns while reducing dust emissions. Then, the hot working fluid produced from the cooling process can provide thermal energy for use elsewhere in the plant – for example, upstream in the production process to preheat combustion air feeding steam boilers.

In low-temperature applications, MBHEs can be uniquely combined with industrial heat pumps to upcycle energy from waste to a heat source. By adding a heat pump, the temperature of a cooling water stream can be increased to levels that are useful to plant operators. Temperatures between 110°C and 150°C are easily achievable, with the ability to reach around 180°C in some cases. Further, since heat pumps are electrically driven, they do not create any additional direct emissions.

Case studies

The following examples demonstrate how the technologies described above are playing respective roles in minimising energy consumption and reducing emissions.

Case study 1: Oil refinery air preheater

Oil and gas refineries often encounter issues with traditional air preheaters due to flue gas

Project data from 2020 HPHE replacement in an oil and gas refinery

Technical data	Value
Exhaust gas mass flow, kg/h	12,000
Exhaust temperature in, ˚C	400
Exhaust temperature out, ˚C	265
Combustion air mass flow, kg/h	6,400
Combustion air temperature in, ˚C	30
Combustion air temperature out, ˚C	245
Energy recovered, kW	530
Recovered energy value, $/yr	155,000
Project cost, $	210,000
Payback period, months	16.2

Table 1 *(Source: Econotherm)*

Project data from 2007 HPHE installation in an aluminium furnace air preheater application

Technical data	Value
Exhaust gas mass flow, kg/h	89,900
Exhaust temperature in, ˚C	430
Exhaust temperature out, ˚C	155
Combustion air mass flow, kg/h	78,600
Combustion air temperature in, ˚C	15
Combustion air temperature out, ˚C	340
Energy recovered, kW	7,100

Table 2 *(Source: Econotherm)*

acid condensation, leading to equipment failure and air leakage. In 2019, an integrated oil and gas company in Illinois sought to replace an underperforming DEKA air preheater with minimal modifications to existing ductwork.

A 7.1 MW HPHE retrofit was completed in 2020, using vertically oriented finned heat pipes in a cross-flow configuration. Adaptive transition pieces connected the unit with minimal duct modifications. The HPHE included temperature-sensing heat pipes and specialty stainless steel heat pipes to guard against condensation during start-up and shutdown. Cleaning nozzles were also included to handle high particulate matter exhaust.

Table 1 shows that the HPHE met the customer's expectations, and the client is now considering additional replacements at other refineries worldwide.

Case study 2: Aluminum furnace air preheater

In 2007, a leading multinational client assessed the need for waste heat recovery at its automotive parts casting facility in Kentucky, US. Prioritising reliability, low fouling susceptibility, and ease of maintenance, the client selected an HPHE to handle the plant's air preheating needs.

Installed outside the existing building housing the aluminum furnace (see **Figure 5**), the HPHE was connected to a cold combustion air stream, directing preheated air back to the smelter burners. Existing smelter exhaust was rerouted to the HPHE inlet, with new piping and an exhaust fan installed.

Table 2 shows that the HPHE exceeded expectations by delivering $150,000/year in energy savings against an initial estimate of $130,000/year. The project cost was $210,000, with a payback period of 16.2 months.

Completed in March 2008, the installation has operated reliably with minimal maintenance for 15 years, prompting the purchase of two additional units. The total net benefit to the client has been more than $2.8 million and 4.257 MWh saved based

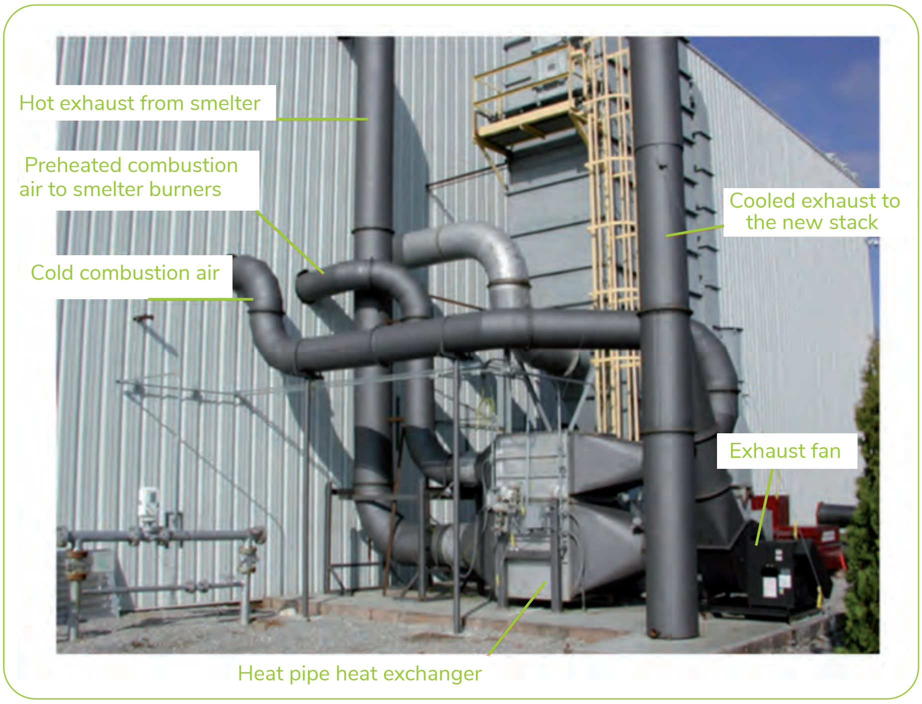

Figure 5 External HPHE unit installation as a combustion air preheater *(Source: Econotherm)*

Examples of typical MBHE installations (*Source: Solex Thermal Science*)

on continuous operations, including nearly 12 tons of net CO_2 reduction.

Case study 3: Slag cooling and vertical tube MBHE

Platinum is an essential material in vehicle catalytic converters, which reduce nitrogen oxide emissions from hydrocarbon fuel combustion. During platinum production, the slag byproduct must be cooled from a molten state at around 1,500°C to ambient temperature for safe handling. This cooling is typically achieved through granulation, transforming the liquid slag into a solid form. Even after solidification, the slag retains a significant amount of energy.

With a slag production rate of 100 tons per hour, a vertical tube MBHE can cool granulated slag from 1,000°C to 350°C, recovering about 20 MW of thermal energy. When this thermal energy is used with a heat recovery steam generator and a steam turbine operating at roughly 65% efficiency, it can generate nearly 13 MW of electrical energy, enough to power approximately 100 electric vehicle superchargers.

Conclusion

Achieving a more sustainable energy future relies on reducing carbon footprints through smart technologies and smarter energy consumption. Global climate policies, geopolitical factors, and public pressure for net zero commitments will continue to ramp up, thereby pushing industries to keep adopting advanced carbon-reducing strategies and enhance their energy efficiency.

HPHEs and MBHEs will play leading roles in this energy transition. One offers a proven solution for capturing difficult-to-recover heat such as hot and/or dirty exhausts, while the other provides a means to transfer energy to and from free-flowing granular materials. Both enhance overall industrial efficiency and stability, contributing to a shift in what is considered possible in both traditional and non-traditional processing industries.

Whether it comes to reusing industrial waste heat in metallurgical processes or providing a more efficient heat exchange solution during automotive parts casting, we are only beginning to uncover the potential of today’s heat integration technologies.

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