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TECHNICAL BULLETIN

Topic: Low-charge DX Ammonia Industrial Plant Design
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When designing an industrial refrigeration plant for low-charge (DX) ammonia, there are a number of critically important concepts to consider which differ significantly from traditional pumped ammonia plant design. These "big ideas" are described briefly below.

I. Capture and Removal of Water
II. Oil-less (<1 ppm) Ammonia Liquid
III. Oil-less Hot Gas for Defrost
IV. Subcooled Ammonia liquid
V. Evaporator Design
    a. Mitigating Separated (Stratified/Wavy) Flow
    b. Managing Non-Uniform Distribution
    c. Managing Non-Uniform Circuit Loading

<u>Removal and Capture of Water</u>. It has been observed that most pumped ammonia refrigeration plants in operation in northern Europe operate with an average of 2-6% water in the ammonia liquid (Nielsen 1998). In the UK similar amounts of water in ammonia refrigeration plants were measured (Cotter 2007). 2-6% water in ammonia shifts (increases) the bubble point at the entrance to the evaporators by 0.4 to 1.3 °K (0.7 to 2.3 °F). As the ammonia-water liquid boils through the evaporation process, the water is "left behind" in the remaining liquid and the water concentration increases, increasing the bubble point and reducing the capacity of the evaporator.

In pumped ammonia evaporators operating with circulation numbers of n=3 or 4, this effect of increasing bubble point is somewhat masked, and many times is not noticed by the plant operators. However, the negative effect of the water (increasing bubble point) becomes more and more pronounced as the circulation number falls below about n=2 (Nelson 2010). In the case of a direct expansion (DX) evaporator, where n=1, even small amounts of water in the ammonia liquid results in a severe penalty (as much as 50%) to evaporator performance. Control of superheat at the exit of a DX ammonia evaporator operating with water in the ammonia also becomes problematic (in fact, impossible).

Therefore, good performance and control of DX ammonia evaporators depends on supplying liquid ammonia to the evaporators which is dry or very nearly dry. Fortunately, this is not difficult to do if the refrigeration plant is designed with the low pressure vessels piped in such a way that water is captured and retained on the low side of the system. This design strategy is explained in detail in the DX Ammonia Piping Handbook published by Colmac Coil Manufacturing (Nelson 2016). Essentially, a DX ammonia refrigeration plant should be designed so that it "dries itself out" by recognizing that any water that enters the system can be "distilled" in the evaporators during normal operation and captured and held in the low pressure accumulator vessel(s). Capturing and keeping the water in in the low pressure vessels, rather than transferring it back to the high side of the system with some type of transfer system, is the important point. A plant designed in this way will, over a short period of time, result in very dry ammonia being found in the high pressure receiver which can then be subcooled and delivered to the evaporators.

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Oil-less Ammonia Liquid. The vast majority of industrial ammonia refrigeration systems use immiscible lubrication oil in the compressors. Most of this oil is captured in coalescing oil separators installed in the discharge line at the outlet of the compressor(s). These separators are very efficient and capable of removing oil from the discharge gas to approx. 10 ppm oil in ammonia.

The coalescing elements in these separators are designed to capture and coalesce the liquid oil droplets entrained in the discharge gas, however, they cannot remove the oil that is in the vapor phase which passes through the separator with the ammonia vapor. Hence, there is a theoretical limit to the amount of oil that can be separated, captured, and returned to the compressors in these vapor-liquid separators. 10 ppm oil in the ammonia vapor does not sound like a lot, however, this oil which will pass into the system piping, vessels, and heat exchangers has a number of very negative effects:

- Fouling of heat exchanger surfaces and reduction of cooling capacity,
- Health and safety risks associated with periodic draining of oil from vessels and heat exchangers,
- Cost of replacing the lost oil in the compressors

The amount of oil escaping the separator can be calculated as in the following example:

System Cooling Duty: 1 MW
Operating Hours per Annum: 8,000 h
Latent Heat of Vaporization @ -25°C: 1345 kJ/kg
Ammonia Mass Flow Rate: 2700 kg/h
Oil Mass Flow Rate @ 10 ppm: 0.027 kg/h
Total Mass of Oil Lost to the System: 216 kg/y
Total Volume of Oil Lost to the System: 0.25 m3/y (65.6 gal/y)

When put into the context of the volume of oil passing into a typical ammonia system (more than one 55 gal drum of oil every year), 10 ppm does not seem so small!

So, since immiscible oil escaping the separator and passing out into the system is undesirable in any type of ammonia refrigeration system, it would make sense to look for a way to remove it completely before the liquid ammonia leaves the engine room. That is, send only oil-less ammonia liquid out to the system in the liquid lines. Fortunately, any oil that escapes the separator in the vapor phase will condense to liquid oil in the condenser and end up in the high pressure liquid in the form of suspended oil droplets. These droplets can then be separated from the ammonia liquid by gravity, with or without the help of a coalescing element.

Companies producing refrigerant-grade oil-less ammonia are faced with this challenge of removing lubrication oil from ammonia as a normal part of their manufacturing process. The Pall corporation produces such devices for removing oil from liquid ammonia with coalescing elements (see: Pall PhaseSep Y Series Liquid/Liquid Coalescer). The company's oil separating device is described in the paper shown as a reference below (Wines 1998). The Danish consulting company, Cool Partners, also developed a gravity separation device for removing immiscible oil from liquid ammonia (their "CPO" vessel) which they claim to produce ammonia liquid with <1 ppm oil.

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As described below, DX ammonia evaporators depend on enhanced internal tubing surfaces for proper "wetting" with liquid ammonia and good cooling performance. The enhanced surface typically consists of grooves or a "wicking structure" needed for developing sufficient capillary pressure to pull the small amount of liquid ammonia running along the bottom of the tubes up onto the tube walls where it evaporates and contributes to cooling capacity. Keeping the enhanced tube surfaces free of oil (and water) is critically important, and so supplying liquid ammonia to the evaporators that is oil-free is an important point. Any DX ammonia system should include a secondary (liquid-liquid) separation device to remove oil from the high pressure subcooled liquid.

Oil-less Ammonia Hot Gas. Most industrial ammonia refrigeration systems use ammonia discharge gas ("hot gas") for defrosting evaporators. Common practice is to take the hot gas directly from the compressor discharge and send it to the evaporators via a dedicated hot gas line. This design practice introduces whatever oil is contained in the discharge gas (minimum 10 ppm) directly into the evaporators during defrosting where it condenses into liquid oil which then coats and fouls the internal tubing surfaces.

Oil-less ammonia vapor for defrosting can and should be taken from the top of the high pressure receiver, downstream of the condenser. At this point the oil that was in the vapor phase has been condensed out of the discharge gas and is entrained in the condensed liquid ammonia. Since the majority of the energy released during defrosting the evaporators comes from the ammonia condensing process taking place inside the tubing, defrosting using this "cool" gas off the top of the high pressure receiver proceeds very nearly as fast as by using the superheated discharge gas, and most importantly, avoids fouling the evaporator tubing surfaces with oil.

Subcooled Ammonia Liquid. Active subcooling of the ammonia liquid leaving the high pressure receiver is critically important in a DX ammonia design to avoid the formation of flash gas in the liquid line due to:

- Increase in elevation (lift)
- Frictional pressure drop
- Heat gain

The subcooler needs to be installed immediately downstream of the exit of the high pressure receiver before the liquid enters the secondary oil separator.

Internally Enhanced Tubing. With smooth tubing (no internal enhancement) at evaporating temperatures below about -10°C (+14°F) it becomes difficult to design air cooler evaporator circuiting for an ammonia mass flux high enough to avoid separated (stratified/wavy) two-phase flow. Separated flow results in extremely poor evaporator performance and unstable expansion valve operation. Below -15°C (+5°F) it becomes impossible to design evaporator circuiting to avoid separated flow. With smooth tubing, the evaporator designer increases the circuit length required to reach a mass flux high enough to produce annular flow, but finds that the increase in frictional pressure drop results in very rapidly decreasing cooling performance.

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The solution is to use tubing with a surface enhancement which produces a "wicking effect" similar to the enhancements used in heat pipes. This "wicking structure" produces the capillary pressure needed to cause the stratified liquid ammonia running along the bottom of the tubes to be "pumped" up onto the walls of the tube where it can evaporate and produce boiling heat transfer coefficients similar to annular flow. Colmac Coil has developed effective wicking structures for ammonia which can be applied to either aluminum or stainless steel tubes. Because the wicking effect occurs at the surface of the tubing, unlike a turbulator device, the disturbance to the flow of the ammonia vapor is minimized. It was observed that these wicking structures cause a negligible increase in frictional tubeside pressure drop.

Non-uniform Distribution. With conventional industrial DX evaporator designs having multiple parallel circuits, a distributor device is required just downstream of expansion valve to distribute equal amounts of the expanded (two-phase) refrigerant into each circuit. These distributor devices use different approaches to achieve this distribution effect. One commonly used type of distributor uses an orifice plate to produce a relatively large pressure drop and mixing effect ahead of small diameter tubes ("leads") feeding each circuit. Another type uses a venturi section with a comparatively lower pressure drop to get the required mixing effect ahead of the leads. A third-type, called a "tank" distributor, works as a small gravity separation vessel to first separate the expanded refrigerant entering the tank, and then remix it into equal amounts of liquid and vapor at the entrance to each lead through graduated orifices. This tank distributor design operates with the lowest pressure drop of the three types.

In the author's experience, the different types of distributors mentioned above all perform slightly differently in terms of distribution effectiveness. In all cases the challenge of getting exactly equal amounts (by mass) of refrigerant delivered to each circuit increases with the number of parallel circuits and the size of the evaporator. Other factors such as the amount of liquid subcooling at the expansion valve inlet can also affect the distribution effectiveness. Distributing different amounts of refrigerant to each circuit is what is termed non-uniform distribution. A conventional DX evaporator expansion valve is controlled based on a superheat signal. An industrial evaporator having multiple parallel circuits with non-uniform distribution means that the circuit having the greatest mass flow of refrigerant will control this superheat signal and the position of the expansion valve. A design with very high non-uniformity can adversely affect cooling performance.

On large evaporators, one solution to non-uniform distribution is to design the evaporator with multiple distributors and expansion valves. Each expansion valve then operates to optimize performance in its own "zone". Another solution is to eliminate the refrigerant distributor(s) altogether by feeding each parallel circuit in the evaporator with its own expansion device. Colmac Coil has developed this technology, and refers to it as their "ADXi" system. This approach optimizes performance by eliminating the challenges described above related to non-uniform distribution.

Non-uniform Circuit Loading. Another similar challenge with DX evaporators arises when the load on each of the parallel circuits is unequal, or non-uniform. Similar to the non-uniform distribution problem described above, non-uniform circuit loading will cause the circuit with the lowest heat load to control the superheat signal and the expansion valve position. This non-uniform circuit loading in industrial DX evaporators can be caused by:

- Uneven frost accumulation
- Uneven dirt accumulation
- Airflow blockages or velocity gradients across the face of the evaporator
- Air temperature gradients across the face of the evaporator

The same solutions described above to solve the challenge of non-uniform distribution can be applied to mitigate and minimize performance penalties associated with non-uniform circuit loading, and will improve overall evaporator control and performance in many cases.

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