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Capacitive Sensors Measuring the Vapor Quality, Phase of the refrigerant and Ice thickness for Optimized evaporator performance

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1. ABSTRACT

New measurement methods make it possible to design more energy-efficient Low Charge Systems with Zero Superheat as well as demand driven defrost with increasing safety aspects when using natural refrigerants as Ammonia, Propane and CO2. Increasing energy prices as well as requirements to reduce global warming (GWP) and CO2 emissions have encouraged the need for using natural refrigerants which have initiated numerous of new efforts and developments worldwide. Applications using new measurement principles and design methods in the refrigeration industry may significantly affect the objective of lower global power consumption with a reduction of 20 to 40% while increasing the safety by minimizing and controlling the refrigerant charge with a reduction factor of up to 1000 times for Ammonia DX vs. a traditional pump circulated system.

2. INTRODUCTION

This paper describes a new sensor system for optimizing Evaporator Control including description of the measurement principle for measuring the phase of refrigerant as Vapor Quality. In this paper it is described how the “X”-sensor measures Vapor Quality as degree of dryness and how a demand driven defrost sensor measures the ice build-up (thickness) on the surface of the air cooler. This paper does also provide information about sensor design, laboratory testing, system design, field testing, applications, summary and conclusions.

Experience in testing and installation on primary Ammonia systems have proven that a Vapor Quality Sensor mounted in the outlet of an evaporator optimizes the entire system and makes it possible to control and limit the amount of refrigerant in the system under all conditions (including part load operation). The sensor measures Vapor Quality as the ratio of the vapor and liquid in a two-phase flow as a volumetric Void Fraction measurement. The same measurement principles in the form of a wire mounted on the outside surface on the evaporator fins can be used to measure ice build-up on air coolers at operating temperature below 0°C (32°K) and thus start the defrosting when necessary (on demand).

Accomplished laboratory tests have shown that it is possible to calibrate the sensor to react as an "X" sensor that directly measures the degree of dryness where “X”=0.5 (50% liquid) and “X”=1.0 (dry Vapor gas). Empirical tests have proven that the sensor can be calibrated to control a DX evaporator and to ensure that the Vapor gas in the outlet is close to zero superheat which leads to highest possible energy efficiency. On pump circulated and overfed systems it is possible to control the pump and/or regulate a liquid valve to minimize the circulation rate. By doing this it is possible to minimize pressure losses in risers and wet suction lines, while also ensuring a higher freezing capacity with lower charge of refrigerant. This paper will describe the measurement principle, Bachelor thesis, laboratory test, as well as experience from a Cold Store in Melbourne, Australia.

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3. HOW IT WORKS

The sensor is based on the capacitive measurement principle in which two or more measuring electrodes/conductors measures the charge and change in electrical field/resistance depending on difference in the dielectric properties of various media. Hereby the ratio between vapor and liquid amounts is measured instantaneously, i.e., without delay as a volume based Void Fraction measurement.

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.

$$\boldsymbol{C} = \frac{\mathbf{Q}}{\Delta\mathbf{V}}$$

Where Q is the charge stored at a given potential voltage difference.

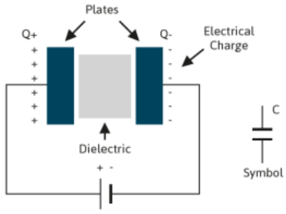

Figure 1: Capacitance schematic

Capacitors are like small batteries. Capacitance is a time based measurement on 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 medias with different dielectric constants **"ε"** (relative permittivity), refrigerant Vapor is close to 1.0 as the density is very low compared with liquid.

$$\boldsymbol{C} = \frac{\boldsymbol{q}\ \varepsilon_{o}\ \varepsilon_{r}}{\boldsymbol{l}}$$

Where C is the charge stored, q is the sensing area in m2, ε_o is the dielectric constant for dry air, ε_r is the dielectric constant for used media, l is the length of the coaxial sensor tubes.

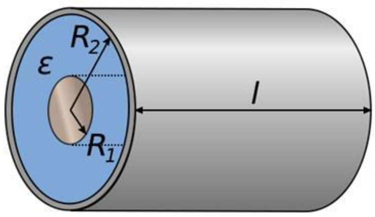

Figure 2: Capacitance coaxial sensor design

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.

The dielectric constant (relative permittivity) is a numerical value on a scale of 1 to 100 which relates to the ability of the dielectric material to store an electrostatic charge. 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. Generally materials with a higher dielectric constant are less affected by temperature and pressure variation.

Material buildup: The most devastating effect on the accuracy of capacitive measurements is caused by the buildup of conductive material on the conductor/sensor surface. Non-conductive buildup 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.

Dielectric constant "ε" liquid, Ammonia = 17, CO_2 = 1.5 to 2.0, R134a = 9.24, (20°C/68°F).

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Thermodynamics: Parameters which influence the flow pattern and have strong impact on heat transfer:

$$X = \frac{\text{mass vapor}}{\text{mass total}}$$

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. Quality “X” can be calculated by dividing the mass of the vapor by the mass of the total mixture.

Void Fraction:

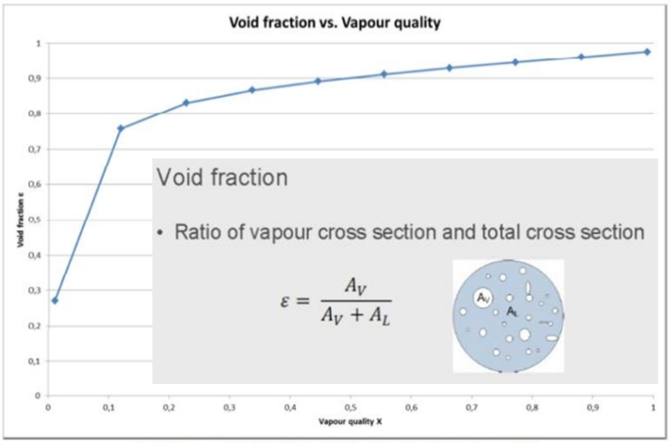
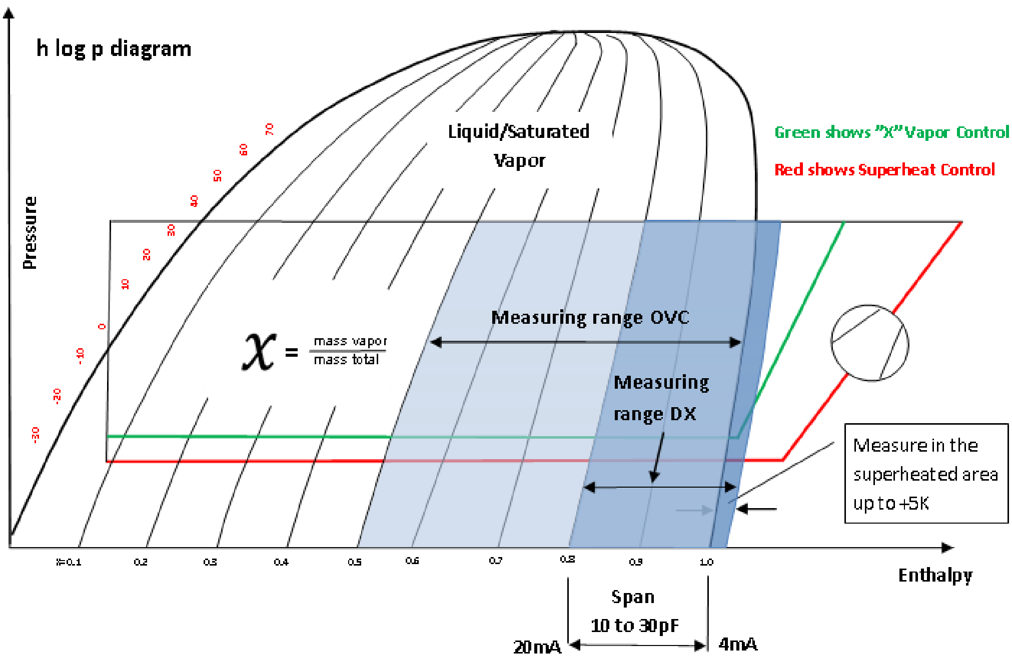


Figure 3: Void fraction vs. vapor quality

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 3

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



OVC…. (Optimum Vapor Control) is used for Overfed Systems.
DX…… (Direct expansion Control) is used for DX systems.

Figure 4: Measuring ranges DX and OVC shown in h log P diagram

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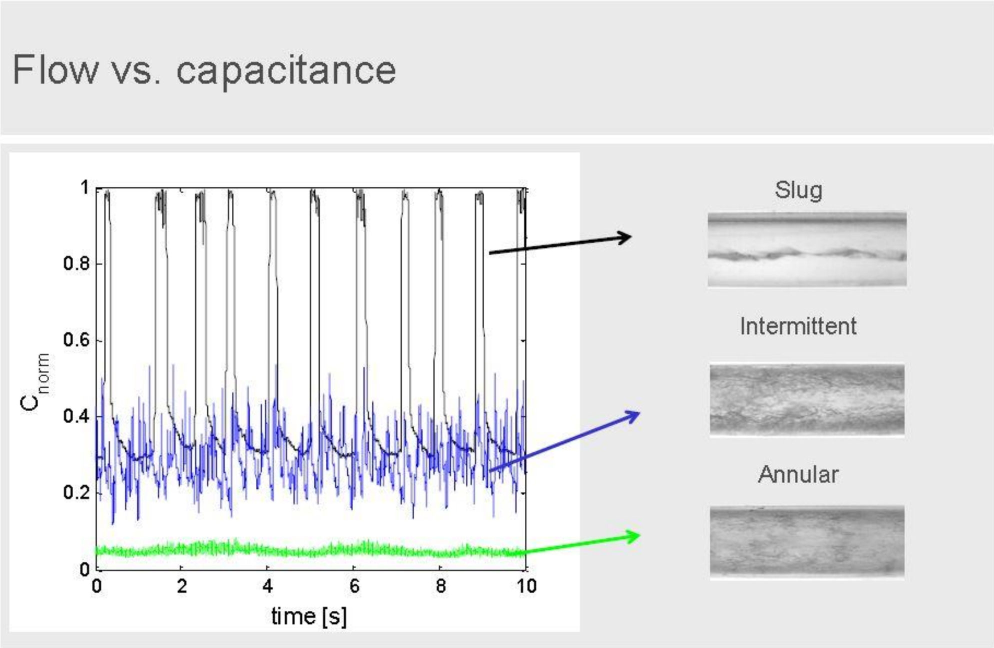

Figure 5: Flow vs. Capacitance (C_{norm} is capacitance value in pF)

Figure 5 shows flow vs. capacitance for different flow patterns measured at Gent University. 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 control 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 flow situation inside the piping, for 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 unstable flow pattern as slug flow with long intervals indicates a non-uniform refrigerant supply, while a stable homogenous signal indicates annular flow in rising pipes or stratified flow pattern in horizontal pipes.

OVC control on 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. Experience from several installations show that OVC control is a superior principle for both flooded and DX systems, with significant impact on the overall heat exchanger performance.

A statement from the world's leading heat exchanger company Alfa Laval:
“To obtain optimum heat transfer adopt a Vapor Quality Sensor in the outlet”
Optimum circulations rate (flooded) ”X” 0.7 to 0.85…...CR 1.2 to 1.4

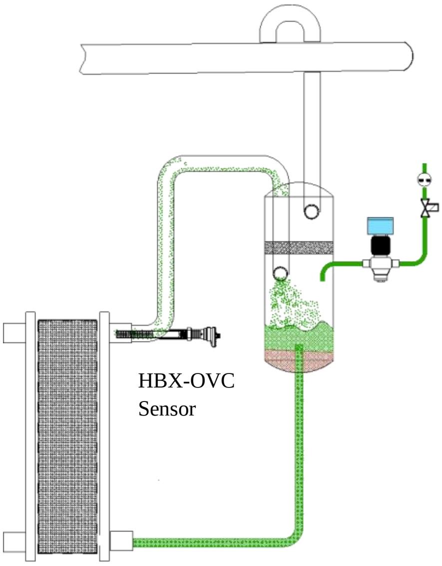

Figure 6: X-sensor on Plate Heat Exchanger

4. BACHELOR THESIS BY OLIVER KACIC

Validation of the HB-Products gas quality sensor as well as an efficiency analysis of a direct-evaporation R717 refrigeration system with gas quality sensor in comparison to superheat control.

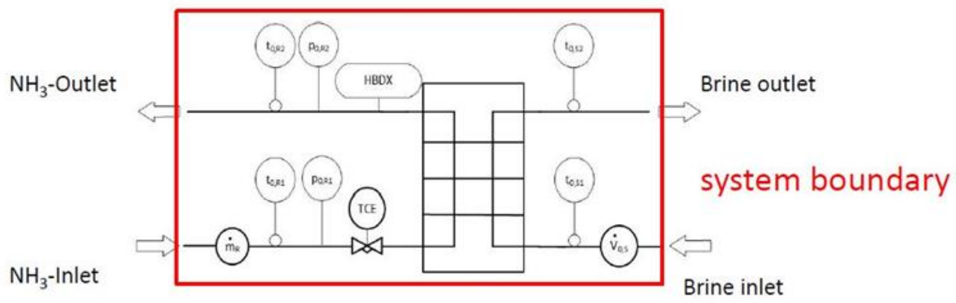

Figure 7: Heat pump with Plate heat exchanger, 100 kW

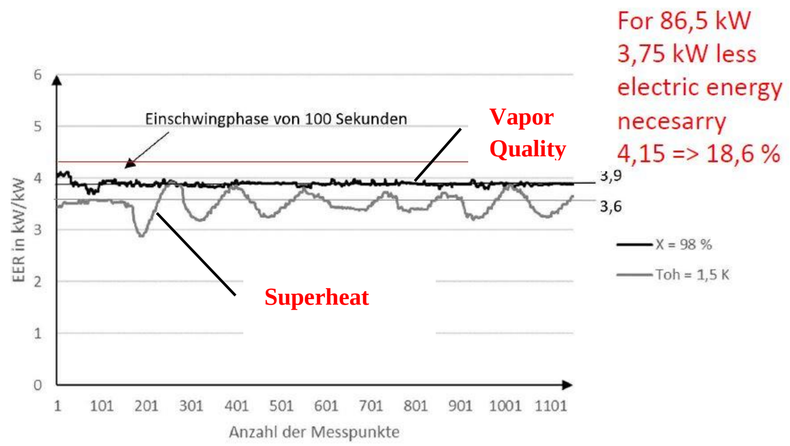

Figure 8: Test results, Vapor Quality vs. Super Heat Control

Energy Efficiency Ratio, 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% (EER = Energy efficiency Ratio).

It was confirmed that a direct-evaporating ammonia refrigeration plant can be operated in a stable state by the gas quality sensor. It was also shown that an efficiency increase of up to 18.6 % is possible due to the gas quality control, with an X-value of 98%, against an overheating control with 1.5 K. It was also found that the gas 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 partial load range, further research is required for the operation of the gas quality sensor.

Comment: conclusion from his testing was that the benefit of controlling with the HBX-DX vapor quality sensor is only present at max 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`s 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 regulation works fine when the system was in balance and when the evaporator load was changed from 100 to 50%. The vapor quality was homogeneous with strong relation between the sensor signal and valve operation.

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5. LABORATORY TESTS

Laboratory tests show that the sensor reacts as an "X" sensor that directly measures the degree of dryness where: “X”=0.5 (50% liquid) and “X”=1.0 (dry vapor). The system used for laboratory testing is designed to establish a two-phase ammonia flow where the vapor quality can be determined. The test system is adjusted to the desired test point and a steady state condition is achieved. This condition is maintained for 10 minutes where the last five minutes are used as data for the results. The data is collected in a lab view based data acquisition system developed and maintained by the Danish Technological Institute with a logging frequency of five seconds. Subsequently, the data are processed in a calculation model in the Engineering Equation Solver. The signal from the X sensor is a 4-20 mA signal, which is scalable to any desired range. Based on the measured mA signal, the raw sensor signal has been calculated. During tests, the signal from the sensors has also been visually read via the software named “HBX Tool” to avoid subsequent calculation errors.

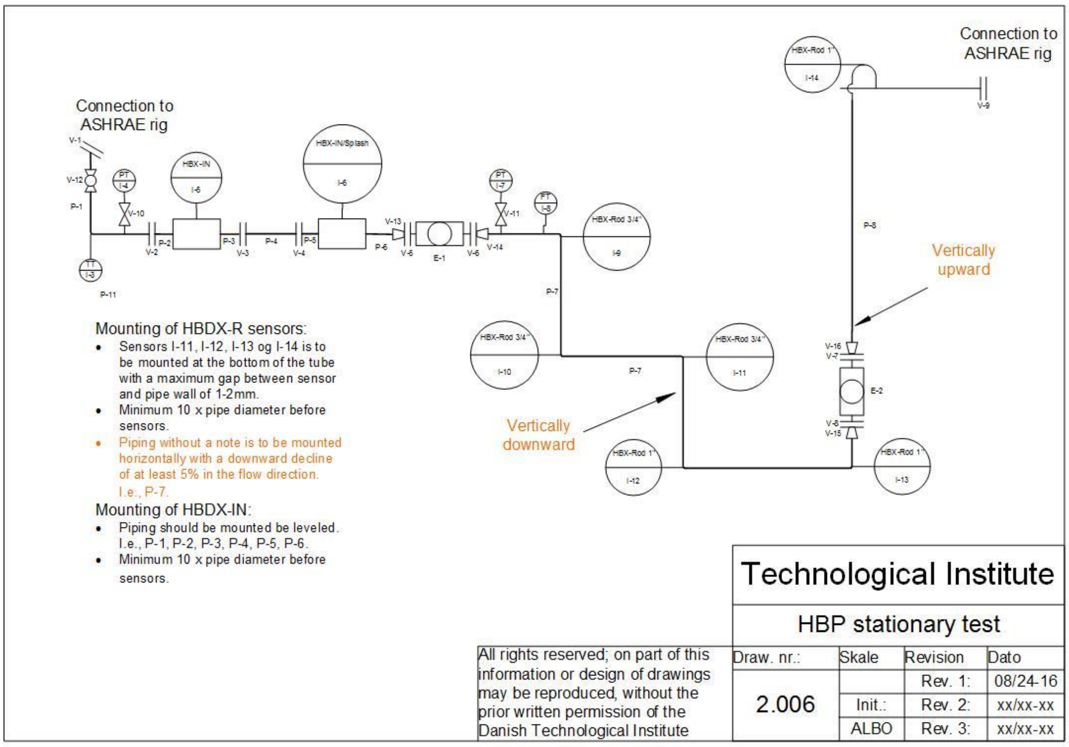

Figure 9: PI diagram for the Laboratory testing

Reference sensors:

1. Gas volume flow [m3/s] Orifice acc. DIN1952 [-]
2. Gas temperature [°C] PT100 76755
3. Gas pressure [bar] Danfoss AKS33 8570
4. Liquid mass flow [kg/s] Danfoss Mass 2100 4772
5. Liquid temperature [°C] Danfoss Mass 2100 [-]
6. Liquid pressure [bar] Danfoss AKS33 [-]
7. Sensor inlet pressure [bar] Danfoss AKS33 8592
8. Sensor pressure drop [mbar] Yokogawa EJA110A 81835

The graph/plot in Figure 10 covers -30°C/-22°F ammonia with a gas velocity of 24.5 m/s.

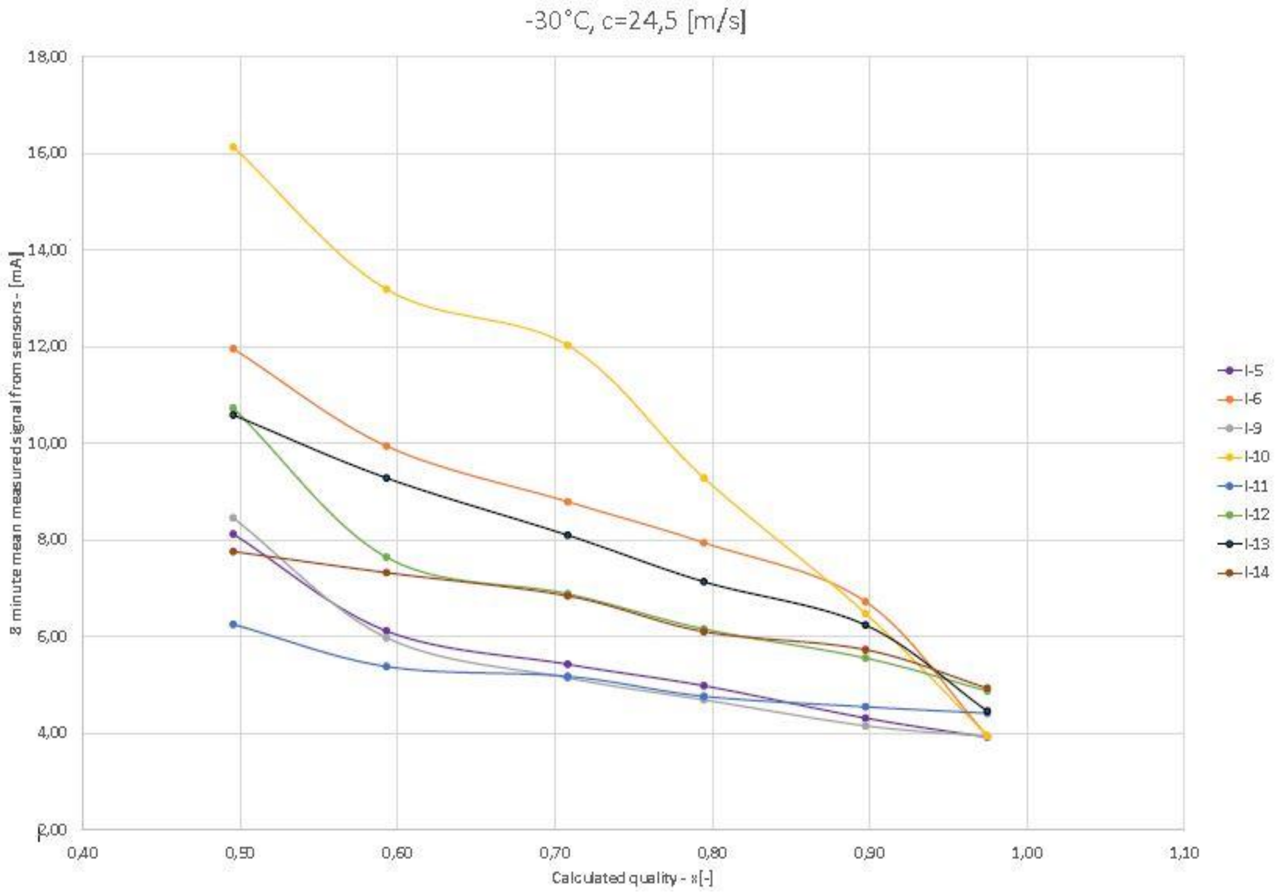

Figure 10: Graph with results from the laboratory test

The graph in Figure 10 shows all tested HBX- DX/OVC sensors plotted as a function of the output signal from the sensor in mA. The signal output ranges from 4–20mA, and the quality ranges from 0.5 to as close to 1 as possible. The plot covers -30°C/-22°F ammonia with a gas velocity of 24.5 m/s.Comment: The plot shows that the mounting of the sensor has a large influence on the measurements. All graphs in the plot are more or less linear in the range of quality 0.6–1, which makes it possible to read the quality. For sensor I-10 the measurement stands out at a quality of 0.7. The tests show that the temperature of the two-phase flow does not have a significant influence on the measurements. On the contrary, the velocity is of great importance, especially at low velocities.

Sensor I-5 is a 2 in. in-line sensor mounted in vertical piping. The graph for I-5 lines up closely to the graphs for sensors I-9 and I-11. These two sensors are both ¾ in. rod style sensors and are mounted counter current in vertical piping, which gives them a similar liquid flow into the sensor as with the in-line sensor.

Sensors I-12 and I-13 are both rod style 1". sensors respectively mounted co-current and counter current in a p-trap just before the riser. Naturally, liquid accumulation will occur in the p-trap, which gives the sensors a medium-high signal. Sensor I-13 gives the highest signal of the two because it is mounted just at the bottom of the riser. I-12 is mounted in the beginning of the p-trap.

Sensor I-14 is a 1 in. rod style sensor mounted co-current in the top of the riser. The sensor output signal aligns closely with the output signal of I-12, although the sensors are mounted in two very different places. They do have in common that they are 1 in. sensors and mounted co-current.

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4. ZERO SUPERHEAT & LOW CHARGE DX DESIGN

The desire to use the world’s most energy-efficient refrigerant, ammonia, in dry expansion refrigeration systems has led to many challenges and has rightly earned the reputation of being a poor solution that does not always work well. There have been many problems, and over time, many attempts have been made without any significant breakthroughs. It was necessary to compromise from the normal DX design and to install liquid separators before the compressors and set superheating very high in order to avoid liquid hammering and potential compressor damage. High superheating, and inefficient/non-thermodynamic evaporators with uneven liquid distribution combined with ammonia’s high latent heat of vaporization have caused most of the challenges. Altogether, this has led to very poor energy efficiency. It is also a fact that water in ammonia changes boiling point and thus the calculated superheat values; 1% water in the ammonia increases the boiling point by around 5K towards the end of the evaporation process (Nelson, 2010), this phenomenon will act as a false” superheat signal and will react accordingly with poor control.

Cold store in Melbourne, Australia:
Freezing: 3 DX evaporators -31°C/-24°F evaporating temperature, unit refrigeration capacity approx. 60kW, refrigerant operating charge of 1.42kg/3lb per evaporator.

- **The main points regarding the implementation of the system in Melbourne are:**
  Use of aluminum evaporators with tank distributors and internal surface enhancement.
- Vapor/gas quality based injection evaporator control.

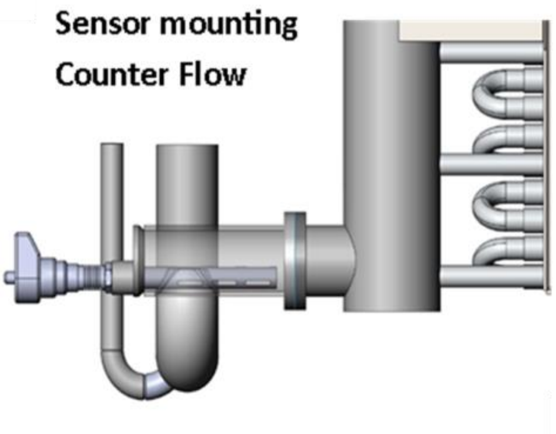

Figure 11: Sensor mounted in the outlet of a DX Air-Cooler in Australia

Measuring Superheat: The reason why the Vapor Quality sensor measures wet conditions when the superheat measurement indicates superheated vapor is due to the fact that unevaporated small liquid drops/mists are carried out by the vapor/gas flow towards the evaporator outlet. The liquid drops consist of most refrigerant, but may also contain small amounts of water and oil droplets. The sensor is very sensitive and reacts predominantly to the refrigerant. Small amounts of water and oil have only minimum influence.

Experiences gathered from four ammonia systems operating in Australia shows that the systems with vapor quality measurement/control are more energy efficient and do not result in pressure variations of the same magnitude as DX systems based on superheat controlled refrigerant injection (Jensen, 2015).

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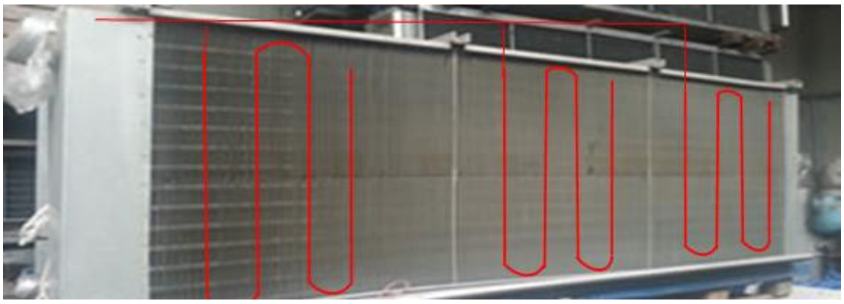
6. CAPACITIVE ICE SENSOR CONTROL - DEFROST ON DEMAND

Defrost Strategies result in significant Savings as well as optimization of the entire Systems.



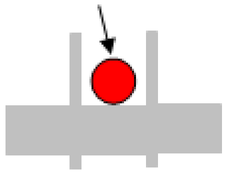


Figure 12: How to mount defrost sensors on air coolers

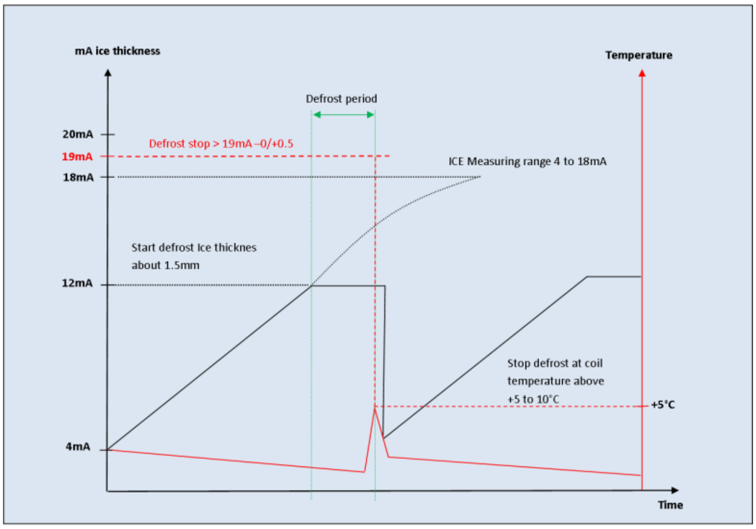


Figure 13: Defrost on demand - control strategy

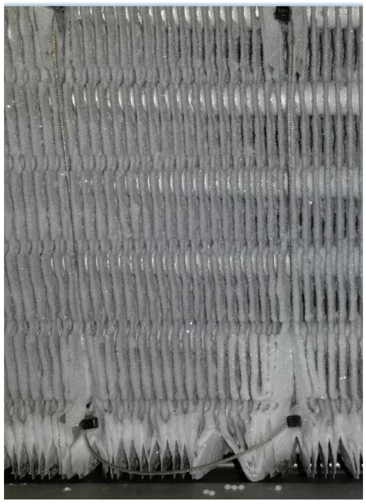


Figure 14: Air cooler with ice and defrost sensor wire mounted

The Defrost sensors are based on capacitive measuring principles, in which an insulated steel wire acts as a conductor and the evaporator fins and tubes act as the second conductor and jointly forms an usable electrical capacitor. A change in the measured signal occurs when ice is build-up between the fins; the sensor is measuring the dielectric difference between air and ice. The thickness of the ice has an impact on the measurement. The sensor output signal is a 4-20 mA signal; **Dielectric constant "ε" ice is 3.2.** When the evaporator is free of ice, the sensor emits 4mA. Depending on the ice build-up, the sensor emits up to 20 mA. A visual inspection must be carried out to determine when defrost should be performed, and the system's defrost control should be set to perform defrost at that given signal level (for example 1.5mm ice gives about 12 mA). Defrost must be stopped when the outside coil temperature is approximately 5 to 10°C / 41 to 50°F, remaining water droplets from the melted ice should be frozen after defrost, here the signal is in the range 4 to 5mA and indicates a clean evaporator without ice.
Examples with deposited grease and dirt e.g. from a slaughterhouse will also affect the measurement and can be used to control the cleaning of the evaporator (if the signal after defrost is e.g. 6mA then the evaporator must be cleaned).

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7. INSTALLATION OF THE "X" SENSOR

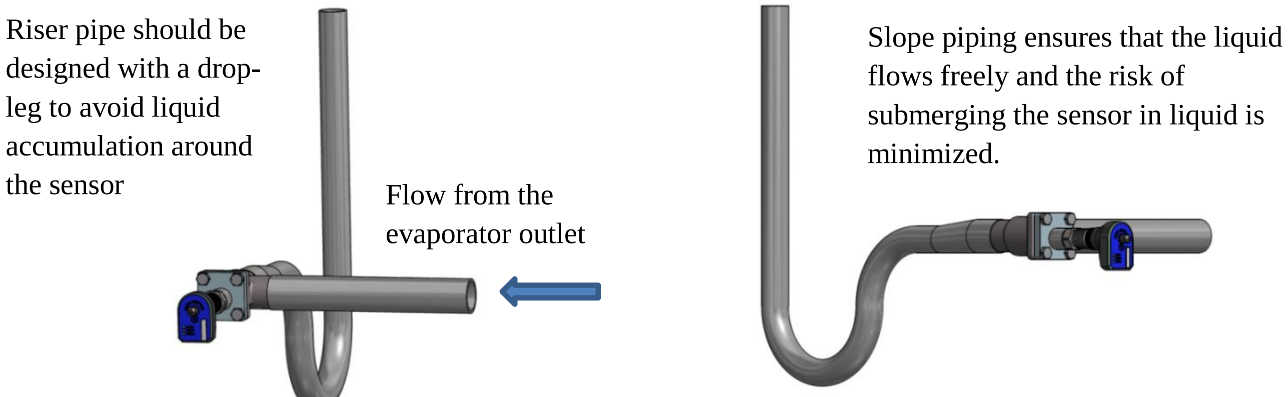

Figure 15: HBX sensor mounted in an angle strainer

8. 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 ensure a uniform and homogeneous load on every evaporator section with a very small pressure variation/droop compared to a normal controlled system (Super-heat and over-feeding). The sensor method works with all types of refrigerants. A prototype of the "X" sensor for CO2 refrigerant has been tested at DTU (Technical University of Denmark). The result from this test is briefly described by Martin R. Kærn in his paper entitled "COMPARISON OF A CO2 REFRIGERATION AND HEAT PUMP TEST SYSTEM WITH AND WITHOUT EJECTOR".

Safety: Significantly smaller ammonia charge increases safety and reduces regulatory burden.

Energy Saving potentials (saving potentials are always system dependent).:

- DX, liquid injection control into the evaporators……………..10 to 25%.
- OVC, Elimination of liquid within suction lines and risers…...10 to 30%.
- ICE, Defrost on Demand represents a large saving potential versus "time-based defrost cycle".

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