

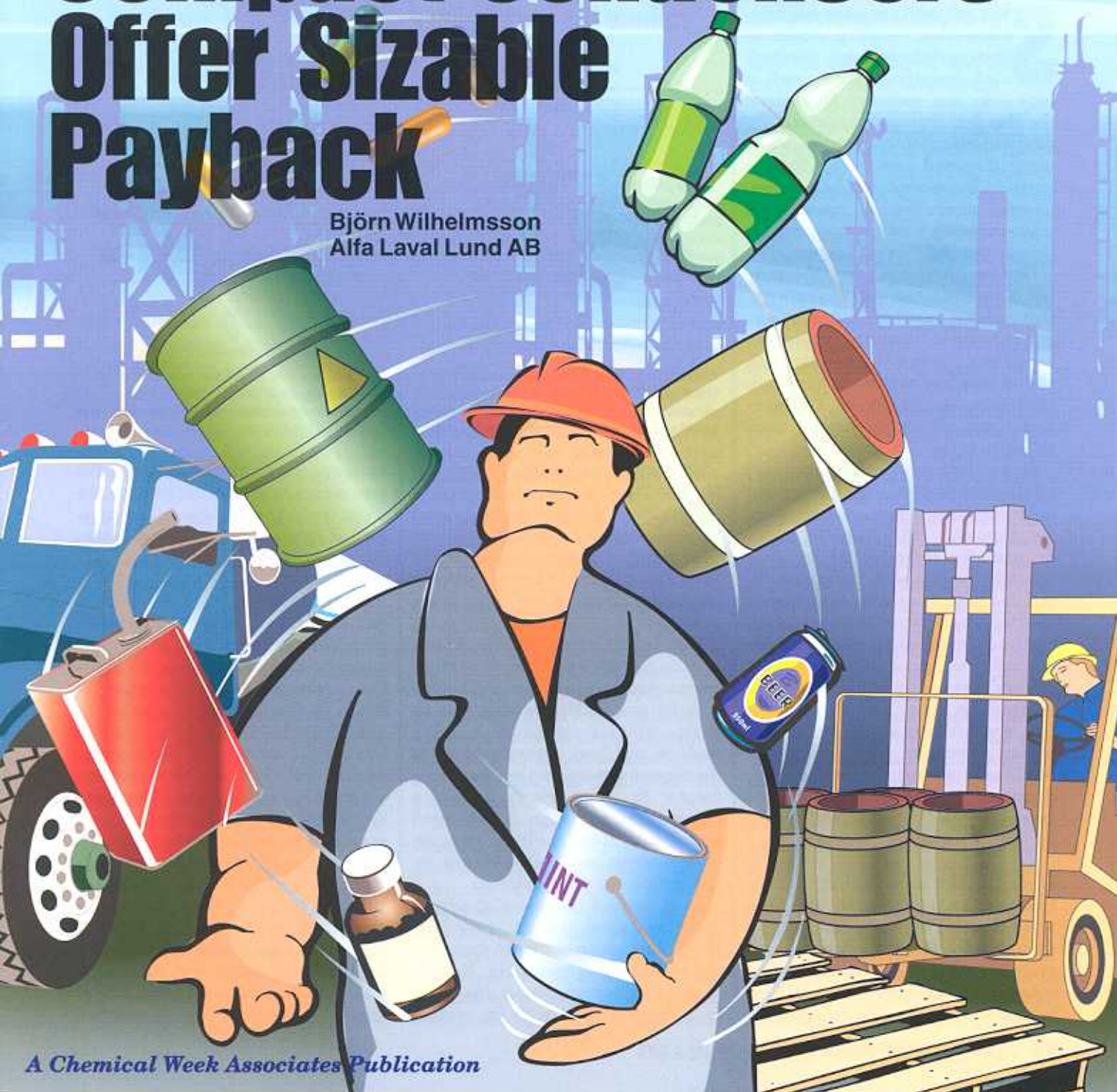
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Compact Condensers Offer Sizable Payback

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Since reliability is a key consideration when selecting condensation equipment, and unscheduled downtime carries such a high price tag, operators throughout the chemical process industries (CPI) are understandably cautious about using new and relatively unproven types of equipment [1]. As a consequence, most remain conservative when selecting condensers, opting for time-tested and proven designs.

However, in recent years, the number of successful installations of compact process condensers has grown, and in many of these applications, the newer unit shows equal or better reliability than the workhorse shell-and-tube condenser. As a result, CPI operators are slowly becoming more receptive to the new technology.

Cost — both total installed cost and total operating cost — is an important criterion when selecting condensers. As discussed below, compact condensers offer the potential to reduce not only the cost of the condenser itself, but also to save on costs associated with installation and ongoing operation. Installation costs include expenditures related to labor, vacuum system design and installation, civil engineering, piping and instrumentation, and auxiliary equipment such as pumps. Operating costs include expenditures related to maintenance, downtime, startup time, makeup and pumping of cooling water, and operating costs for the vacuum system.

Defining the terminology

Compact is a relative term, especially when it comes to condensers. For instance, in the literature, various definitions of the degree of compactness of a heat exchanger can be found. Hesselgreaves [4] gives a definition of

For condensing vapors, today's compact systems can reduce the cost of the equipment itself, and trim installation and operating costs

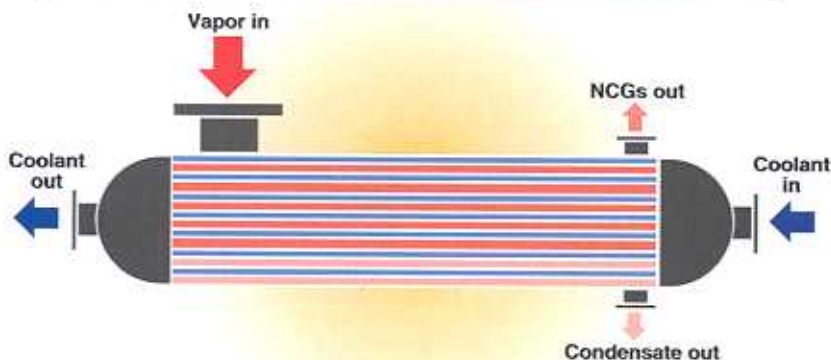


FIGURE 1. While shell-and-tube (S&T) condensers are not available in a compact configuration, the S&T is considered the workhorse against which all other condensers are compared. The S&T system shown above operates with one pass on the condensing side and one pass on the cooling side

>200 m²/m³, whereas Shah and Mueller [7] cites a threshold capacity of 700 m²/m³. However, when it comes to condensers — especially vacuum condensers — applying these definitions is not straightforward, due to the large volume of the vapor being condensed.

Based on their operation, condensers may be classified as steam heaters or process condensers. In a steam heater, a liquid process stream is heated by steam, which functions as a utility medium, and heat energy is added to the process stream as the steam condenses. In a process condenser, a gaseous process stream is condensed by a liquid utility medium, typically cooling water, and heat energy is removed from the process stream.

In an indirect condenser, the vapor being condensed is kept apart from the cooling medium by the design of the condensation equipment. By contrast, in a direct condenser, the vapor is in direct contact with the cooling

medium. This article discusses the pros and cons of each of the main designs that are available in the category of compact, indirect process condensers.

Pressure drop

Any condenser operating at sub-atmospheric pressure has to be connected to a vacuum system, where either a vacuum pump or a water or steam ejector is used to create the needed suction. The costs required to achieve the needed vacuum increase rapidly, and the size of all vapor-handling equipment becomes exponentially larger, with decreasing pressure. In addition, when designing the vacuum system, one cannot look only at the nominal load of non-condensable gases (NCG; including residual vapor); rather, one must also consider inevitable leaks (through flanges, for instance) and hence size the equipment for this additional load. In this article, NCGs are defined as residual

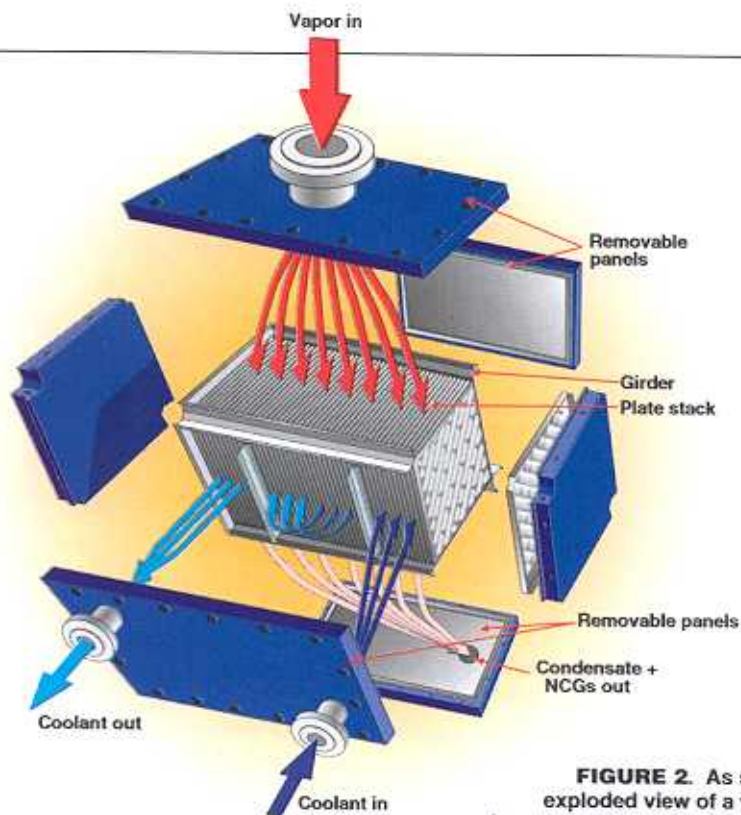


FIGURE 2. As shown in this exploded view of a welded-block plate condenser, operation is one-pass on the condensing side and four-pass on the cooling side. The four side panels can be removed to ease inspection and cleaning of the heat transfer surfaces

vapor and inert gases (note that the content of residual vapors will be reduced if they subsequently condense at a lower temperature).

If the total pressure drop from the source of the vapor (the column, evaporator or boiler, for example) to the vacuum-generating equipment can be kept at a minimum, the vacuum system can operate at a higher pressure and, thus, become less costly. Therefore, one should strive for a low total pressure drop in the condenser, including its inlet and outlet ducts and nozzles. The allowable pressure drop will typically be a function of the absolute pressure. As a rule of thumb, one can say that the pressure drop in the condenser should always be no more than 10–20% of the absolute pressure at vacuum.

Heat transfer

In most cases, the heat transfer coefficient on the condensing side is significantly higher than that on the cooling side. When this is the case — for instance, in a typical steam heater — the liquid-side heat transfer coefficient is the size-determining factor. However, there are also cases where the converse is true.

One example in which the condens-

ing side may be a bottleneck is when a mixture of vapors with different dew-points is being condensed. In this case, the mass transfer resistance in the gas boundary layer adjacent to the condensate film may set the limit on heat transfer (for details, see Ref. [2] and Ref. [9]). Another example of condensing-side limitations is the condensation of vapors with large amounts of NCGs.

A given condenser's ability to cool any NCGs strongly influences both the load and the size of the downstream vacuum system. For example, if a condenser can cool the NCGs to a lower temperature (for instance, more effectively), then there will be a greater amount of condensate and a smaller volume of remaining NCGs; thus the load on the vacuum system will be reduced, and that system can be sized smaller.

Different types of condensers have different NCG cooling capabilities, mainly depending on the flow configuration. In any condenser, the coldest part is where the cooling medium enters. In a countercurrent condenser, this is also where the NCGs exit. A colder wall means that more of the residual vapor in the NCGs will condense, thereby decreasing the volume



FIGURE 3. In this installation, three shell-and-tube (S&T) condensers are shown at the lower left, and three welded-block plate condensers are shown at the top right. Despite their small size, the block condensers have 50% greater capacity than the S&T units

of NCGs that remains, and reducing the load on the vacuum system.

By contrast, in a cocurrent condenser, the condensing vapor and the cooling liquid run in parallel. The dividing wall will be at its warmest where both fluids exit, and more of the residual vapor will leave without being condensed.

A crossflow condenser is somewhere in between a countercurrent and cocurrent unit, in terms of efficiency. Other factors such as geometry and heat transfer characteristics may also influence NCG cooling capacity, but to a lesser extent.

Often the condenser is an integral part of a plant's energy-recovery system. When this is the case, it is of particular interest to achieve as high a temperature as possible for the outlet temperature of the cooling liquid (such as water). This puts specific demands on the design of the condenser in terms of a small temperature approach (that is, the difference in temperature between the inlet vapor and the outlet cooling liquid). The smaller you make this difference, the larger and more expensive becomes the equipment. For this reason, one must trade off energy-recovery savings versus capital cost, and the optimum will be different from case to case.

Another benefit of having a small temperature approach is that the amount of cooling liquid can be minimized. This can result in substantial savings as the cost for makeup and pumping of cooling water can be reduced [3].

The reader interested in details on designing condensers is referred to Refs. [2, 4, 5, 6, 7, 9]. Readers should note that to date, relatively little de-

design information for compact condensers is publicly available. However, as interest from industry grows, so do both public and proprietary research efforts in the area of compact condensers, as well as efforts to develop better design software for such systems.

Pressure drop vs. heat transfer

Pressure drop and heat transfer are intimately related to each other in any heat exchanger system (the condenser being a subset of the heat exchanger), and the designer must determine how to balance the two in order to achieve an optimal condenser. At one extreme, a large pressure drop can be used to achieve better heat transfer and, thus, allow for a smaller and less expensive condenser for a given condensation duty. However, a design that accommodate a larger pressure drop also requires a larger, more costly vacuum system.

At the other extreme, if the design is made for very low pressure drop, the result is a significantly larger, and more expensive, condenser. The positive result of such an approach is that the required vacuum system can operate at a higher pressure, and thus becomes less costly.

Condenser options

The most common types of process condensers are reviewed below and compared with respect to design, applicability and features. This discussion is not a complete listing of condenser types that are available or used in the CPI. For greater detail, see Ref. [4], where the available literature is surveyed more comprehensively.

Even though the shell-and-tube (S&T) heat exchanger is generally not considered to be compact, it must be included in an overview of compact process condensers, as it is considered by many to be the standard against which the performance attributes of all other types of condensers inevitably must be measured.

Shell-and-tube heat condenser

Design. The general design of a S&T heat exchanger is well known (Figure 1) and will not be described here. Of

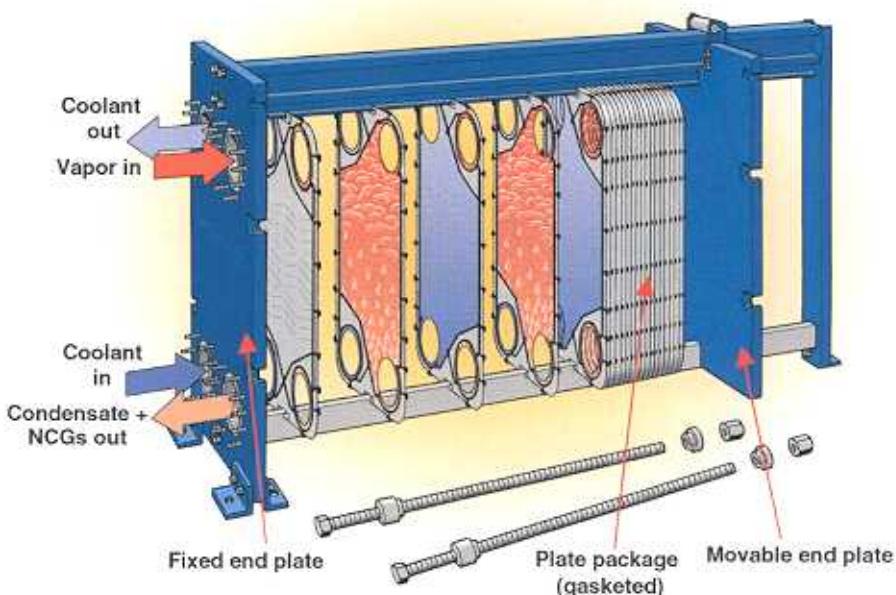


FIGURE 4. Shown here is an exploded view of a gasketed plate-and-frame condenser. Once the unit is opened, the heat transfer surfaces are fully accessible for inspection and cleaning

particular interest for condensation applications, however, is the choice between exchangers that condense on the tube side or the shell side.

For high-pressure vapors, it is advantageous to have condensation occur inside the tubes, as this will allow for lower design pressure on the shell [8]. Similarly, if the vapor is corrosive, it should preferably be kept on the tube side of the exchanger, as this allows the use of a lower-grade shell material. For vacuum service and duties slightly above atmospheric pressure, condensation is typically carried out on the shell side, to accommodate large vapor volumes.

Applicability and features. For many years, the S&T condenser has been the dominant type of condenser in the process industries. It has rightly gained a reputation for being sturdy and relatively straightforward to design, from both the mechanical and thermal points of view. Due to its relative simplicity, it is normally available from local manufacturers. Also, internationally accepted standards from the Tubular Exchanger Manufacturers Assn. (TEMA) and the American Petroleum Inst. (API) facilitate the specification and use of S&T heat exchangers for condensation.

The design is very flexible and can

be adapted to suit a large range of condensation duties, from extremely high pressure to high vacuum, and from large to small capacity applications. The S&T exchanger can be designed with very small pressure drops on the condensing side, also for high-vacuum applications.

However, once built and installed, S&T condensers offer little flexibility when it comes to being adapted to changing duties. Another drawback is the relatively poor heat transfer of S&T exchangers, which leads to larger surface areas, volumes and weight compared to those of many of the compact condenser types.

The use of finned tubes and tube inserts can improve heat transfer, but these modifications result in a more costly design. Because it needs a large amount of metal, another disadvantage of the S&T is the cost of materials, particularly when a high-grade alloy is necessary for the tubes or the shell. And, due to the mainly crossflow configuration, the S&T cannot cool NCGs very well.

Welded-block plate condensers

Design. In the welded-block plate condenser, thin, corrugated metal sheets are welded together to form a central assembly of heat transfer plates. (Figure 2.) The plate stack

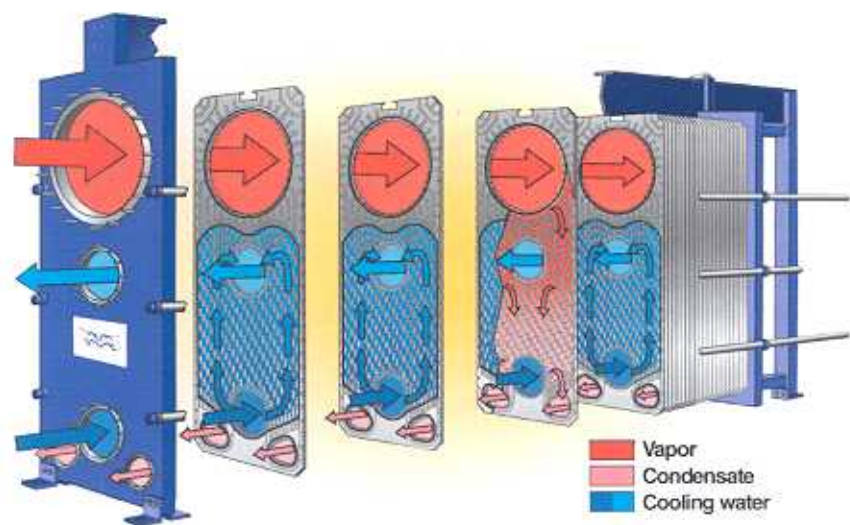


FIGURE 5. Note in this exploded view of a plate condenser how the size of the connections have been designed to fit the condensation duty

slides inside a girder frame that is bolted to pressure-retaining panels. Inlet and outlet nozzles are welded to the panels, and their size and position are adapted to the specific duty of the condenser. By design, it is a crossflow heat exchanger. Any number of baffles can be inserted between the plate stack and the panels to make up the required number of passes in a globally cocurrent or countercurrent condenser.

Applicability and features. This type of condenser is normally mounted horizontally, as shown in Figure 2. The vapor enters through a large nozzle in the top panel and is distributed in the parallel channels. Condensate and NCGs are extracted through a nozzle in the bottom panel. The cooling liquid enters through a nozzle in one of the side panels. Depending on the inlet and outlet temperatures of both the hot and cold fluids, the cooling liquid may run in single or baffle-guided multipass flow through the heat exchanger.

The relatively short flow path on the vapor side of a welded-block plate condenser compensates for the narrow (typically 5-mm or 0.2-in.) plate-type channel, so that the pressure drops are kept low, even at high vacuum. Due to a combination of highly efficient heat transfer surfaces and the

use of baffles on the coolant side, close temperature approaches and efficient NCG cooling are possible with this condenser option.

For applications involving larger amounts of NCGs (typically >1% of inlet vapor mass flowrate), a baffle can be inserted on the condensing side, next to the top panel, thereby creating a two-pass condenser. With such a setup, the majority of the condensation takes place in the first pass (downward flow), while further condensation and NCG cooling takes place in the second pass (upward flow), which also serves as a mist eliminator. In terms of ability to adapt the once-built design to changing service conditions the welded-block plate condenser ranks between the S&T and the plate-and-frame exchanger.

The design is quite compact, which creates the potential for large installation cost savings. Figure 3 shows an application involving ammonia, where three welded-block plate condensers perform about 50% more duty than three S&T condensers, in just a fraction of the space. In this particular case, the cost of retubing S&T condensers with stainless steel tubes was investigated but found to be considerably higher than the cost of three new welded-block plate condensers in stainless steel.

Plate-and-frame condensers

Design. The plate-and-frame condenser consists of thin, corrugated metal sheets assembled between thick, pressure-retaining end plates (Figure 4). The tightened plate package forms two separate flow compartments, which are sealed by either gaskets or seam welds.

The hot fluid, vapor in this case, is directed through one of the two upper connections, through the manifold duct and then downward into every other channel. The condensate and NCGs are extracted via the corresponding lower outlet connection. The coolant is similarly directed to the second flow compartment where it may flow either co-current or counter-current to the vapor.

Applicability and features. Due to issues of potential chemical or thermal incompatibility, the use of rubber gaskets often poses a restriction on the use of plate-and-frame condensers in CPI applications. In the pair-welded design (in which seam welds and rubber gaskets alternate), every second channel is sealed by a seam weld. If the fluid that is aggressive to rubber gaskets is contained in the welded channels, the chemical compatibility problem can often be overcome.

In the all-welded design, all gaskets are replaced by seam welds, so chemical compatibility problems are eliminated. In addition, the maximum operating temperature is increased to 350°C (660°F). By comparison, the practical temperature limit with rubber gaskets is 180°C (350°F).

The classical plate-and-frame exchanger was developed for liquid-to-liquid duties but can be used for vapor condensation in many cases. Particularly for pressures above atmospheric, it can be a cost-competitive alternative to many other condenser options.

The efficient heat transfer, in combination with true countercurrent flow, enables a relatively small surface area, the possibility for heat recovery with a very close temperature approach of 1–2°C (2–4°F), and very efficient NCG cooling. Other features of the plate-and-frame condenser include low weight, a small footprint and small holdup or retention volume. Depend-

ing on the sealing method (gasket/gasket, gasket/weld, weld/weld), the plate-and-frame condenser also offers the possibility to add or remove additional plates to customize the amount of surface area needed, and provides easy access to the same for inspection or maintenance.

The major disadvantage is most apparent below atmospheric pressure, when the narrow distance between the plates (typically 3 to 5 mm, or 0.1-0.2 in.), will create relatively high pressure drop. In order to achieve a reasonable pressure drop, more plates have to be added, but this tactic can easily oversize the unit in terms of heat transfer area, which may make this type of condenser less cost-competitive than other options. Another disadvantage is that the dimensions of the connections are not well-suited for low-pressure vapors, as the velocities through these connections will be too high.

Plate condensers

Design. The plate condenser is based on the plate-and-frame heat exchanger, but it is tailor-made for low-pressure condensation. In this context, low-pressure refers to pressures below 0.2 bar absolute (3 psia). The plates are pair-welded, again to avoid the need for rubber gaskets and thus allow these condensers to be able to handle aggressive vapors that flow inside the welded channel.

Meanwhile, the connection sizes have been adapted to fit the volumetric flowrates of the inlet and outlet streams (Figure 5.) A large inlet connection can accommodate large amounts of low-pressure vapor with moderate velocity and small pressure drop. Condensate and NCGs are extracted through two smaller connections at the bottom. The coolant enters and exits through two centrally placed, medium-sized connections.

Applicability and features. The plate condenser can be used advantageously for high-vacuum duties where the normal plate-and-frame fails. The pressure drop in the vapor channels is kept very low due to a relatively short flow path and a large channel gap on the vapor side. The pattern of the plates is designed to keep the vapor pressure losses low yet allow for a

high turbulence corresponding to a high heat transfer capacity.

The large channel gap for the vapor is counteracted by a small gap on the coolant side, where it is important to keep a high velocity and turbulence, in order to get a good heat transfer performance. Due to the countercurrent flow, NCGs can be cooled very efficiently, which decreases the load on the downstream vacuum system.

The low pressure drop and customized connection sizes, in combination with the features of the pair-welded plate-and-frame, make the plate condenser the most cost-efficient choice for most low-pressure condensation applications.

Spiral condensers

Design. The spiral condenser, like the spiral heat exchanger, consists of a long metal sheet that is wound like a spiral around its center. Studs are spotwelded to the sheet to keep the distance to the next outer turn of the sheet, and thereby create two separate flow channels. These are originally open along their outer edges and can either be left completely open for lateral flow, or welded so that a channel is closed on either one or both sides.

Standalone condenser. The wound spiral body is welded to the inside of a cylindrical vessel, as shown in Figure 6. The vapor enters through a nozzle at the top and flows through the open channel, where it is exposed to walls that are cooled by the coolant. The coolant flows in the spiral channel that is closed on both sides. Condensate and non-condensed gases are extracted at the bottom of the vessel through separate nozzles. This design offers a very low pressure drop and the possibility to handle large amounts of NCGs.

Top-mounted. The vessel assembly can also be placed directly on top of any column to drastically reduce the need of piping, pumps and structures (Figure 7). Here, the vapor enters from below, flows up through a central pipe, makes a 180-deg turn and then down through the spiral body, as in Figure 6. The condensate can either be directly refluxed back into the column or extracted via a baffle arrangement.

Applicability and features. The

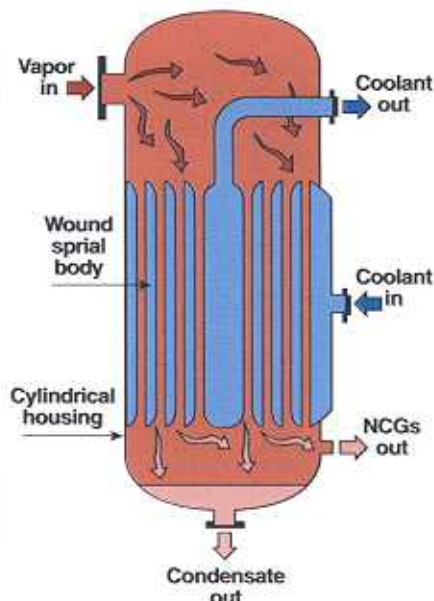


FIGURE 6. As shown in this schematic of a standalone spiral condenser, the vapor channel is completely open both at the top and the bottom to provide very low pressure drop

open flow channels for the vapor makes the spiral condenser well-suited for condensation duties at very low pressures (typically below 0.1 bar absolute, or 1.5 psia). Also, large amounts of NCGs can be effectively handled in all designs. At pressure above atmospheric, the spiral condenser works equally well, but may not always be cost-competitive. As with S&T and plate-fin condensers, there is virtually no flexibility in adapting the design for changing duties once the unit has been built.

From a heat transfer point of view, the spiral condenser outperforms the S&T condenser when the cooling side is the thermally limiting factor. This is due to the turbulence-promoting studs and the curvature of the surface, which help to enhance the heat transfer performance. As with the S&T condenser, cooling of NCGs is not particularly effective in a spiral condenser, due to cross-flow.

Plate-fin condensers

Design. Fin structures are fixed by brazing, and located between non-corrugated parting sheets that are typically made of aluminum. The fins have two functions: to enlarge the available surface area, and to act as structural support between the plates. From a



FIGURE 7. In this installation, a column-mounted spiral condenser is installed on top of a dehydrator column (and highlighted in the circle)

Multi-streaming also facilitates efficient NCG cooling. A small hydraulic diameter, typically 1 to 2 mm (0.04 to 0.08 in.), enables relatively high heat transfer, a very compact design and a temperature approach of 1–2°C (2–4°F). However, for vacuum applications, the resulting pressure drop will restrict the use of this type of condenser. Another drawback is a lack of flexibility once the condenser is built.

pressure-retaining point of view, the core of plates and fins is self-supporting. External headers and side plates are fitted to make the heat exchanger complete. The construction is based on the crossflow principle and allows multi-stream design. Up to 18 streams have been used in the same core.

Applicability and features. As a condenser, the plate-fin heat exchanger has found use mainly in cryogenic applications, such as air separation, hydrocarbon processing, and industrial and natural gas liquefaction. At higher temperatures, typically 150°C or 300°F, the mechanical characteristics of aluminum are less well-suited, and stainless steel or copper often replaces aluminum as the construction material of choice.

Multi-streaming is the practice by which many different streams within one heat exchanger body are used to cool, heat, condense or vaporize. Plate-fin condensers that use multi-streaming are able to use different coolants at different temperatures, which makes this type of condenser extremely compact when compared to a configuration in which several condensers are connected in series. By contrast, many other types of condensers are typically able to handle one coolant stream within one body.

Some final thoughts

Today, there are many compact alternatives that perform as well as, or better than, the workhorse S&T condenser. In many cases, they are superior to the S&T in terms of operating and installation cost, heat transfer and size. It is fair to say that none of the compact types are as widely applicable as the S&T, but for most duties below about 300°C (570°F) and 30 bar (440 psi), it is possible to find a suitable compact alternative.

To help users to overcome resistance to these newer options, manufacturers and vendors of compact condensers must continue to demonstrate the viability of existing and new compact condensers, in terms of reliability and savings. However, in order for the CPI to capitalize on the cost and performance improvements of compact condensers, ongoing research-and-development activities are also required. For instance, new theories and correlations for heat transfer and pressure drop must be developed for compact designs.

New types of condensers will also need new design guidelines, and these must be based on extensive live testing. Here, it will be helpful if design procedures are incorporated in design software suites, such as those from Heat Transfer Research, Inc. ([\[net.com\]\(http://net.com\)\) and Heat Transfer and Fluid Flow Service \(\[www.htfs.com\]\(http://www.htfs.com\)\), and in commercially available process-simulation software.](http://www.htri-</p>
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Furthermore, product development must be focused on dedicated condensers, not on all-purpose compromises. The plate condenser is a good example of a new tailor-made condenser that arose from the well-known and proven plate-and-frame technology. Large cost savings are available, but concerted efforts from universities and research institutes, equipment manufacturers, contractors and end users will be necessary in order to achieve these savings in the end. ■

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Engineering

The first step in the design process is to define the problem. This involves identifying the requirements and constraints of the project. Once the problem is defined, the next step is to develop a conceptual design. This is done by brainstorming ideas and sketching out the basic layout of the system. The conceptual design is then refined into a preliminary design, which is used to estimate the costs and schedule of the project. The final step in the design process is to develop a detailed design. This involves creating a set of drawings and specifications that will be used to manufacture the system. The detailed design is then reviewed and approved by the client.

The design process is a complex and iterative one. It often involves several cycles of design, testing, and refinement. The designer must be able to communicate effectively with the client and other team members. They must also be able to work under pressure and meet deadlines. The design process is a key part of the engineering profession, and it is essential for the success of any engineering project.

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