Interstage coolers, a "hot item"

by:
Titus M.C. Bartholomeus,
Senior Development Engineer,
Grasso Products b.v.

Introduction

Interstage cooling is necessary for two-stage compression to:

- cool down the compressed gas of the LP stage to a level acceptable for the HP stage, and/or
- to increase the total efficiency by subcooling the condensation.

Ambient air as refrigerant for interstage coolers of cold compressors is not an option, because:

- the compressed gas temperature is too low (R507/R404A), or
- the cooling is not deep enough and the remaining superheating is too much for the high pressure stage (R717).

Subcooling the condensation achieves the effect of slightly increasing the COP with ambient air, if the condenser has been designed correctly (division of the condensation and subcooling sections).

Machine cooling in the shape of a low pressure compressed gas cooler is not necessary for R507/R404A. The remaining superheating for the HP stage is a maximum 40K without cooling, and is not important to the HP compressed gas temperature. As described in the article "Two-stage piston compressors", the much lighter gas due to the superheating will influence the mass output of the HP stage by about 0.5% per degree. However, two-stage compression still remains a much better solution, even without a cooler on the interstage pressure. Dividing the pressure stages has an enormous influence on the swept volume, and therefore the cooling capacity.

Because ambient air is not an option, part of the refrigerant is used to evaporate at interstage pressure and discharge the compressed gas and condensation heat this way. This is a necessary evil, as:

The total refrigerant used for cooling the compressor is not used for product cooling and therefore directly reduces the cooling capacity! The lower the heat of evaporation of the refrigerant, the higher its influence. The loss in cooling capacity with R507/R404A is about 7 times higher than with ammonia.

By using an air-cooled compressed gas cooler as precooler in an ammonia two-stage compressor, the COP will increase by 5%, because less refrigerant is needed to cool the gas. As the interstage pressure is almost always below the starting temperature of the environment, the danger of refrigerant condensation is as good as impossible. Despite the small 20% heat extraction, it is a much more sensible decision to place a heat recovery on the LP compression rather than in the HP pressure line. Heat recovery in the high pressure does not directly influence the COP. The improved oil separation due to part condensation of the oil vapour present in the compressed gas will mean less plant pollution, but it makes the operational management much more complicated and therefore more susceptible to trouble.

Using a compressed gas condenser that is not cooled by refrigerant at the interstage pressure in an ammonia two-stage compressor is a reliable solution that increases the total COP by 5%.

If we cool gas through a condenser, so indirectly, the heat transfers are disrupted. That is why there is often a considerably increased heat transfer surface on the gas side. A suitable condenser is one of the tube & fin type.

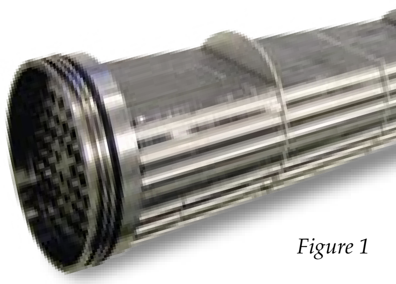


Figure 1

Much more intensive cooling can be achieved by putting the gas into direct contact with the evaporating liquid. The question we are now faced with, is: which method works best:

- evaporating drops in the hot gas flow, or
- cooling gas bubbles in a liquid bath?

We can use Nusselt (Nu) to find the answer:
Medium means the substance in which the drop/bubble is located.

$$Nu - 2 + 0.6Re^{1}/_{2} \cdot Pr^{1}/_{3}$$

$$Re = \frac{v_{drop,\ bubble} \cdot d_{drop,\ bubble} \cdot \rho_{medium}}{\eta_{medium}}$$

$$Pr = \frac{\eta_{medium} \cdot cp_{medium}}{\lambda_{medium}}$$

Evaporating drops in the hot gas flow

Refrigerant is injected through an expansion valve into a compressed gas pipe. Under the influence of the high pressure difference it atomizes and flash gas is created. The mist contains droplets with a diameter between 0.1 and 1 mm. Drops of this size will be swept along by the gas flow. The relative speed v_{drop} between the gas and the drop thus is zero, and thus Reynolds (Re) is also zero. That makes Nusselt (Nu) 2 for a drop, and the heat transfer of gas/drop.

$$\alpha_{\text{drop , bubble:}} \text{-Nu} \cdot \frac{\lambda_{\text{medium}}}{d_{\text{drop, be}}}$$

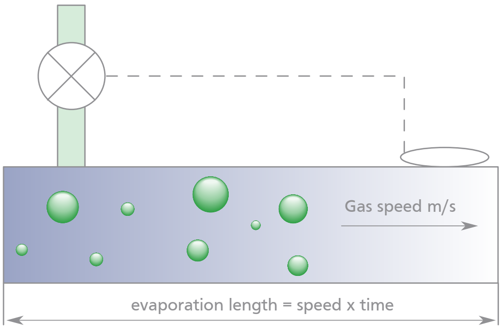


Figure 2

As example we take ammonia gas of about 100^{o}C at an interstage "pressure" of -10 ^{o}C. With the largest starting droplet diameter of 1 mm the heat transfer coefficient becomes α=100W/m2K. Diagram 3 shows the time required to evaporate an ammonia drop in a gas flow that is cooling down due to it.

Drops with a diameter of 0.1 mm need 1 second to evaporate; drops of 1 mm need 1 minute! Drops < 0.1 mm can only be obtained by using atomizers. The gas speed at this pressure is well above 10m/s. Consequently, if we need 1 second evaporation time, we require a pipe length between the low pressure compression and the high pressure suction of more than 10 m?! Of course, this is exceedingly impractical.

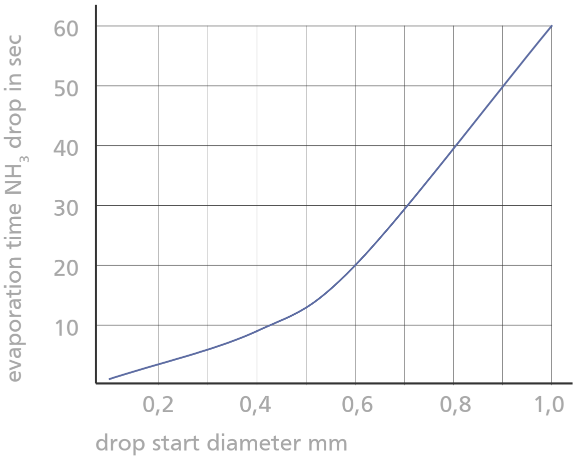


Figure 3

Cooling gas bubbles in a liquid bath

If gas flows through a hole in a liquid, bubbles form. The size of the bubbles depends on the speed in the hole, the shape of the hole and its diameter. Large bubbles will break up into several smaller ones when they rise, limiting the bubble size to 1 cm. The maximum rising speed of a bubble is 0.3 m/s. For ammonia Reynolds is about 10,000, Prandl is 1.6 and therefore Nusselt is 72. The heat transfer coefficient for the maximum bubble size of 10 mm then becomes about 4,000W/mK, 40 times more than the 1 mm drop in the gas.

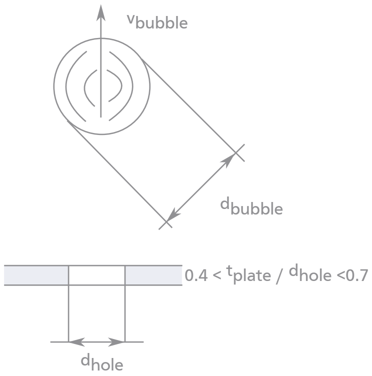


Figure 4

Conclusions:

1. **Cooling gas by bubbling works 40 x better than by evaporating drops**
2. **To cool a bubble to about 5 K above the saturation temperature, a maximum of 1 second is required**
3. **To evaporate a drop, a minimum of 1 second is required. That makes the required trajectory length impractically long (>>10 m)!**

Open flash, old-fashioned?!

Recipe for a "modern" open interstage cooler

The design of the bubbling system is extremely important for the refrigerant content, thus the bath depth (see diagrams 4 and 5).

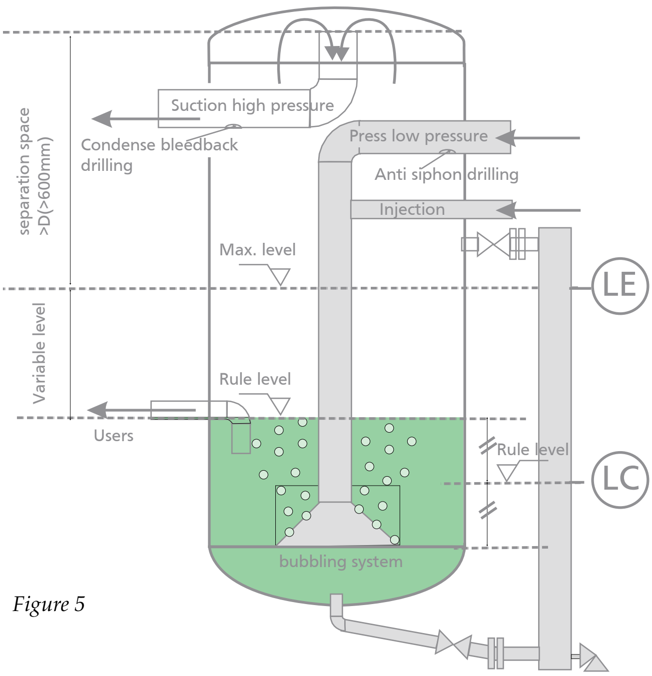


Figure 5

Bubbling holes that are too large and/or gas speeds that are too slow will result in discontinuous bubbling with large bubbles. A long bubbling time is required to have the gas cool down sufficiently. That is why bath depths of about 1 m are common, so that it is rarely used with the expensive synthetic refrigerants. As striving for lower filling while retaining the function is a priority, the bath depth will have to be reduced drastically. A well-thought out design can reduce the filling by >>80%:

- the pre-pressure in the bubbling system will have to be about 0.1K above the interstage pressure; then
- the bubbles will be no more than 2 times the diameter of the bubble hole. Bubbles larger than 1 cm break up when rising, so
- the bubing hole diameter must be < 5 mm.
- the bubbling system must be so designed that the bubbling pressure remains constant, also during part load.

With a well constructed bubbling system it is possible to cool the heavy synthetic refrigerants down to 5K superheating inside a bath depth of 100 mm. Ammonia needs a bath depth of 200 mm. At 300 mm the exiting gas is as good as saturated.

The diameter required for the open interstage cooler will have to be matched to the maximum expected gas discharge at maximum gas density, so the starting situation. As the rising speed of a bubble is a maximum of 0.3 m/s, it is not useful to choose a higher gas speed in the tank, even if the falling speed of the drop to be separated does allow this. On the basis of the above, the tank diameter can be calculated simply from the high pressure swept volume with the following derived formula:

$$\mathrm{Dtk\ (mm)} := K \cdot \left[V_{\mathrm{slagHD}} \cdot \left(\frac{\mathrm{m}^3}{\mathrm{h}}\right) \right]^{0.5} \quad K_{R717} = 35 \text{ en } K_{RXYZ} = 40$$

If the prevailing pressure in the interstage cooler is too small for the injection valves of the users, this can be solved by applying a condenser in or below the interstage cooler. Usually a coil is placed in the liquid bath of the interstage cooler. The coil consists of one or more lengths of rolled tube. At a condensation speed of about 2 to 3 m/s in the coil (pressure loss < 1 bar) and a desired subcooling of < 10K above the interstage "pressure", about 30 kW/m^2 can be transferred. A coil diameter that fits the tank diameter will become about 300 mm, which means the refrigerant filling is trebled. That makes a condenser built in beneath the interstage cooler a good, but expensive solution.

A detail often overlooked in the interstage cooler is the anti-siphon hole. This hole, situated in the bubbling tube a good way above the maximum level, ensures that the liquid bath is not siphoned into the compressor if the compressor is stationary. Siphoning can occur because the compression or suction valves always leak, even if that is just a little. The injection is therefore preferably mounted on the bubbling tube. If this is not done, when the injected condensation flashes a strong spray cone will arise, forcing the gas part to go much higher unnecessarily. At a speed of 0.3 m/s, the liquid bath will consist of more than 50% vapour. The level in an outside stand pipe, with no gas bubbling through the liquid, will therefore be at least half as much lower. The level controller mounted in the stand pipe must therefore be set to half of the desired level. The distance between the liquid surface and the suction pump must be at least equal to the diameter of the tank but no less than 600 mm. If the interstage cooler is also used to collect refrigerant variation on the user side, the liquid bath will have to be able to vary equally as much.

Advantages:

- it is possible to cool the low pressure compressed gas to saturation
- the buffer function makes it less sensitive to fluctuations in the condensation supply
- the liquid-separating capacity means oil remains behind and with NH_3 plants this oil can be returned to the compressor
- condensation can be subcooled down to interstage "pressure"
- highest possible COP

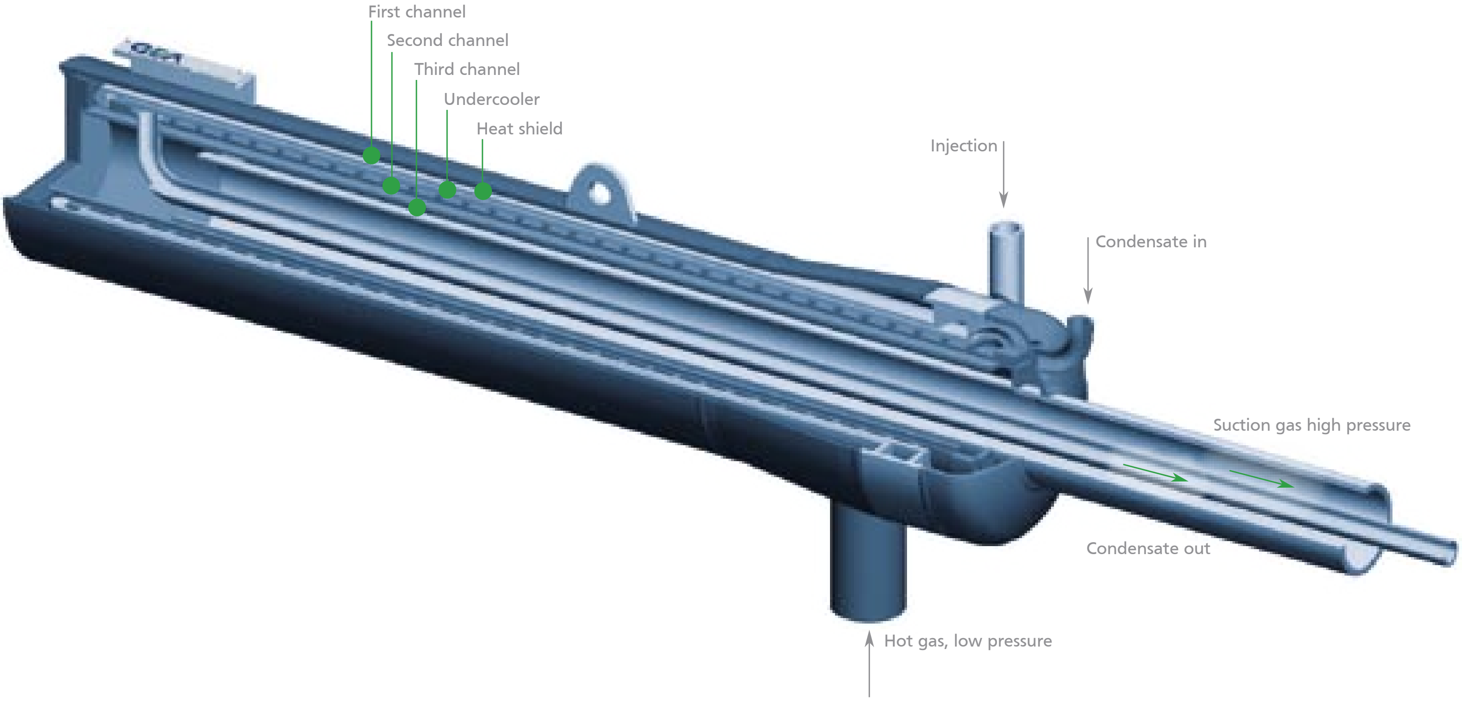
Disadvantages

- high refrigerant filling
- low pre-pressure at start over user injection
- pressure equalization required for unloaded starting
- longer “pull down” time
- the liquid-separating capacity means oil remains behind; this oil can pollute the low pressure system
- 2 oil separators required per compressor
- extra piping, shut-off valves, non-return valve and suction filter
- insulation
- automatic block shut-off valves around pressure vessel
- level control and alarm
- complicated and expensive

Ammonia DX is Nothing?!

Interstage cooler with gas cooling and/or condensation subcooling by refrigerant injection

Because this kind of interstage cooling system is much less expensive, it continues to stimulate the developer. As the above shows, an impractically long flow channel is needed for evaporation of a floating drop. Up to now, "tricks" have been applied in the attempt to solve this, stretching physics and therefore also the connected compressor cylinders. Shortening the floating path turned out not be meaningful, because a drop simply needs a certain amount of evaporation time. The answer to this contradiction is: slow down the drops!



If a gas flow charged with drops flows through a slit-shaped channel fast enough, the drops will fly to the slit wall as if attracted to it. This is called the Coanda effect. The drops that hit the slit wall now flow further at an extremely low speed (<< 1 m/s). Various changes in direction will eventually get all the drops to hit the slit wall and slow down. To prevent the slowed down liquid from sinking to bottom due to gravity and not wetting the entire slit wall, the gas speed must be sufficiently high. The speed in the condenser must therefore be kept higher than the ring speed; only then is the total condensing surface wetted. With direct expansion, the complete wetting is also necessary to keep the control mechanism, the superheating, stable under all conditions. Filling the evaporation pipes with a part load, rivulet flow, will otherwise result in the expansion valve "hunting". Distributing the gas-liquid mixture after the expansion valve over the various users is a difficult feat in itself. After all, the volume percentage of gas is well above 90%, leaving only a very little liquid to be divided.

With the patented **Grasso interstage cooling system B**
this is solved by using just one evaporation channel! The hot gas from the low pressure stage flows past the pipe walls moistened with evaporating refrigerant and that cools it down. The gas goes through several passages. The inner wall of the first passage is double-walled and that forms a channel for the condensation to be subcooled. The injected refrigerant comes in between the subcooler and a heat shield. The latter keeps the evaporating refrigerant away from the outer jacket, so that cold insulation is not needed. The system is positioned horizontally so that the oil swept along by the compressed gas can keep moving under all conditions. The pressure loss on the gas side is at the same level as with the open interstage cooler chain (full load < 3K). The open interstage cooler chain means, in order: pressure line, oil separator, non-return valve, shut-off valve, interstage cooler, shut-off valve and suction filter. In system B all these components are absent, which improves the simplicity, the construction volume and the investment. The integrated subcooler has a maximum pressure loss of 1 bar.

Because it concerns extremely highly loaded coolers (>50 kW/m^2), the reaction time is correspondingly fast. By way of illustration: an air cooler has a reaction time of about 2 minutes; the Grasso system B interstage cooler reacts within 4 seconds to a change in injection. A continuous condensation supply is therefore extremely important. The supply line to the expansion valve must therefore have priority above that of the users (see diagram). The expansion valve on this interstage cooler can be a mechanical or electronic valve. Mechanical valves have a reaction time of about 3 minutes, and the capacity control must be matched to this. Usually a faster response is required of the compressor; in that case electronic expansion valves are the solution. They can be connected to the compressor control (Grasso Monitron or GSC) or simply to a superheating controller (Danfoss EKC315A).

Disadvantages:

- sensitive to discontinuous condensation supply
- higher superheating than with open flash
- COP for Ammonia about 3% lower than for open flash.

Advantages:

- refrigerant filling <<1% of the open flash
- integrated with the compressor, so extremely compact
- no extra floor space required for interstage cooler system
- no insulation required
- only 1 oil separator per compressor
- short “pull down” time
- insensitive to variable interstage pressures
- simple
- investment savings of up to 20% on the unit
- savings of up to 60% on installation costs.

Status Quo:

The direct expansion (DX) interstage cooler developed by Grasso has been installed successfully with several hundred compressors since its introduction. The significant savings to be obtained with the Grasso system B easily compensate for the slightly lower COP.

If you would like to react to this article or have questions, you can contact: Grasso Products b.v., Jan-Pieter Habraken jphabraken@grasso.nl