New sensor technology optimizes evaporator performance especially during part load on both DX, flooded and pump circulation systems.

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1. INTRODUCTION

The increased requirements to reduce global warming (GWP) lead to a desire for the use of natural refrigerants. The use of natural refrigerants is associated with major challenges, like safety (R717 & R290) and poor system efficiency (R744).

New measurement methods make it possible to increase safety and achieve higher energy efficiency with both zero super-heat and demand driven defrost control. The use of Superheat control has for decades been necessary for safe operation of refrigeration systems. Superheat is however an area where a lot of energy is wasted without adding any value. A new revolutionary patented technology solves one of the main challenges when using CO_2 and other refrigerants. CO_2/NH_3 refrigerant is very dynamic and reacts strongly on small changes in load and pressure-/temperature. With the new Vapor Quality Sensor solution measuring the dryness of the vapor and the phase of refrigerant flow (two-phase flow regime) it is possible to achieve a more balanced system performance with minimum Superheat and less pressure fluctuation (Semi-Flooded operation). By this solution it is possible to control the evaporator capacity faster and more accurate within a Superheat range of 0.5 to 1.0K.

The sensor measures the Vapor Quality as the ratio of the vapor and liquid in a two-phase flow. The same measuring principle (capacitive) is also used for measuring ice build-up on air coolers at operating temperature below 0°C in form of a wire mounted between some of the evaporator fins and thus defrost cycles only starts when needed (On Demand)

The sensor reacts as an "X" sensor that directly measures the dryness where "X"0.0 = 100% liquid and "X"1.0 = dry vapor gas. This paper and the following presentation will describe the sensor's measuring principle, system design and the location of the sensor, as well as experiences from tests performed on both NH_3 and CO_2 system. A brief presentation of tests performed on CO_2 systems will also be included.

2. HOW IT WORKS

The sensor is based on the capacitive measurement principle in which two or more measuring electrodes/conductors measure the dryness as the change in electrical field/resistance depending on difference in the dielectric properties named "dielectric constant" according to the ratio between vapor and liquid. Measuring is instantaneously, i.e., without delay.

Dielectric constant (relative permittivity) is a unique value on a scale of 1 to 100. The value can be used as a media's DNA, because it is unique and related to the molecular structure/polarization with respect to a changing electric field in a dielectric medium (e.g., the refrigerant vapor and liquid mixture between two conducting surfaces).

The consequence is a very safe measuring system with 100% repeatability with direct link to the chemical formula. Compared to control based on temperature and pressure measurement, the Vapor Quality measurement based on the capacitive principle is a more direct and stable measurement of the phase and dryness of the fluid in the outlet of evaporators, liquid separators and for compressor protection.

Temperature & Pressure CO_2 NH_3 HFC/HFO
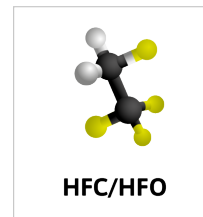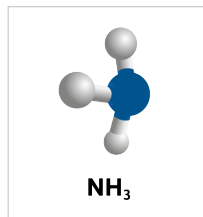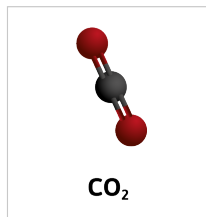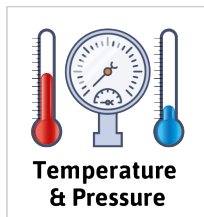
The dielectric constant of a material is determined in a special (designed) test cell. Values for many media/materials are published on the internet. The dielectric constant of most materials varies with temperature and pressure, which affects the measured capacitance. Materials with a higher dielectric constant are generally less affected by temperature and pressure variation.

Material build-up: The most devastating effect on the accuracy of capacitive measurements is caused by the build-up of conductive material on the conductor/sensor surface. Non-conductive build-up is not as serious since it only represents a smaller part of the total capacitance. Oil is non-conductive where metal impurities as dirt is an example of a material that is conductive.

Media	ε_r dielectric constant of	
Ammonia	Liquid,	17 to 25
CO2	Liquid,	1.4 to 1.7
Ice	Solid black,	3.2
Air/Vapor	Dry gas,	1.0

ε_r varies with temperature and pressure

Figure 1: Capacitance schematic

$$C = \frac{Q}{\Delta V}$$
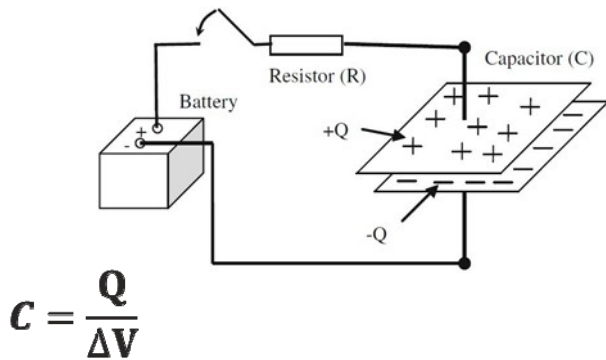
Where Q is the charge stored at a given potential voltage difference.

What is an electrical capacitor? A capacitor is a component designed to create and hold an electric field, which means that capacitors can store energy. It takes energy to pull electric charges apart and to establish an electric field between the separated conductors.

Capacitors are like small batteries. Capacitance is a time based measurement of the electric charge needed to produce a given potential voltage difference between two separated/isolated conductors. The media/material between the conductors is known as the dielectric material. Typical dielectric materials used in electronic systems are ceramics, plastics and air. The vapor and liquid mixture/ratio inside the piping acts as different insulation media with different dielectric constants "ε" (relative permittivity), refrigerant Vapor is close to 1.0 as Vapor density is very low compared with liquid.

$$C = \frac{q \, \varepsilon_o \, \varepsilon_r}{l}$$

Sensor area

Where C is the charge stored in Farad
q is the sensing area in m2
ε_o is the dielectric constant, dry air
ε_r is the dielectric constant, media
l is the length of the coaxial sensor
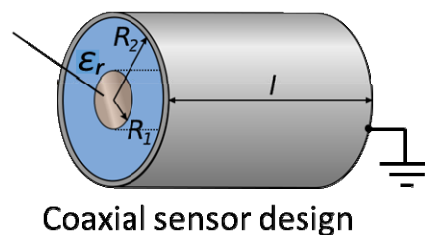
Coaxial sensor design

Figure 2: Capacitance coaxial sensor design

The measured value *C* is dependent upon the total sensing area and the internal distance between the conductors. The ratio of the capacitance measured in pF is dependent upon the media between the electrodes. Relative permittivity is the factor by which the electric field/charges is changed and named as dielectric constant ε, Refrigerants have "ε" > 1.

3. Thermodynamics

Parameters which influence the two phase flow pattern and have strong impact on the heat transfer

In thermodynamics, Vapor Quality is the mass fraction between vapor and liquid in a saturated wet mixture; i.e. dry vapor has a quality of 1.0, and pure liquid has a quality of 0.0, Quality "X" can be calculated by dividing the mass of the vapor by the mass of the total mixture.

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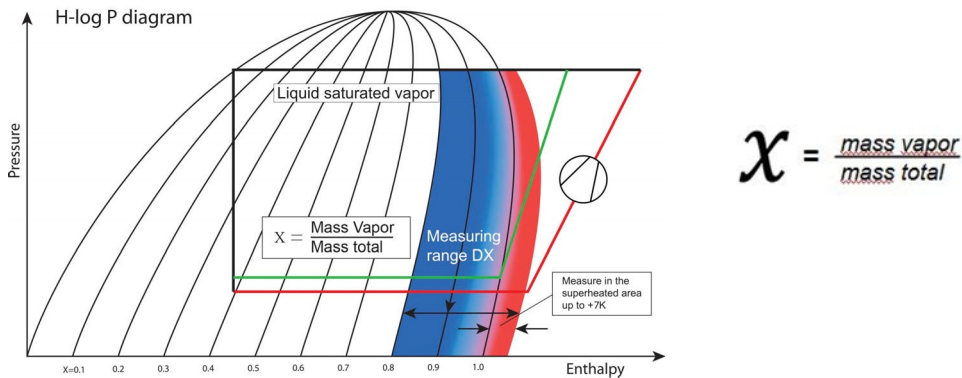

Figure 3: Measuring ranges DX shown in h log P diagram

The volumetric Void Fraction is defined as the ratio of the volume occupied by the liquid in the tube and the total volume of the tube. It can thus be seen as an average of the cross sectional Void Fraction over the tube.

For vapor qualities above 0.5, there is approximately a linear link to the Void Fraction as shown on Figure 5

The "X" sensor measures vapor quality as the ratio of the vapor and liquid part in a two-phase flow as a volumetric Void Fraction measurement.
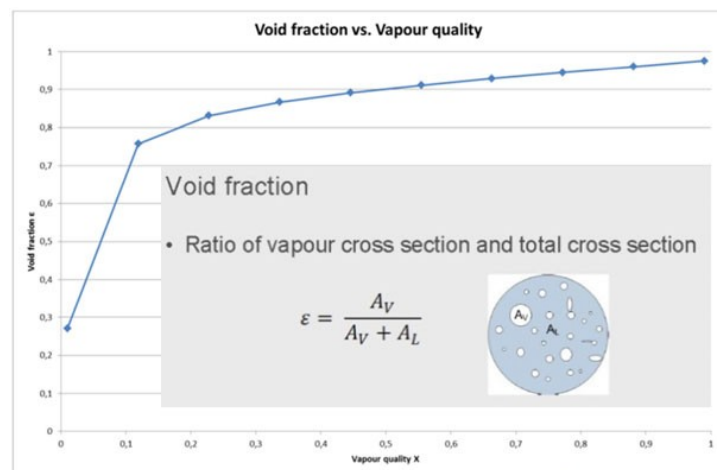

Figure 4: Void Fraction compared to vapor quality

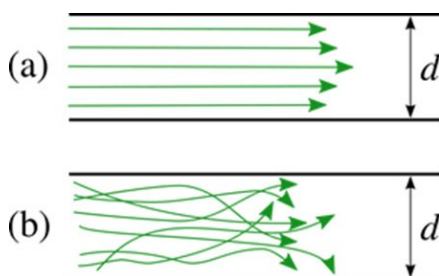$$Re = \frac{v_m \cdot 2 \cdot R_h}{\nu}$$

Figure 5: Reynolds numbers

Reynolds numbers used to characterize different flow regimes, such as laminar or turbulent flow, laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion. Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

Fluid flow is generally chaotic and even very small changes to the shape and surface roughness can result in very different flows. Nevertheless, Reynolds numbers are a very important guide and widely used.

Facts: High turbulence in the medium − this gives a higher convection, which results in efficient heat transfer between the media. The consequence of this higher heat transfer coefficient per unit area is not only a smaller surface area requirement but also a more efficient operation.

Flow Patterns and heat transfer Coefficient "β"

Various flow structures are observed in a boiling flow, and those are defined as two-phase flow patterns. Flow patterns of vertical and horizontal flow generally differ, as flow in horizontal pipes is influenced by the effect of gravity, which acts to stratify the liquid to the bottom and the gas/vapor to the top of the channel. Refrigerant evaporators usually have vertically orientated channels, where two-phase liquid and vapor refrigerant flows in a co-current upward manner.

Internal flow that is boiling/forced convective boiling is associated with bubble formation at the inner surface of a heated channel. Bubble growth and separation is strongly influenced by fluid motion, and the hydrodynamic effect differs significantly from those corresponding to pool boiling.
The process of a flow boiling is associated with the existence of nucleate boiling and forced convection. The nucleate boiling part occurs in the first part of the evaporator sector where the liquid proportion is high. The forced convection boiling occurs when the fluid velocity and turbulence is increased by evaporation of the refrigerant. The forced convection part should be the dominating parameter in two-phase flow to obtain optimum heat transfer.

The major benefit of semi flooded operation is the improvement of the heat transfer coefficient.
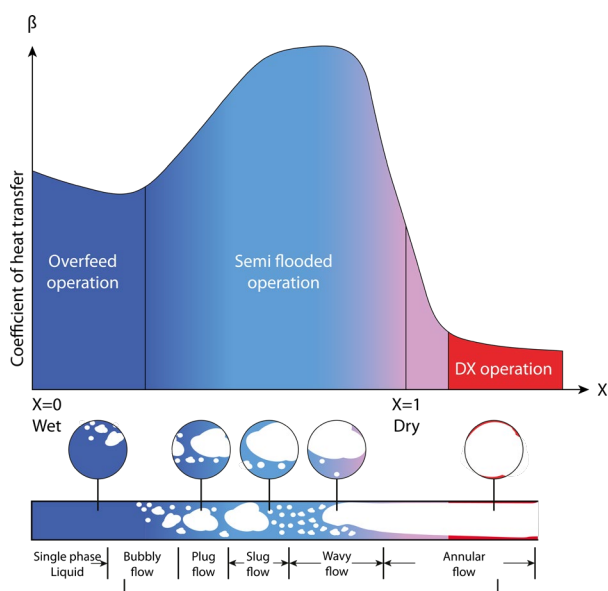

In dry expansion systems (DX) a part of the heat exchanger area is used to secure dry vapor, further tube length/area is added to obtain Super-heating of the vapor. In this area the heat transfer is very low.

In pumped system, with flooded evaporators, the refrigerant is not boiling completely. Too much refrigerant will limit evaporation as the boiling is performed as bubbly and plug flow, characterized by low values of the heat transfer coefficients compared with the heat transfer coefficient that can be achieved during boiling flow in semi flooded evaporators.

Figure 6: Coefficient of heat transfer & Flow regime

A normal two-phase flow pattern is a subjective observation, and there is no general assessing method which identifies and describes flow patterns precisely. Now it is possible to measure both the degree of dryness/liquid ratio and flow pattern by mounting a Vapor Quality Sensor in the evaporator tube. The sensor is normally installed in the outlet of the evaporator for controlling the liquid supply according to the heat load.
Semi flooded operation ensures a much more balanced system with minimal variation of pressure and very little Super-heat from 0.5 to 1.0K. Semi flooded operation ensures maximum efficiency as 98% of the evaporator surface is wet. A controlled wet surface ensures optimum thermodynamic operation with higher heat transfer.

Thermodynamic Effects by using Vapor Quality Sensors:
- Semi Flooded evaporator operation ensures optimum heat transfer at all loads
- Increased evaporation pressure & temperature
- Lower discharge temperature
- Optimal performance in all climates
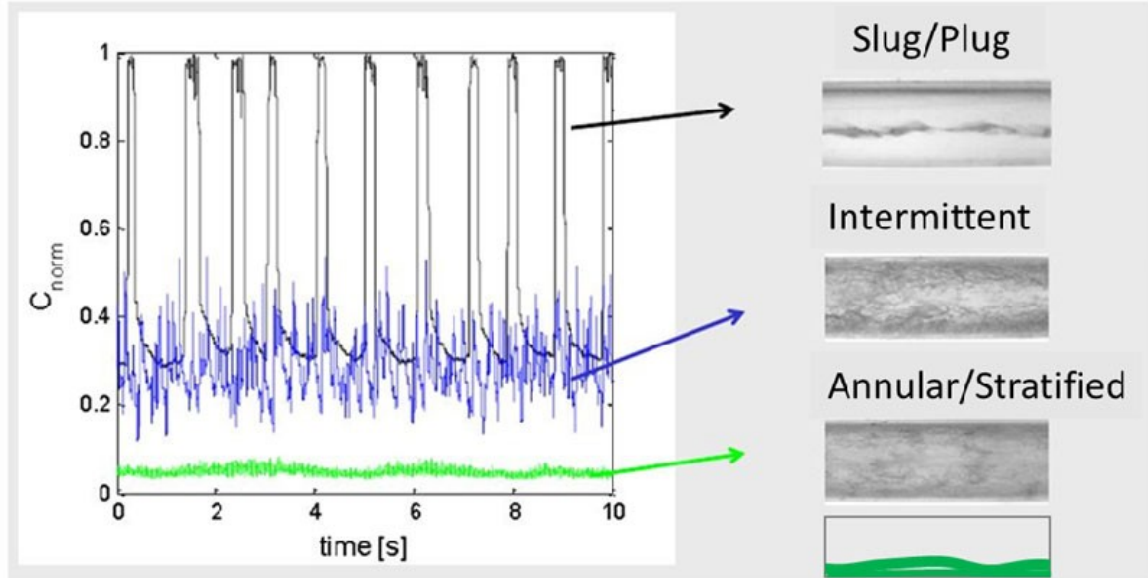- Compressor protection

Figure 7: Flow vs. Capacitance (C_{norm} is capacitance value in pF)

Figure 8 shows flow vs. capacitance for different flow patterns. (Measurements made by Gent University in Belgium). For two phase flow, the dielectric constant of both phases strongly influences the measured capacity (De Kerpel, 2013).

Optimum efficiency is achieved by measuring the Vapor Quality (X-value) at the evaporator outlet and controlling the liquid feed to the evaporator according to the Vapor Quality signal. The time-based flow pattern shows that by measuring the vapor quality it is possible to measure and regulate liquid feed depending on the evaporator load to obtain an optimal and homogenous flow pattern. The sensor signal is a mirror image of the current flow pattern inside the piping. As an example it is possible to measure if the evaporator is overfeed or with non-uniform liquid flow distribution. Slug and intermittent flow with short intervals indicates overfeeding, while an unstable flow pattern as slug flow with long intervals indicates a non-uniform refrigerant supply, whereas a stable signal indicates homogenous flow.

Plate heat exchanger: It is often associated with challenges to control the capacity of a plate heat exchanger since calculations and design are based on 100% load. By measuring the vapor quality with an "X" sensor, it is now possible to optimize the refrigerant supply to match the load. Experiences from several installations show that a Vapor Quality control is a superior principle for both flooded and DX systems, with significant impact on the overall heat exchanger performance.

Statement from the world's leading heat exchanger company Alfa Laval: "*To obtain optimum heat transfer, adapt a Vapor Quality Sensor in the outlet*".

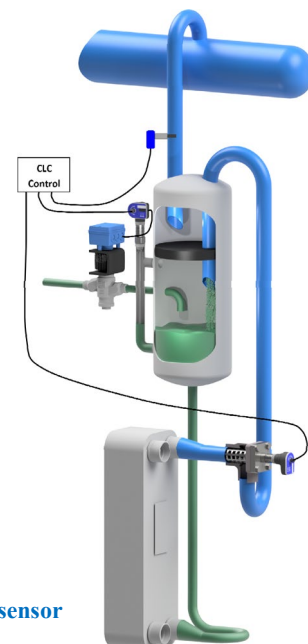Optimum circulation rate (flooded) "X" 0.7 to 0.85…CR 1.2 to 1.4

Figure 8: A thermosyphon evaporator system mounted with Vapor Quality sensor and liquid level control.

4. BACHELOR THESIS BY OLIVER KACIC

Validation of the Vapor Quality sensor as well as an efficiency analysis of a direct-evaporation R717 refrigeration system with Vapor Quality sensor in comparison with Superheat control.

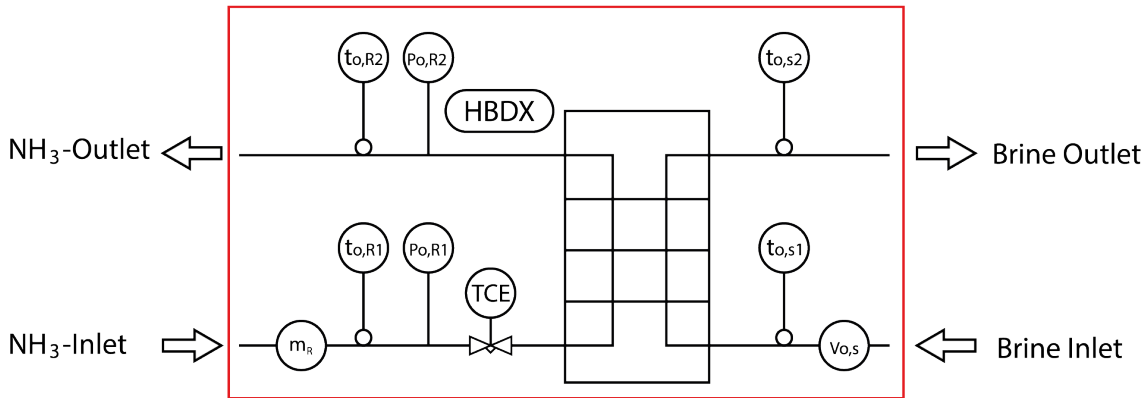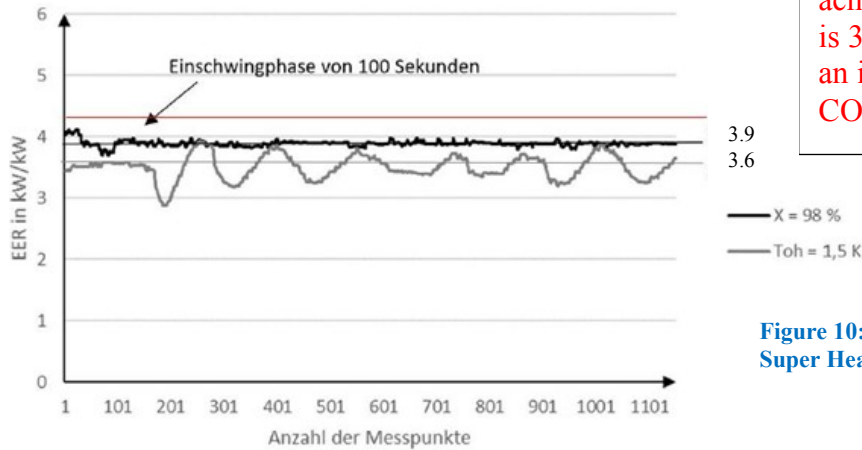**Test system: Heat pump with 100 kW DX Plate heat exchanger.**

System Boundary

Figure 9: Heat pump with Plate heat exchanger, 100 kV

For a load on 86.5kW, achieved energy savings is 3.75kW, which gives an improvement of EER / COP of 18.6%

Figure 10: Test results, Vapor Quality vs. Super Heat Control

Energy efficiency Ratio (EER): 14°C evaporation temperature, control variables of X = 98% and Toh = 1.5 K, load 100%. For maximum cooling load there was an EER increase of 18.6%.

It was confirmed that an ammonia refrigeration system for direct-expansion can be operated in a stable state by using the Vapor Quality sensor. It was also shown that an efficiency increase of up to 18.6% is possible due to the Vapor Quality control, with an X-value of 98%, against Super-Heating control with only 1.5 K. It was also found that the Vapor Quality control depends on the flow regime in the plate evaporator. Consequently, this excludes smaller performance ranges for gas quality control. With regard to the flow types and control in the part load range, further test and research is needed to find the relationship between evaporator load and "X" dryness.
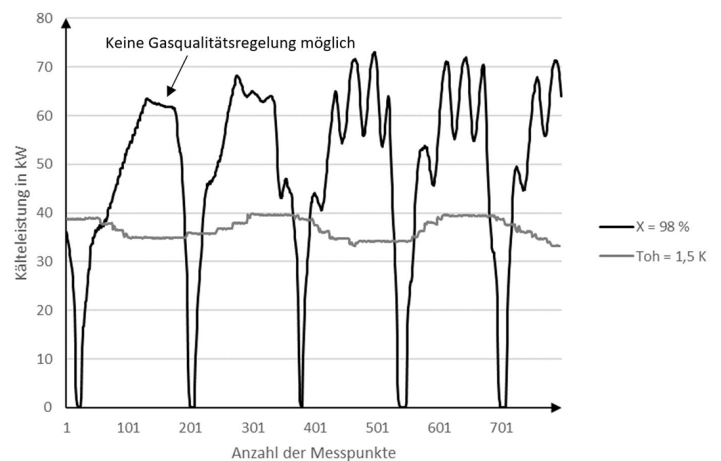
Fgure 11: Graph shows that at low evaporator load the flow pattern changes to an unstable slug flow

5. Study of the relationship between temperature/pressure and measured signal in pF.

The goal and requirement for the new Vapor Quality control sensor, is that it must be Plug and Play and that it can be used as a thermostatic expansion valve. During daily work with the new HBX-DX-CU "copper sensors" it has been shown that the mechanical part of the sensor itself changes its electrical capacity (measured in pF). The changing capacity is due to the coppers (CU) thermal expansion in line with the temperature which has a large variation compared to e.g. stainless steel. Next, it is known from experience that the operating pressure also has an influence on the measurement of the electrical capacity in the sensor due to the change in molecular density. The basis of the study is to find the amount of how much the electrical capacity (measured in pF) changes in line with the sensor's temperature and operating pressure.
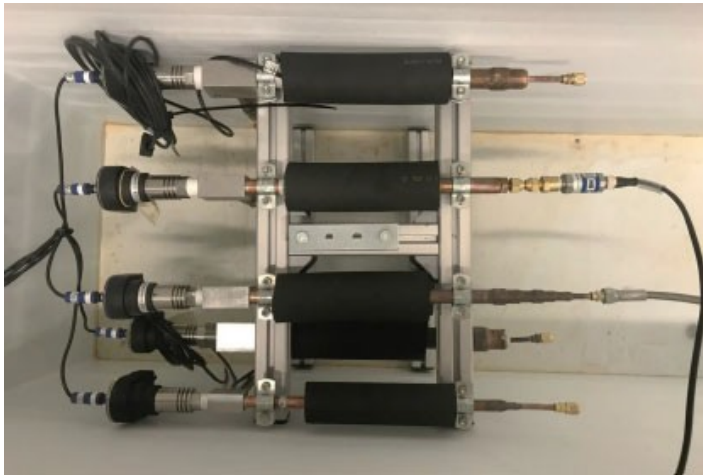

The test fixture consists of five HBX-CU sensors in five different sizes mounted parallel. As shown on figure 13 the sensors are supplied with refrigerant at the same time using a filling manifold.

A pressure transmitter is used to monitor the pressure.

Figure 12: Test Fixture

Test with CO2 as refrigerant:

When testing the sensors using CO2 as refrigerant, the capacity changed as a function of the temperature/pressure (See Figure 14).

Example the 1 1/8" HBX-CU sensor:

  -33℃ the capacity is 92.3pF.
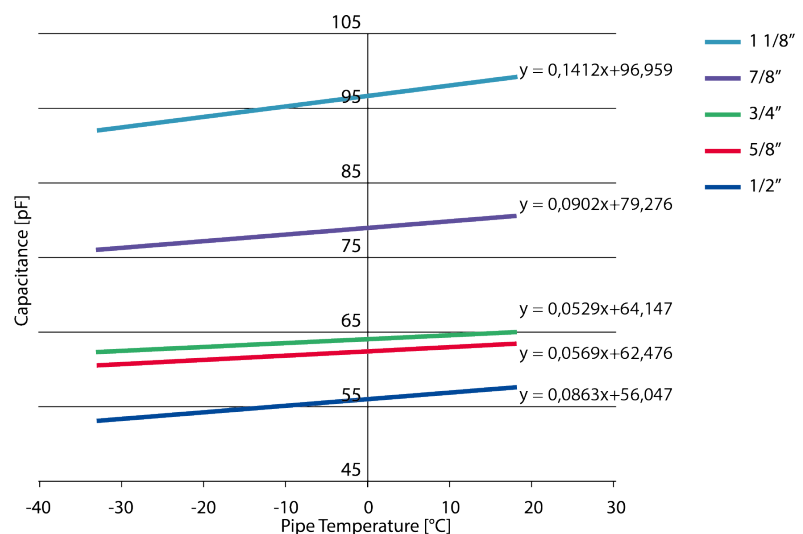
  +35℃ the capacity is 100.9pF.

  Difference is 8.6pF

Figure 13: Graph showing change in pF in relation to temperature with CO₂.

Summary

By using the HBX-DX-CU´s integrated temperature offset function, the sensor can now be used in all refrigeration systems where the temperature is not constant. The build-in temperature offset function is automatically compensating the value of the dry calibration (measuring zero start point) making the readings more precise regardless of temperature and operating situation. This enables improved control during startup and not least it is possible to deliver the system as Plug & Play, ready to run.

6. Transcritical CO₂ system Controlled by Vapor Quality Sensors

R744 demonstration system built up of a standard condensing unit and a DX air cooler. The evaporator is controlled by a Vapor Quality Sensor. There has not been changed or added other equipment.
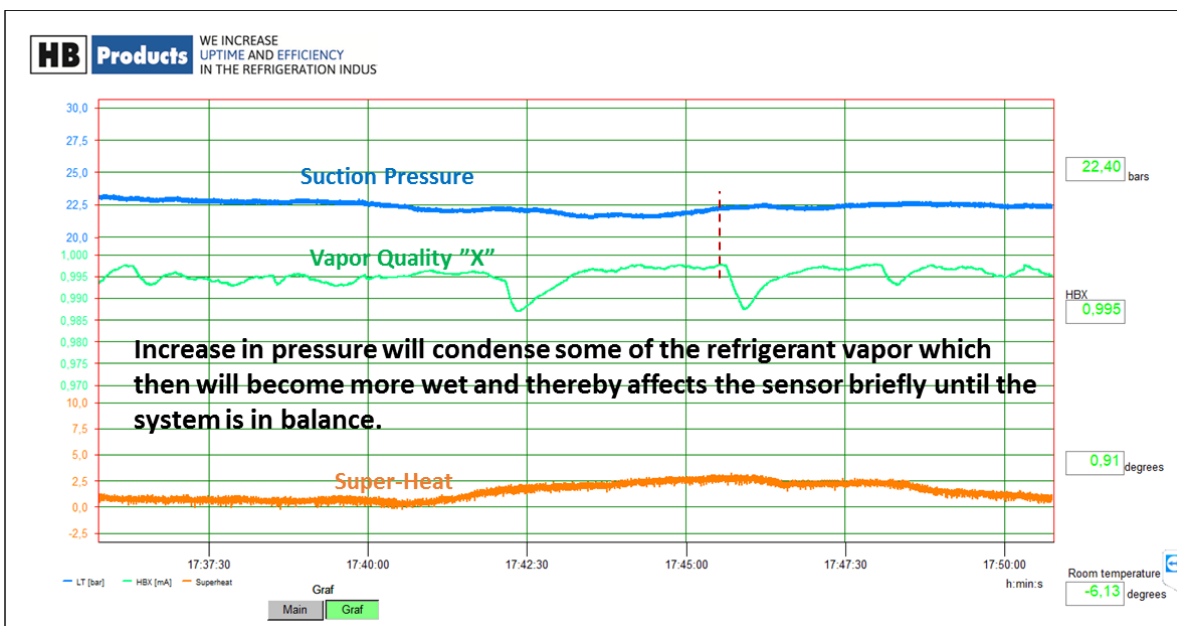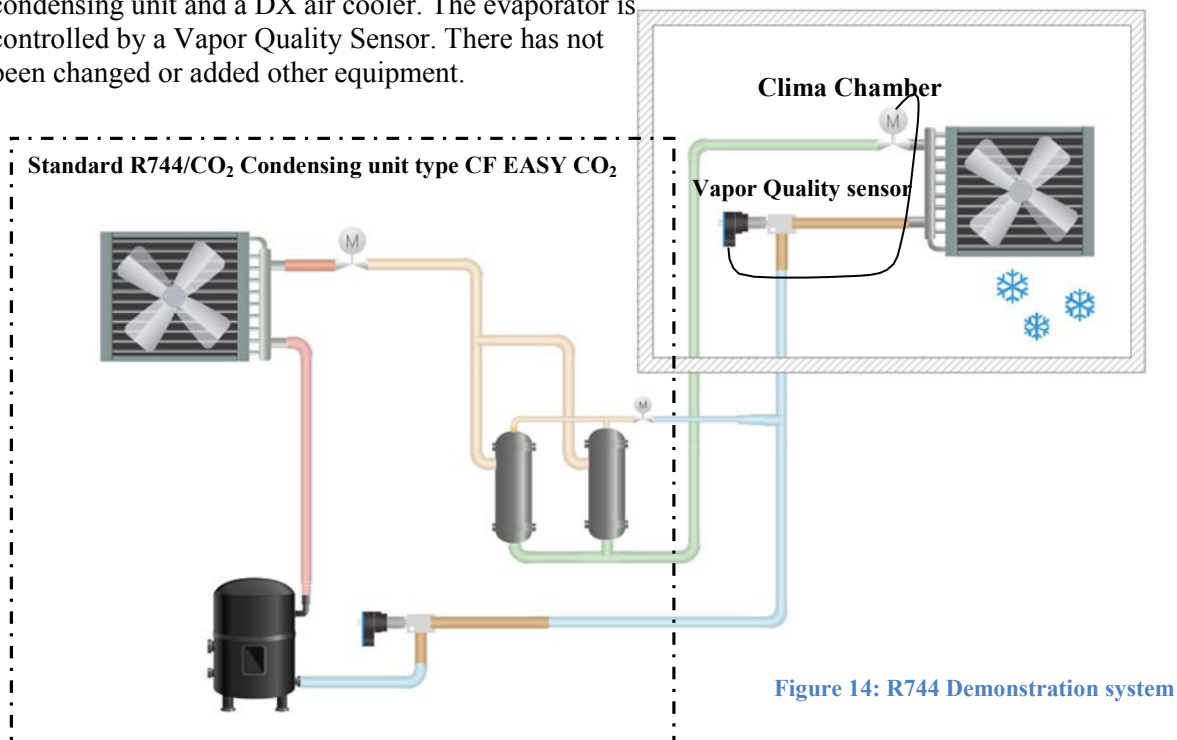

Figure 14: R744 Demonstration system

Figure 15: Test graph/data from test performed in October 2018

The graph shows that there is great cohesion/relation between the suction pressure and the dryness of the gas. When the pressure rises it can immediately be seen that there is a reaction from the Vapor Quality Sensor as it becomes more wet. It is therefore possible to control the evaporator more accurately with close to zero super-heat and at the same time have increased safety against liquid hammering.

CO_2 refrigerant is very dynamic and reacts strongly on even small pressure/temperature changes. It is now possible to measure the dryness of the vapor and achieve balanced dryness of the evaporated vapor in the evaporator outlet with minimum Super-heat, thereby controlling the evaporator capacity much faster and more accurate relative to the evaporator load with close to zero Super-Heat (range of 0.5 to 1.0K).

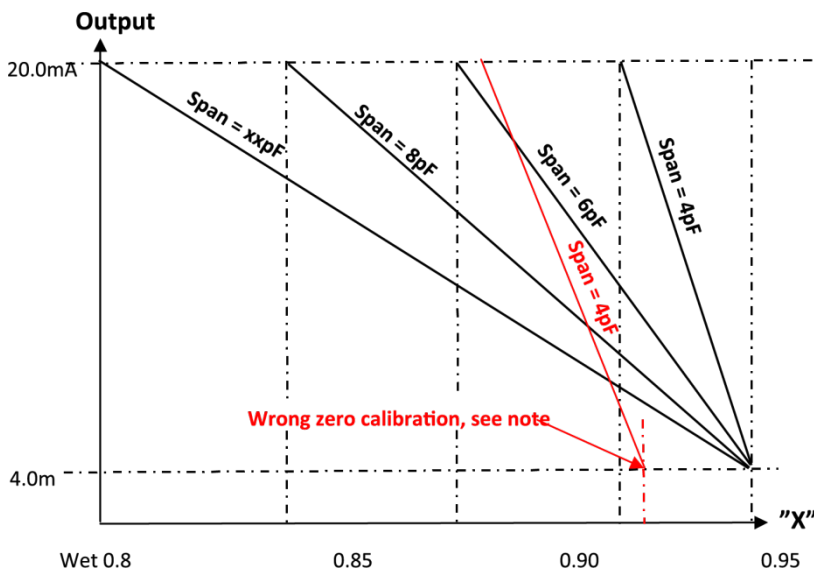## 7. Graphical view of the relationship between "X" and span settings in pF for HBX-DX-CU-3/8 ", CO_2

Figure 16: relationship between "X" and span settings in pF

Span settings in pF:

4pF, very sensitive, should only be used for compressor protection.

6pF, measuring range "X"0.9 = 20mA……1.0 +5ºK = 4mA (sensitive)

8pF, measuring range "X" 0.850 = 20mA…..................1.0 +5ºK = 4mA (standard sensitivity)

The sensor has built-in an advanced control where it is possible to control all types of evaporators. Expansion valve open and close time can be varied from 0.1 to 10% / sec. Start-up with ramp function and sensor drying ensures secure startup. Low limit safety alarm closes the liquid valve to minimum opening.

External start and stop function from a master control system is required when the sensor is used for direct control of a liquid valve.
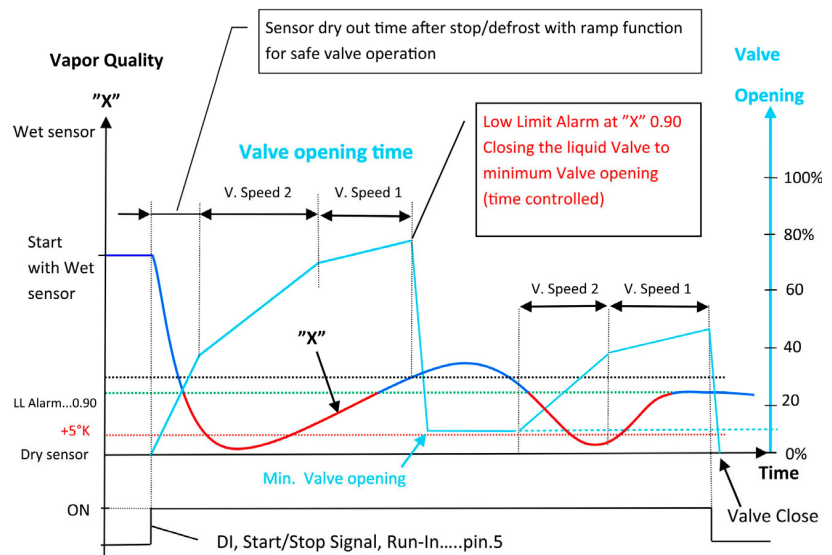

Figure 17: Control Pattern

I. If a control system does not modulate correctly, this will typically be either an not correctly calculated expansion/liquid valve (Kvs value) or the sensor system is too sensitive or wrongly calibrated.

II. By selecting a too small measuring range there is a risk that the system will be to sensitive and reacts too excessive on even small changes of liquid content (wet vapor) in the gas, then the control system is not modulating appropriately and acts more or less as ON/OFF control where the control valve fluctuates (hunting).

III. If zero calibration is carried out with a wet sensor it will result in a sensor offset where the sensor is not measuring from completely dry, Hereby there will be a risk of too wet vapor/gas and thus increased risk of liquid overflow/flood back.
The build-in temperature offset function is automatically compensating the value of the dry calibration (measuring zero start point) making the readings more precise regardless of temperature and operating situation. This enables an improved control during startup and not least it is possible to deliver the system as Plug & Play, ready to run.

9. Conclusion

This paper describes the capacitive measuring principle used for optimization of key processes in a refrigeration system. It is now possible to measure and control the phase of refrigerant on all types of evaporators. The two-phase flow pattern highly depends on the evaporator load. By controlling the supply of refrigerant in an intelligent way, you can minimize pressure loss in wet suction lines and riser pipes and with even liquid distribution it is possible to ensure a uniform and homogeneous load on every evaporator section with a very small pressure variation/drop compared to a normal controlled system (Super-heat and over-feeding).

The sensor method works with all types of refrigerants. Especially heat pumps where the operating conditions changes, here it is recommended to use an HBX sensor to protect the compressor against liquid hammering.

The same measuring principle (capacitive) is also used for measuring ice build-up on air coolers to perform demand defrost control (only defrosting when needed).

Facts & Summary

600 HBX sensors are sold and installed World Wide. It is extremely robust with molded-in electronic and built-in heating element to avoid stress and condensation.

The setting is simple and can now be delivered as a plug and play for CO_2 systems with integrated control.

- Safe ammonia Low Charge DX Control with significantly smaller ammonia charge, increases safety and reduces regulatory burden (paper, 13th IIR Gustav Lorentzen Conference, Valencia 2018).
- Allows design of safe Ammonia & CO_2 DX system, with zero superheat control.
- Semi Flooded evaporator operation ensures optimum heat transfer at all loads.
- By controlling the circulation rate it is possible to minimize pressure drop in risers and wet suction lines.
- Energy saving > 20% - Lower discharge temperature – Optimal performance in all climates.
- Lower installation cost – Compressor protection – Closed loop evaporator control.

Comment to Oliver Kacic Bachelorarbeit: The comparison is carried out at a very low superheat at 1.5K, the Super- heat range used for Ammonia is normal from 10 to 15K, it is therefore expected that EER will increase further up to 40%. Conclusion from his testing was that the benefit of controlling with the Vapor Quality sensor is only present at 80% to 100% load, at part load and very low load they have not been able to get the system working optimal.

Further testing have indicated that it is possible to optimize the control by changing set point for the dryness "X" by incrementally increasing the settings from "X"0.98 to 1.0 (starving the evaporator), at 0.99 the control works fine, the system was now in balance when changing the evaporator load from 100 to 50%. The Vapor Quality was homogeneous with strong relation between the sensor signal and valve operation. Oliver has now started to test the system again, where it is possible to change the set-point as a function of the evaporator load (floating set-point). The result is expected to be available in my presentation.

REFERENCES

- De Kerpel, Kathleen (2014-2015). "Refrigerant Two-Phase Flow Behaviour" Gent University, Belgium.

- Jensen S.S. 2015, Recent Advances in Ammonia Dry Expansion Applications. Proceedings 2015 International Congress of Refrigeration, August 16-22, Yokohama, Japan.

- Nelson B, 2010. "Thermodynamic Effects of Water in Ammonia on Evaporator Performance". Proceedings 2010IIAR, Ammonia Refrigeration Conference and Exhibition, San Diego, California.

- Bachelorarbeit, von Oliver Kacic, -Nr.: 46032, Hochschule Karlsruhe, Prof. Dr. Jens Denecke.