APPLICATION
NOTE

SECOP

Ultra-Low Temperature (ULT) Freezer – Design Consideratons for Low Temperature Stages

Optimization of cooling performance and generic functions in ULT refrigeration systems

Realization of vapor compression refrigeration systems that cool down from normal ambient temperatures from -80 to -90°C touch some technical limits. One example is that commonly used compressor lubrication oils are no longer safe to remain in a fully liquid state. Another example is that refrigerant pressures between evaporation at -90°C and condensation at +40°C are more extreme than standard compressors are made to handle.
As a consequence, either sensitive two-stage cascade refrigeration systems are made for ULTs, or the compressors in single-stage refrigeration systems are seriously overloaded during some operating phases. Design recommendations to mitigate the risk for unreliable functioning or reduced lifetime of the compressor based on Secop research projects are as follows: Since cabinet design and functional balancing of the relevant components can be very different for different cabinet solutions, these recommendations must be taken as a summary of generic behavior.

1. Refrigeration System

1.1 Single Stage, Autocascade, or 2-Stage Cascade

Technical risks and technical complexity of these three setups are very different.
Assuming that standard refrigeration compressors are used, single-stage and autocascade ULTs create overload pressures for the compressor during the starting and pull-down phase. Depending on the composition of refrigerant mixture and temperatures (ambient/cooling compartment) this overload may reduce lifetime and reliability of the compressor. Having a "good" setup can create stable operating conditions that don't harm the compressor during normal operation. Thermal overloading (higher ambient temperature or loading with insufficiently pre-cooled goods may generate serious overload pressures for the compressor.
Two-stage cascade ULTs are comparably complex cooling systems which require a good regulation setup for the compressors. On the other hand, two-stage-cascade ULTs have the potential to work with much broader operation limits (e.g. higher maximum ambient temperatures) without overloading the compressors and thus ensuring very long lifetime and very good reliability.

1.2 Refrigerants

The thermodynamic properties of the refrigerant are the key to reach appropriate temperatures for condensation and evaporation and to realize enough cooling capacity. To cover a temperature gap from ambient temperature (condensation) to ULT compartment temperatures (evaporation at -90°C or lower), a very special refrigerant is needed to create acceptable working conditions (pressures, mass flow of refrigerant) for the compressor. At ULT evaporation temperatures, refrigerants from standard refrigeration (e.g. R290, R404A…) are down to extremely low cooling capacity because pressure and density of the suction gas are very low. Selection of refrigerants with higher cooling capacity at ULT-evaporation temperature is needed. Unfortunately, these refrigerants (or mixtures of refrigerant) create very high pressures when condensing at normal ambient temperature.
Perhaps chemical research will be able to provide a refrigerant with ULT-optimized thermodynamic properties one day, however, single-stage-ULTs currently either suffer from low cooling capacity (large size and ineffective compressor) or from high condensation pressures (safety, reliability).
Refrigerant type and temperature steps (condensation, evaporation, intermediate temperature at two stage systems) must be selected and set in a way that the allowed operating pressures of the compressor (e.g. published in the datasheet) are not exceeded for too long time.

1.3 Recommendation

To avoid risk of a failing compressor and loosing valuable goods inside a ULT freezer Secop recommends to prefer ULT refrigeration systems with a 2-stage cascade.

2. Cooling Capacity Demand

Cooling compartments of ULT freezers are built with very effective insulation to keep cooling demand at a reasonable level while having extreme temperature differences between cooling compartment and ambient temperature.

Compared to the calculation of cooling demand for refrigerators or "normal" freezers, the simple calculation of cooling demand (= function of surface area, insulation thickness,...) is becoming more and more inaccurate. The reason is that heat intake through gaskets and thermal bridges (which is more difficult to predict) becomes more relevant because insulation loss through the walls is very effective.

To evaluate realistic cooling needs, it is advisable to measure heat loss of the cooling compartment directly (KA-test: place heat source inside cooling compartment and measure the difference of inner and outer temperature, when temperatures are stabilized).

3. Pull Down

During pull down, overload pressures on the condensation side are very likely to happen for many types of ULT-compatible refrigerants and mixtures of refrigerants.

These overload pressures may reduce the lifetime of the compressor, and they might not be allowed from a legal perspective. As an effective means to avoid critical pressures, a high-pressure safety switch is recommended to install into the high-pressure side of the ULT-refrigeration-circuit, to cut off the compressor when discharge pressure increases to a critical level.

Multiple activation of the high-pressure-safety-switch can occur during first phase of pull down. The speed of the pull down event will be slowed down a little but overall safety ensured at the best possible level.

When a variable speed compressor is installed in the ULT-refrigeration circuit, it should be verified if critical pressures can be avoided when the motor speed of the compressor is kept low during the first phase of pull down.

4. Intercooler Setup of 2-Stage Cascades (Temperatures and Design)

The target temperature of the intercooler (evaporator of high temperature stage and condenser of low temperature stage) has a significant impact on cooling capacity and thermal balance of the compressors. During stable operation, the evaporation pressure of the low temperature stage and its compression ratio should be at the same level as for normal refrigeration systems (pe: 1..2bara, ratio: <14). Compressors which generate high shell temperatures >80°C should be run at a lower compression ratio (=lower temperature of the intercooler).

It is strongly recommended to keep evaporation and discharge pressures of both stages in mind when selecting refrigerants and setting temperatures (cooling compartment, intercooler, ambient). Please double-check real pressures with operation limits of the compressors (please refer to the datasheets).

Too low temperature of the intercooler may cause low cooling capacity of the low temperature stage if the low pressure drop doesn't feed enough refrigerant through the capillary tube.

Capacity regulation of the refrigeration system (compressors on/off, compressor speed change, fan on/off) may create very fast load changes which can cause liquid refrigerant to return back to the compressor or too high condensing pressure in low temperature stage. Installation of sufficient heat accumulation capacity inside the intercooler can prevent rapid load changes and will keep the switching frequency of the compressors (during high-pressure overload and part load) at a lower level.

5. Capillary Tube Blocking (Low Temperature Stage)

If the evaporation temperature of the low temperature stage is very low, a risk of clogging/freezing of oil becomes more and more realistic. The first position inside the refrigeration system where cold enough temperatures for oil to clog can occur is the capillary tube. Unfortunately, at this position frozen oil can stop the whole refrigeration process. Capillary tube blocking will cause the evaporation pressure in the low temperature stage to decrease. Cooling capacity will decrease to zero when the remaining liquid from the evaporator turns into gas.

5.1 Oil Separator Needed

The freezing of oil is a process which takes some time depending on temperatures, oil properties, and the amount of circulating oil. To keep the risk of the capillary tube from blocking due to frozen oil to a minimum and to allow long intervals between defrosting, it is highly recommended to install an appropriate oil separator between compressor discharge and condenser inlet of the low temperature stage. Analyze capillary tube blocking behavior of the refrigeration system very carefully to define defrosting algorithms with the lowest possible impact to temperatures of the cooling compartment.

5.2 What Happens During Blockage

Direct analysis of blocked capillary tubes which makes it possible to isolate the blocking material is very difficult since the residues are melted/evaporated again when temperatures have reached an adequate level to be handled manually, and the position of the blockage can't be identified from the outside.
Based on measurement of temperatures, pressures, and time, some assumptions can be made:

- Blockages are less frequent when an oil separator is used:
  Either the oil itself or "something" which is carried by the oil or dissolved inside the oil solidifies.
- The cycle time from one to the next capillary tube blockage is long and nearly constant:
  Build-up of the blocking material happens slowly and steadily.
- Before total blockage, significant pressure loss inside evaporator occurs:
  Only when a big fraction of the capillary tube cross section is clogged will the evaporating pressure drop significantly. Feeding refrigerant into the evaporator will almost stop, and superheating of the evaporator will increase rapidly. The consequence is that cooling power decreases to zero while the compressor is operating almost at normal capacity (power consumption will decrease). The decreasing evaporation pressure will cause a further temperature decrease inside the capillary tube which will speed up final blockage of the capillary tube.
- The inner diameter of the capillary tube has influence on the cycle time of the capillary tube blockage.
  Using a comparably "small" inner diameter (with adjusted length) for the capillary tube requires less "material" for clogging because temperature and the mass flow of refrigerant should be equal if a narrow or a wide capillary tube is used. However, the flow speed of refrigerant inside a narrow and wide capillary will be different. This will most likely have a compensating effect.
- Using a thermostatic expansion valve instead of a capillary tube seems to be a good idea to prevent the loss of cooling capacity due to a blocked capillary tube. Currently, there are no (small size) expansion valves available on the market released for temperatures down to -100°C.

5.3 Low Pressure Switch

When the capillary tube is blocked or even when it is almost blocked, all further operation of the compressor will increase the effort (time, needed heating energy) of resetting to normal operation (defrosting of the capillary tube) while cooling performance inside the evaporator is already near to zero.
A very good indicator for a blocked capillary tube is unusually low pressure inside the evaporator. A low-pressure switch (with open pressure approx. 30% below the lowest normal evaporation pressure) can give a fast and reliable signal to stop cooling and start defrosting.
If reactions to a blocked capillary tube are fast, cooling loss, temperature peak, and temperature recovery time inside the cooling compartment can be kept low.
Long operation with blocked capillary tube will lead to compressor operation without a mass flow of refrigerant at very low evaporation pressure (outside of released pressure limits) → The compressor may be damaged by running in this condition (late protector cut-off due to extreme low load → motor overheats).

5.4 Capillary Tube Defrosting

Failing to initiate active measures (by cabinet controlling) when a capillary tube is blocked, means the return to normal operation will take a long time (... compressor operation until breakdown by motor protector, natural defrosting when the compressor is stopped). To keep temperature increases inside the cooling compartment to the lowest possible level, immediate compressor stopping and defrosting is needed when the capillary tube becomes blocked.
If a blocked capillary tube is identified, the compressor must be stopped to prevent further cooling and freezing of the capillary tube and environment. To allow normal operation again, the clogged section of the capillary tube needs to be heated up to melt the blockage. An accurate prediction of the location of the clogged section is not possible (very likely in the last third of the capillary tube) and can be different from instance to instance.

- Natural defrosting
  Switching off the compressor without actively heating the capillary tube (only using heat conduction) is sufficient for defrosting in many cases. The compressor-off time needed for defrosting is specific for each cabinet design and may also depend on ambient temperature (losses in capillary tube insulation).
- Defrosting with capillary tube heater
  Melting of a blocked capillary tube can be sped up by heating up the capillary tube with an external heater when the compressor is switched off. Heating time and heating power must be adjusted carefully. Heating up of the last third of the capillary tube should be enough to achieve the needed effect.
- Defrosting should be started immediately if the capillary tube becomes blocked.
  Preventive defrosting with a fixed cycle time helps much to avoid long recovery time and high temperature increase in the cooling compartment.
- Having an oil separator installed reduces the need for defrosting significantly.

6. Performance Boosting by Internal Heat-Exchanger

It is good practice in many conventional refrigeration systems to increase energy efficiency by installing an internal heat exchanger (capillary/suction line) by accepting a little loss of cooling capacity. However, the effect strongly depends on thermodynamic properties and temperatures of the refrigerant. For ULT setups (refrigerant, temperatures), it can easily be the case that an internal heat exchanger doesn´t bring any positive effects in terms of efficiency. Efficiency and cooling capacity can be calculated to support the decision for or against an internal heat exchanger. However, calculation models for compressor performance with very low suction gas temperature are not yet very accurate.
In any case, an internal heat exchanger is valuable to prevent liquid refrigerant from returning back into the compressor.

7. Capacity Regulation of a 2-Stage Cascade ULT (Fixed-Speed or Variable-Speed Compressors)

In general both compressors of a 2-stage cascade refrigeration system can be made with fixed-speed or variable-speed compressors.

- Fixed-speed compressors in both stages – single temperature input
  On/off control for both stages can be made with reference to the temperature of the cooling compartment only. In this case, the compressor of a high temperature stage should be started first; the second stage should be started with reasonable time delay to prevent super high current consumption. The stability of the cooling temperature and energy efficiency is only moderate in this configuration.
- Fixed-speed compressors in both stages – separate temperature input for both stages
  Both compressors start and stop independently (high temperature stage ←→ intercooler temperature, low temperature stage ←→ cooling compartment temperature). Cabinet controlling must ensure that both compressors do not start at the same time to prevent super high peak current consumption. Switching off the low temperature stage compressor while the high temperature stage compressor still operates may cause a large amount of liquid refrigerant return to the compressor of the high temperature stage → installation of a liquid receiver into the suction line of the high temperature stage is recommended. The stability of the cooling temperature is only moderate; the energy efficiency in this configuration can be better than with a single temperature input.
- Combination of fixed-speed compressor and variable-speed compressor
  Ideally, the variable-speed compressor should be used for low temperature stages to achieve a very stable temperature inside the cooling compartment. Separate temperature input for separate capacity regulation of both cascade stages is needed (high temperature stage ←→ intercooler temperature, low temperature stage ←→ cooling compartment temperature). Energy consumption can be lower than with fixed-speed compressors (in low temperature stages) because lowest evaporating temperature of the variable-speed-compressor setup can be higher than for a fixed-speed-compressor setup.
- Combination of two variable-speed compressors
  Separate temperature input for separate capacity regulation of both cascade stages is needed (high temperature stage ←→ intercooler temperature, low temperature stage ←→ cooling compartment temperature). The energy consumption and stability of the cooling compartment temperature is best with this setup.

8. Warranty

Secop shall not be liable for a breach of the warranty set forth in Section 11.1
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(a) the Buyer makes any further use of such Products after giving such notice;
(b) the defect arises because the Buyer failed to follow Secop´s oral or written instructions as to the storage, installation, commissioning, use or maintenance of the Products; or
(c) the Buyer alters or repairs such Products without the prior written consent of Secop.

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