Scaling

Steven Vallee, Brent Heyrman, Doug Decker and Doug Ducote, Chart Industries Inc., USA, look at the scale-up of plate-fin heat exchangers for a mid scale LNG process.

Luminium plate-fin heat exchangers are at the heart of Chart's IPSMR® liquefaction process and modular plant solutions that offer a CAPEX basis for the liquefaction of natural gas below that of a traditional baseload facility. This article will take a detailed look at the key characteristics of brazed aluminium plate-fin heat exchangers (BAHX) pertinent to the successful scale-up for liquefaction technology. Consequently, it will examine the relationship of flow distribution to thermal performance and describe the techniques used to promote uniform flow distribution as a BAHX system is scaled from a layer to a pitch to a block to a battery.

Plate-fin heat exchanger

A BAHX, as defined by ALPEMA¹, consists of a block (core) of alternating layers (passages) of corrugated fins. The layers are separated from each other by parting sheets and sealed along the edges by means of side bars, and are provided with inlet and outlet ports for the streams. The block is bounded by cap sheets at the top and bottom. A figure of a BAHX with some segments cut away so that the internals can be seen² is shown in Figure 1.

Heat transfer and pressure drop

While a BAHX is typically larger than a vehicle, it is important to remember that all heat transfer is local at the millimeter level. Heat transfer in a BAHX takes place almost entirely by a convection mechanism between the fluid and the metal, which is comprised of a fin and parting sheet. A fin height is typically 6 - 10 mm and a fin spacing is typically 1 - 3 mm, yielding a channel size range of 1 mm x 6 mm to 3 mm x 10 mm. An



Figure 1. Brazed aluminium heat exchanger sketch with some segments cut away so the internals can be seen.



Figure 2. Cross section of a plate-fin layer.

example of the cross section of a plate-fin structure is shown in Figure 2.

Once a fluid is flowing in a channel, there is usually very little communication with the fluid in the other channels.

The sensitivity of heat transfer to the flow distribution among channels is examined in the following analysis. The governing convection equation is:

Equation 1:
$$q = h (A_p + \eta A_s) (T_w - T_b)$$

Where q is the amount of heat transferred, h is the convective heat transfer coefficient, A_p is the primary heat transfer surface area, η is the fin efficiency, A_s is the secondary heat transfer area, T_w is the wall temperature, and T_b is the fluid bulk temperature.

For single phase heat transfer, the convective heat transfer equation is:

Where j is the Colburn j factor (dimensionless heat transfer coefficient), G is the mass velocity, Cp is the heat capacity, and Pr is the Prandtl number. The Colburn j factor as a function of flowrate can then be expressed in the form:

Equation 3:
$$j = A Re^{N}$$

Where A is a constant with respect to the flowrate, Re is the Reynolds number, and N is typically between -0.7 and -0.2. For a given fixed geometry, removing thermophysical properties and substituting equation 3 into equation 2 yields:

Pressure drop in a fin channel can be characterised by the equation³:

Equation 5:
$$\Delta p = 4f \frac{L G^2}{D 2p}$$

Where Δp is the pressure drop, f is the Fanning friction factor, L is the channel length, D is the hydraulic diameter, G is the mass velocity, and p is the fluid density.

Test data for plate-fin structures⁴ has found that f can be expressed in the form:

Rearranged for the mass velocity:

Equation 7: G α Δp^(0.5 to 1.0)

Combining equation 7 with equation 4:

Equation 8: *h* α Δp^(0.3 to 0.4)

Equation 8 demonstrates that the heat transfer coefficient is proportional to the pressure drop along a pressure drop path, but, with the exponent of 0.3 to 0.4, the heat transfer coefficient is not extremely sensitive to pressure drop changes. Therefore, developing uniform heat transfer coefficients should tend toward stability when fluctuations are encountered, even when a heat exchanger design has non-uniform pressure drop paths. The heat transfer coefficient will vary less than the pressure drop or flowrate does.

Chart has proprietary fin designs, and Fanning friction f data and Colburn j data for each fin design is based on experimental testing. Commercial software is available to calculate heat transfer and pressure drop performance for these surfaces not only for single-phase fluids, but also for two-phase fluids. Two-phase fluid heat transfer and pressure drop principles are similar to single-phase fluids in that heat transfer coefficients and pressure drop are also a function of mass flux.

Distribution

In a BAHX, pressure drop of a single stream among multiple flow paths will always be equal; flow to each path will vary such that the pressure drop is the same. Therefore, to promote uniform flow distribution, one must promote uniform pressure drop. This also implies that one must have the ability to calculate pressure drop for multiple flow paths. Chart has the ability to rate heat transfer performance with varying distribution of flow.

After performing many rating calculations, the company has developed design guidelines on how uniform the flow distribution must be and how to promote uniform flow distribution. One technique that is useful in promoting uniform distribution is to maximise the pressure drop in the location where it is desired to have uniform flow (heat transfer finning, two-phase distribution devices), while minimising other pressure drops. The weak dependence of the heat transfer coefficient as a function of flowrate helps to dampen fluctuations and give uniform thermal performance in a BAHX, as the heat transfer coefficient will generally vary less than the pressure drop or flowrate does.

Achieving proper flow distribution through uniform pressure drop is less predictable for two-phase streams. The large density difference between the liquid phase and the vapour phase in a two-phase stream can cause flow maldistribution, particularly in parts of the exchanger with large open cross sections, such as the manifolds and the headers. Maldistribution of a two-phase stream can have a significant impact on the actual exchanger performance vs the simulated exchanger performance. The liquid will take significantly less of the heat transfer area/volume due to its higher density than the vapour phase, but the liquid phase has higher heat transfer coefficients and a higher duty (in boiling services). Therefore, assessing the impact of two-phase distribution and developing design criteria to avoid two-phase maldistribution is critical.

BAHX construction

Layer

A layer contains the flow of a particular stream, and the layers are separated from each other by parting sheets (the outer most layers are sealed on the ends by a cap sheet) and sealed along the edges by side bars. As shown in Figure 3, a simple layer has one stream with an entry port and distributor (1), a heat transfer section (2), and an exit port and distributor (3). Layers can be more complex, with multiple streams entering a layer, but this example is limited to a simple layer. Layer heights are typically 0.375 in. or 0.25 in. Layers are typically 4 ft wide and can be more than 20 ft long. The small layer heights and variety of Chart fin geometries allow for optimised velocities for each stream, unlike shell and tube exchangers, in which the shell velocities are dictated by the tube bundle geometry.

Flow maldistribution can occur due to the different flow path along the left side vs the right side of the layer. For example, in Figure 3, the left hand side will have a lower frictional pressure loss in the entry distribution finning (1), and a higher frictional pressure loss in the exit distribution finning (3) relative to the right hand side. Therefore, it is desirable to configure the entry distributor and the exit distributor to balance the pressure drops through the left side vs the right side flow paths. Note that balancing the left hand vs the right hand pressure drops usually does not mean equivalent distributor sizes, due to the following reasons: change in fluid density with temperature and/or phase; different inlet vs outlet distributor type; and different inlet vs outlet distributor



Figure 3. Layer geometry.



Figure 4. Example of a pitch of layers in a heat exchanger in an LNG application.

finning. The left hand side flow path and right hand side flow path through the heat transfer finning (2) are identical. Therefore, even flow distribution through the layer can be promoted by increasing the pressure drop in the heat transfer finning (2) relative to the pressure drop in the entry distribution finning (1) and the exit distribution finning (3).

Commercially available software can calculate distribution finning and heat transfer finning pressure losses. Chart designs each stream's layers to promote uniform flow distribution. As this calculation is on a single layer basis, there are no scaling issues when more layers are added. This technique has been proven in service for the IPSMR process at plant sizes of 0.3 million tpy, and other LNG processes up to 5.2 million tpy.

Pitch

A pitch is a group of layers that are repeated a number of times along the exchanger height. A pitch is generally the basic group of layers that exchange heat with each other. A typical pitch may only be 3 or 4 in. along the stack height. A design goal for a pitch is to provide uniform heat transfer in the pitch so that it is essentially an adiabatic entity. An example of a six-layer pitch for a heat exchanger in an LNG application is shown in Figure 4, where LPR is low pressure refrigerant and HPR is high pressure refrigerant.

Chart calculates the heat transfer performance of the exchanger (and, therefore, all of the pitches), utilising commercially available software. While the pitch arrangement varies significantly from design to design (BAHXs can have anywhere between two to more than 20 streams), the general concept is to maximise the number of essentially adiabatic, and symmetric pitches, while minimising the overall BAHX size.

Block

When the required volume of flow is more than one pitch can handle, a stack of pitches is used to form a block. A block is a collection of pitches stacked on top of one another up to the maximum height that can be brazed into a single block. Very little heat is exchanged between the different pitches in the block when they are stacked together, since effort is made to design the pitch per the criteria.

In scale-up, the number of pitches can be increased as needed to meet the total flow requirement, as long as the flow distribution entering each layer remains the same. As already stated, it is desirable to design as much pressure drop into the layer as allowed and minimise other losses.

The nozzle is a stub pipe that is used to connect the exchanger to the process piping. The nozzle connects to a header, which is used to distribute the flow to the entry or exit ports of the layers associated with that stream. There is an expansion/contraction pressure loss associated with the nozzle to header transition (1), and the header to port transition (2), as shown in Figure 5. These pressure losses are calculated in commercially available software.

Chart has methodology to analyse the distribution of flow through the header to each individual pitch. It has calculated a maximum mass flow difference of 4% between pitches for a worst case exchanger design/operating case for the IPSMR process. The maximum mass flow difference between pitches for typical IPSMR designs is approximately 2% at design flowrate. Even distribution of the flow from the header to the individual ports is achieved due to the negligible pressure drop associated with flow through the header relative to the pressure drop associated with the layers.

Battery

When the required volume of flow is more than one block (one stack of pitches) can handle, multiple blocks of heat exchangers are piped together in parallel to perform as one heat exchanger. A group of blocks piped together is called a



Figure 5. Example of a nozzle and header.



Figure 6. Example of a multi-core battery.



Figure 7. Layout of separation vessel, core and piping.

battery or assembly, and the connecting piping is referred to as manifolds (Figure 6).

There is an expansion/contraction pressure loss associated with the flow transition between the manifold and nozzles. Commercially available software can be configured using standard pipe network methodology to assess the impact of flow distribution in the battery. Each block is modeled as an individual exchanger in a pipe network. For distribution purposes, it is desirable to design as much pressure drop into the block as allowed and minimise the piping losses in the manifolds (this minimises the flow maldistribution from block to block).

Two-phase inlet distribution

Proper flow distribution for a two-phase inlet stream is less predictable. Therefore, the following methodology to assess the impact of two-phase maldistribution, and design criteria to avoid two-phase maldistribution, is utilised for two-phase streams in Chart's IPSMR process. The first step is to assess if a stream is in two-phase flow during any steady state operating cases. If it is, then a flow regime analysis can be performed to evaluate the flow characteristics of the stream.

For two-phase streams in a flow regime of concern (slug flow, annular flow, etc.), two-phase maldistribution can occur. Chart has developed a method to assess the potential effect of two-phase maldistribution on the exchanger performance. This method varies the amount of mixing of the liquid with the vapour in the two-phase stream (from fully mixed to complete phase separation), and measures the impact on the stream temperature and thus the exchanger overall heat transfer coefficient per unit area (UA). As the amount of liquid mixed with the vapour decreases, the UA required increases due to the changing mixture temperature pinching the cooling curve of the exchanger.

In some cases, separating the liquid and vapour and then introducing them in a controlled manner may be advantageous. For two-phase streams where the UA increase associated with the mixing percentage with no device or perforated plate is detrimental, or for manifolded assemblies of exchangers (where two-phase flow separation can occur not only within the individual core header, but also within the manifolding piping), a separation vessel and a two-phase distribution device are used. Separating the liquid from the vapour in a vessel, and then separately manifolding each phase, ensures that equal amounts of liquid and vapour are sent to every individual core block. Two-phase distribution devices can be inserted at the inlet of any stream or any point along the core length for any stream. A model of the layout of the separation vessel, core, and piping is shown in Figure 7.

The liquid distribution is controlled by having most of the liquid path pressure drop located in the liquid distribution device. The liquid pressure drop, due to other factors (nozzles, manifolds, piping), is kept low, so the liquid path pressure drop from P1 to P2 is mostly at P2.

Chart has developed state-of-the art liquid distribution devices that are incorporated within the core block for BAHX designs for its IPSMR process. These liquid distribution devices allow the introduction of mixed refrigerant (MR) into the heat exchanger at precise locations along the heat exchanger to 'tune' the boiling refrigerant cooling curve and provide a very efficient and robust single mixed refrigerant (SMR) process.

The vapour distribution device exit openings are sized to keep the vapour velocity sufficiently high to prevent liquid runback. The pressure drop, due to other factors (nozzles, manifolds, piping), is kept low.

The liquid level in the vessel relative to the distribution device is determined by the difference in pressure drop between the liquid path and the vapour path from P1 to P2.

Since the two-phase distributor devices are static, the range of liquid and vapour flowrates to meet design criteria and maintain good distribution is limited. Chart has performed numerous designs for its IPSMR process, and confirmed that a flow range of 50 - 110% of design flow can be achieved with uniform distribution.

The vessel diameter is sized to reduce the vapour velocity in the vessel to prevent entrainment of the liquid by gravity separation. For this application, a high degree of separation is not required. The company has developed guidelines for vessel sizing from a variety of sources, including HTRI⁵, GPSA⁶, and Bechtel.⁷ These criteria are used to design vessel parameters, such as aspects of the vessel length and nozzle sizes.

Conclusion

Thermal performance of a BAHX is dependent on promoting uniform flow distribution. The essence of promoting uniform distribution is to maximise the pressure drop in the location where it is desired to have uniform flow distribution, while minimising other pressure drops. For single-phase flow, the heat transfer coefficient typically varies less than the pressure drop or flowrate does, helping to promote uniform thermal performance.

Commercially defined methodology and commercially available software can be configured to evaluate the impact of

distribution across the width of a layer, between layers, and between blocks in a battery.

Distribution of two-phase streams is especially important since, as the amount of liquid mixed with the vapour decreases, the UA required may increase due to possible changing mixture temperature pinching the cooling curve of the exchanger. Chart has developed methodologies for analysing the impact of maldistribution of two-phase streams, and guidelines for two-phase distributor design.

The company's BAHX design criterion promotes uniform distribution. Chart utilises in-house engineering know-how, experimental test data, commercially defined methodology, and commercially available software to rate the thermal performance effect of any potential flow maldistribution. It also ensures that any flow maldistribution effects on thermal performance are accounted for in the design process.

The IPSMR process uses best practices to ensure scale-up of the BAHX package. Chart can match BAHX capacity to the largest aeroderivative gas turbines available, making train size a natural fit and an efficient and cost-effective modular design. BAHXs for the IPSMR process are always oriented with the cold end down – a preferable arrangement to prevent cryogenic liquids from flowing to the warm exchanger surfaces during shutdown. The company has developed state-of-the-art liquid distribution devices that are incorporated within the core block for its BAHX designs. These liquid distribution devices allow the introduction of MR into the heat exchanger at precise locations along the heat exchanger to 'tune' the boiling refrigerant cooling curve and provide an efficient and robust SMR process when utilising a BAHX. Scale-up of the IPSMR process is easily accomplished with current BAHX technology. LNG

References

- 1. The Brazed Aluminum Plate-Fin Heat Exchanger Manufacturers' Association, The Standards of the Brazed Aluminum Plate-Fin Heat Exchanger Manufacturers' Association, (2010).
- 2. Chart Energy & Chemicals, Inc., 'Installation, Operation and Maintenance Manual for Chart Brazed Aluminum Heat Exchangers (BAHX) and Core-in-Kettle[®] Assemblies', (2015).
- PERRY, et al., Perry's Chemical Engineers' Handbook, sixth edition, (1984), pp. 5 – 24.
- 4. Chart Energy & Chemicals internal fin testing data.
- 5. Heat Transfer Research Inc. Reports Book 3B, BK $1-2, \ (1970).$
- Gas Processors Suppliers Association Engineering Data Book, Vol. 1, 13th edition, (2012).
- DIWAKAR, P. and VALAPPIL, J., Bechtel Oil, Gas & Chemicals, Inc., 'Efficient Operation of Vertical Liquid-Gas Separators', AIChE Spring Meeting, (2015).



Innovation. Experience. Performance. ®

Website: www.chartindustries.com E-mail: bahx@chartindustries.com