An Integrated Solution Enabling Low Superheat Operation for Improved Performance in Reversible Chiller Systems

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ABSTRACT

The adoption and proliferation of variable speed compressors and electronic expansion valves (EXVs) in high-efficiency reversible chiller systems provides the opportunity to optimize the performance of the unit around a new set of variables. This paper details the benefits of a controls framework designed to enable low-superheat (below 5K) operation to optimize the seasonal energy efficiency ratio (SEER) of a commercial-scale chiller in a safe manner. The various attributes of low-superheat operation over conventional (>5K) chiller operation, including the necessary changes in circuit controller management and reliability of the compressor, is discussed. The performance benefit for a range of capacities and operating conditions, with particular attention to evaporator effectiveness, is also presented. Ultimately, this provides a template from which significantly improved system performance can be achieved.

1. INTRODUCTION

The increasing cost of energy, coupled with the recent drive for energy security and climate change mitigation have provided the impetus for improving the performance of heating and cooling systems. In Europe, historically, performance criteria have revolved around nominal ratings in cooling mode (Energy Efficiency Ratio – EER) and heating mode (Coefficient Of Performance – COP). These had to be measured according to EN14511 and published. Seasonal performance in cooling mode was also often indicated by manufacturers in the form of Eurovent's ESEER certified value, but only on a voluntary basis. Since January 2015, minimal seasonal performance requirements are enforced for heating systems (including residential and commercial heat pumps, up to 400 kW rated capacity) as defined in the Lot 1 of Energy-related Products (ErP) Ecodesign Directive (2009/125/EC). European energy labels, intended to inform end-users, are also mandatory for systems below 70kW rating capacity. Since January 2018, similar regulation (2016/2281**)** for AC systems has been in force and the first tier of the requirements defined for chillers are in application across European Union. In conjunction with other regulatory initiatives (e.g. Energy Performance of Buildings Directive and European F-Gas Regulation aimed at reducing the environmental impact of high GWP refrigerants), these have provided a strong incentive for manufacturers of chiller systems to improve the performance of their equipment.

One method of improving the performance of chiller systems is to reduce evaporator superheat. The hypothesis is that this improves performance in two ways: 1) the reduced superheat allows for a lower "pinch point" in the evaporator, thereby improving the approach temperature between the refrigerant and the cooling media; and 2) by improving compressor performance. In this regard, this paper focusses on investigating these phenomena, primarily through an experimental approach. The first part of this paper describes the development of the solution, including compressor, controller and test-rig advancements needed to facilitate low superheat (low-SH) operation. The second part of the paper discusses the results from the test campaign, and evaluates the potential of this approach to improving overall chiller performance.

2. DEVELOPMENT OF AN INTEGRATED SOLUTION

Implementation of low superheat operation in chiller systems requires a coordinated approach that includes robust control to manage the refrigerant circuit, as well as mechanical robustness of the compressor itself. Further complexity is introduced in the case of systems that include variable speed compressors, whereby a change in the compressor speed (due to a change in the capacity request, or a change in the evaporating or condensing conditions) can influence control stability. Therefore, an effective solution requires a comprehensive software package able to manage the various actuators - valves and compressors - across the operating envelope.

Controller Considerations

The objective of the circuit controller is to manage all the actuators in the refrigerant circuit – principally the compressors and the expansion valve. This includes systems with multiple compressor combinations (tandem and trio combinations of fixed and variable speed compressors). The fixed speed compressor is activated (started or stopped) by the circuit controller according to the capacity request demanded by the unit or plant controller. The controller also ensures that the variable speed compressor operates within the prescribed operating envelope at each speed, and when required, drives the compressor in a smooth manner across the different regions of its operating envelope (Figure 1). Note that in addition to managing the speed ramps and the on/off activation of compressors, the controller also has to manage the expansion valve during these events. Apart from managing the compressor superheat, expansion valve control during transient events is vital for safe operation. In addition, expansion valve management during cycle transitions (cycle reversing for defrost, cooling/heating mode transitions, oil recovery cycles etc.) also needs to be managed by the controller.

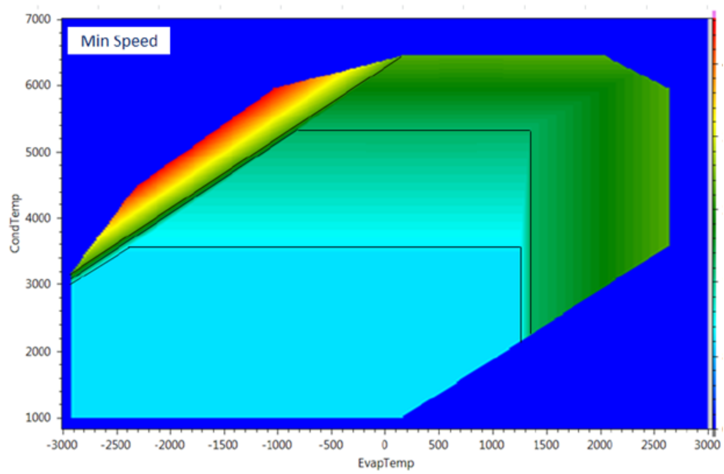

Figure 1: Variable speed compressor envelope with different speed regions indicated

Expansion valve control is critical to ensure optimal system efficiency in steady-state operation. A superheat setpoint that is too high leads to inefficient operation, due to the large difference between the evaporating temperature of the refrigerant and the cooling media in the heat exchanger. For a given temperature of the cooling media (typically water in chiller systems), this leads to lower evaporating temperatures and higher compressor specific power consumption. On the other hand, lowering the evaporator superheat is beneficial for overall system performance, but increases the risk of flooding the compressor with liquid.

Optimal superheat control necessitates the use of a electronic expansion valve (EXV), rather than a thermostatic expansion valve (TXV), in the chiller system. A TXV based system would not have sufficient modulation capability in order to function effectively, particularly since low superheat operation may introduce periodic instability in the evaporator. A typical embodiment of a chiller system capable of low superheat operation is shown in Figure 2 below. A typical list of the inputs and outputs for a controller driving this system is given in Table 1 .

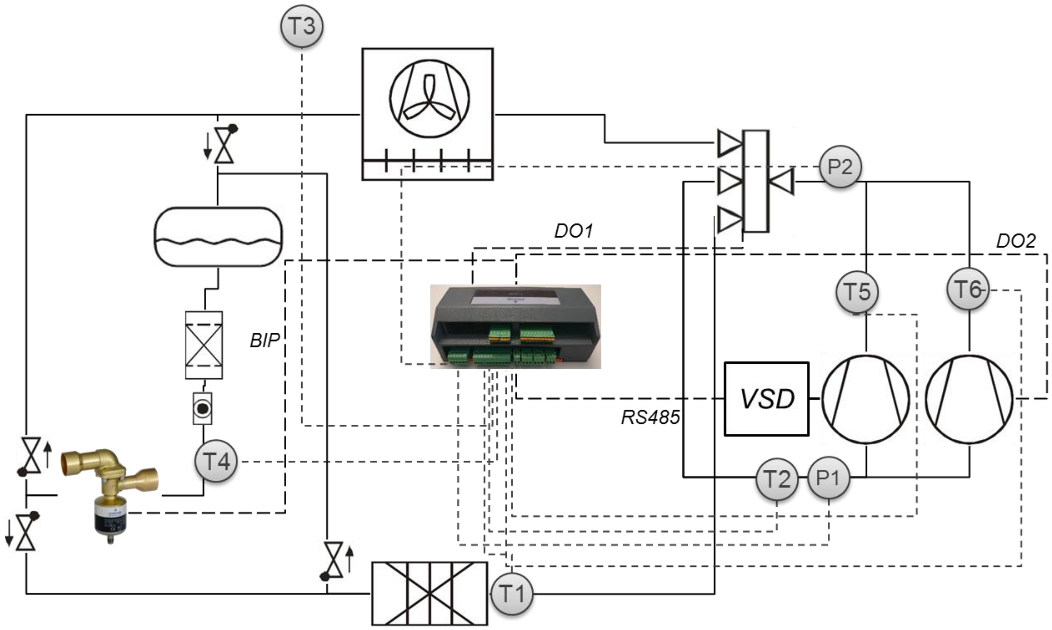

Figure 2: Typical arrangement of the main elements of the integrated solution for a low superheat capable chiller

Table 1: Schedule of typical inputs and outputs for a low superheat capable reversible chiller

I/O	Function
P1	Suction pressure for superheat control, high superheat protection and envelope management
P2	Discharge pressure for envelope management
T1	Evaporator outlet gas temperature for suction superheat control and high superheat protection
T2	Compressor suction gas temperature for suction superheat control and high superheat protection
T3	Ambient temperature
T4	Liquid temperature before main EXV for energy counter function & EXV management
T5	Variable Speed Compressor Discharge temperature
T6	Fixed Speed Compressor Discharge temperature
P1	Power Supply
P2	Battery Backup or Supercap for EXV control during unscheduled shutdown
DO1	4-way valve
DO2	Fixed speed compressor command #1
DI1	Feedback Safety (emergency pressure switches, flow switches etc.)
DI2	Demand On/Off (for defrost request)
DI3	Cooling / Heating Mode request
EXV/BIP	EXV control
Bus Inverter	Communication with inverter drive
Bus Ctrl	Communication with system controller

Given these considerations, we can define the objective of low-SH operation: to lower the refrigerant superheat at the entrance of the compressor to a value as low as possible while maintaining safe operation.

Key control attributes, in accordance with the objective of the low superheat algorithm, include the following:

- Maintain stable operation at low-SH conditions (0K< SH < 5K)
- Allow for protection and/or compensation when system phenomena force a deviation from these conditions
- Allow for effective low-SH control even for multi-circuit and tandem/trio system configurations

Previous research has shown that attaining superheat values lower than 5K is challenging, and requires an understanding of valve positioning, compressor discharge temperatures, heat transfer rates with the ambient environment and their interactions with the suction superheat. This stems from the fact that, in case of flooding (i.e. a condition where a significant amount of liquid refrigerant enters the compressor), the suction superheat remains the same (at 0K). In other words, there is no indication of the amount of "flooding" in a compressor, since the saturation temperature of the refrigerant is constant (in the case of azeotropic refrigerants). Furthermore, the boundary between positive superheat operation and flooded operation may be blurred due to the potential for measurement error, temperature sensor measurement tolerances, sensor resolution, sensor calibration etc.

For this purpose, a comprehensive control scheme, including fuzzy logic, adaptive PID control and dynamic valve prepositioning, have been implemented as detailed in Bertagnolio *et al* (2016). In order realize low superheat operation in a safe and reliable manner, algorithms relying on compressor and valve performance mapping are used. These increase control robustness and achieve optimal superheat levels well below the standard 5K threshold.

Compressor Validation Considerations

In addition to control considerations, operation in a low superheat regime necessitates mechanical robustness of the compressor itself. Note that low superheat operation does not preclude periodic droplets entering the compressor, given the possibility of transient events and the reaction time of the system to respond to these events. Continuous operation at low superheat conditions can wash oil off bearing surfaces and dilute lubrication oil. Therefore, a compressor designed to operate in a low superheat environment must be sufficiently robust to mitigate these phenomena.

In order to ensure long-term reliability of the compressor for low-superheat operation, a rigorous testing campaign was undertaken in order to mitigate various failure modes. The main elements of this campaign included:

- Several hundred start/stop cycles with the compressor sump filled with liquid refrigerant (to mitigate concerns about liquid hammer)
- Continuous operation of the compressor in floodback conditions over several thousand running hours. This was performed to take a safety margin beyond 0K superheat operation, the most severe condition expected. Furthermore, this was performed at several operating conditions.
- Continuous operation of the compressor in floodback conditions at different oil levels, once again over several thousand running hours. This was performed to mitigate concerns regarding lubricant dilution and washing.
- Tuning of control laws across the operating envelope. This was performed in order to ensure stable operation across the envelope, as well as to identify regions of the envelope where low superheat operation would not be permissible.

At the end of this comprehensive campaign, the performance of the compressor was compared to its performance before being subjected to the reliability tests. A representative result is shown in Figure 3 and Figure 4 below.

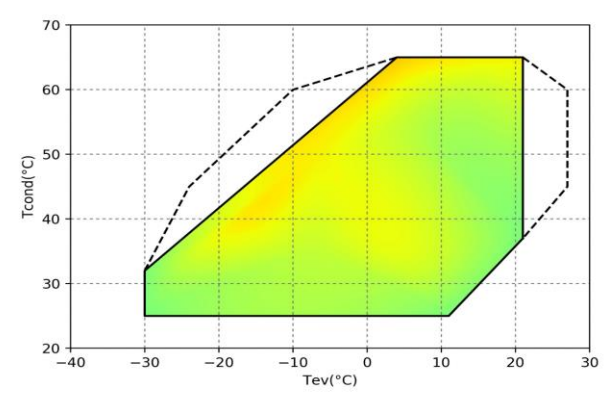

Figure 3: Deviation of Compressor Power Input Values before and after reliability testing

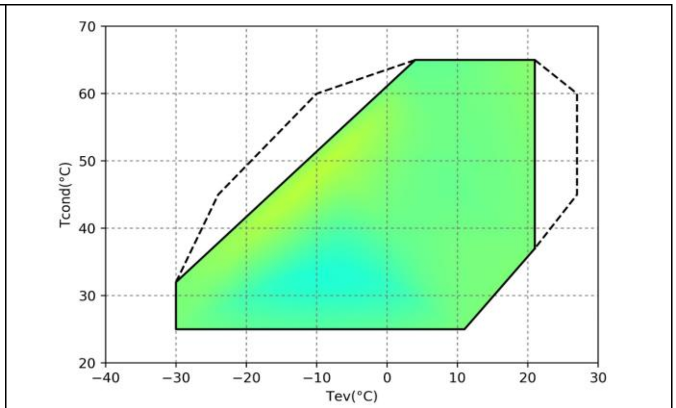

Figure 4: Deviation of Compressor Cooling Capacity Values before and after reliability testing

The results show that the performance deviation before and after the reliability campaign is negligible, for both compressor power input and compressor cooling capacity. This means that volumetric efficiency and frictional performance of the compressor are maintained, despite the severe reliability tests. This is an important consideration because the performance gain due to low superheat operation should not be offset by a corresponding loss of compressor performance due to component wear. A teardown of the compressors subjected to the reliability campaign also showed no undue wear, thereby confirming the robustness of the design for low superheat operation.

3. TESTING AND DESIGN QUALIFICATION

In order to understand the benefit of low superheat operation, a purpose-built test setup was installed and instrumented for experimental tests. The test rig consisted of an in-production Air to Water (A/W) chiller system, modified to include pressure transducers and temperature sensors across all the main components (evaporator, condenser, expansion valve, compressors, 4-way valve etc.). High accuracy temperature sensors are installed in-pipe at the suction of each compressor, in order to have highly accurate superheat readings. In addition, high-accuracy in-pipe temperature sensors are also installed on the water side. The electrical cabinet was modified in order to install current clamps and power monitoring on each compressor, as well as the unit as a whole. All-in-all this provided a comprehensive test platform to conduct the experimental campaign.

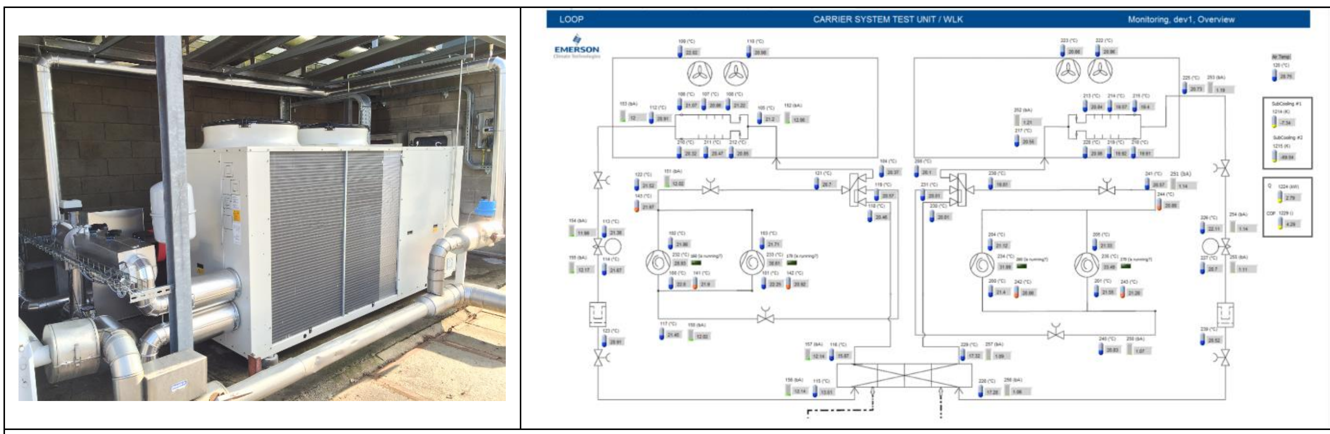

Figure 5: A/W Chiller with Variable Speed Scroll Solution (left) and corresponding instrumentation suite (right)

4. RESULTS AND DISCUSSION

Figure 6 to Figure 11 show the results of experimental tests performed on an Air to Water Chiller at various superheat levels. The tests were performed at water-side temperature differences of 1.5K, 2K and 4K: that is, the difference between the leaving water temperature (LWT) and the entering water temperature (EWT) in the evaporator were 1.5K, 2K and 4K.

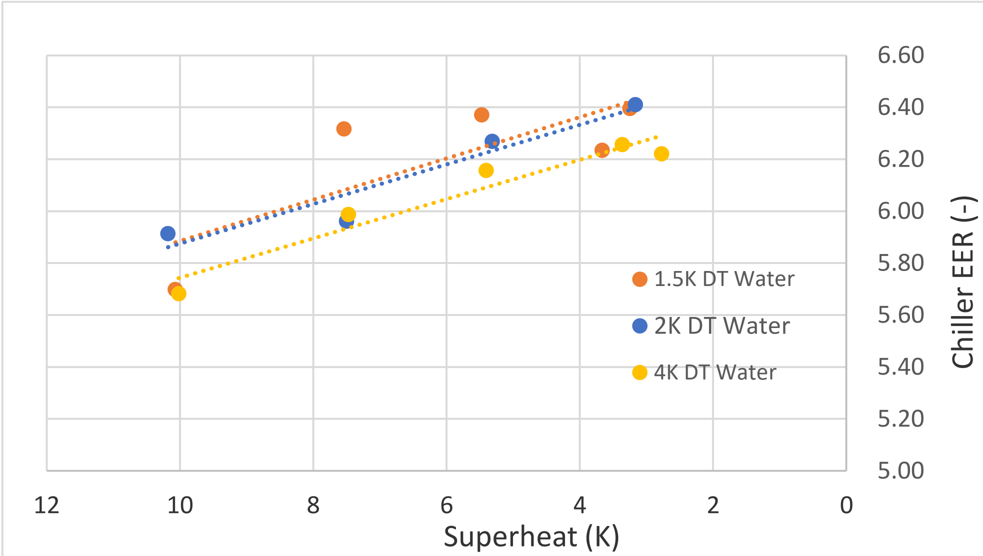

Figure 6: Chiller EER as a function of Superheat for water-side temperature differences of 1.5K, 2K and 4K

Figure 6 clearly shows that the chiller EER improves significantly as superheat decreases. The margin of improvement is on the order of 10% for the range of superheats studied. This is true for all water-side temperature differences; in fact, the improvements are roughly linear in all cases. In addition, the margin of improvement is roughly the same for all temperature difference levels.

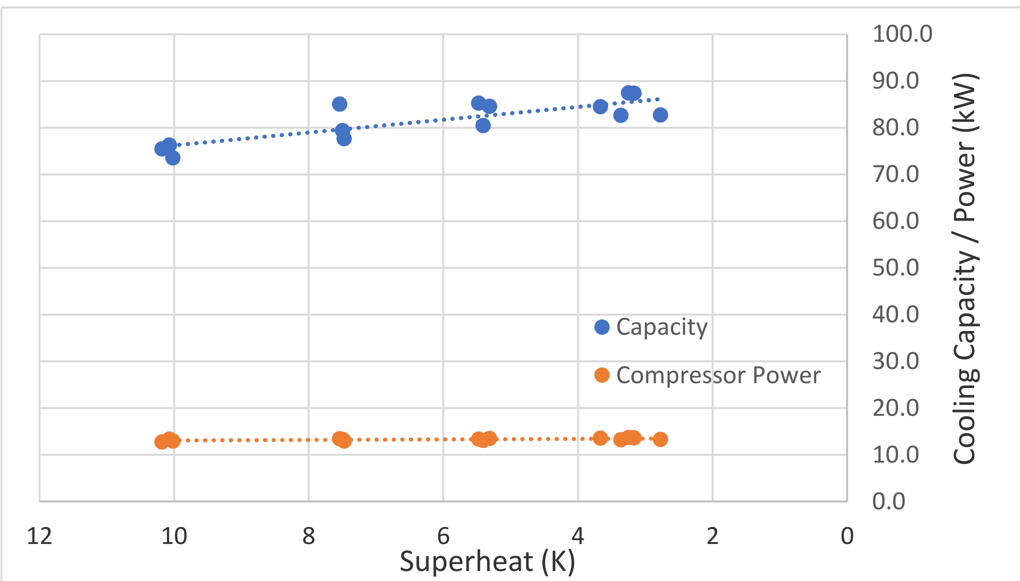

Figure 7: Compressor Capacity and Power Input as a function of superheat

Figure 7 shows the compressor capacity and the input power as a function of superheat. It provides a breakdown of why the chiller EER improves as superheat decreases as shown in Figure 6: as the superheat decreases, the capacity increases significantly while the compressor input power required is roughly constant.

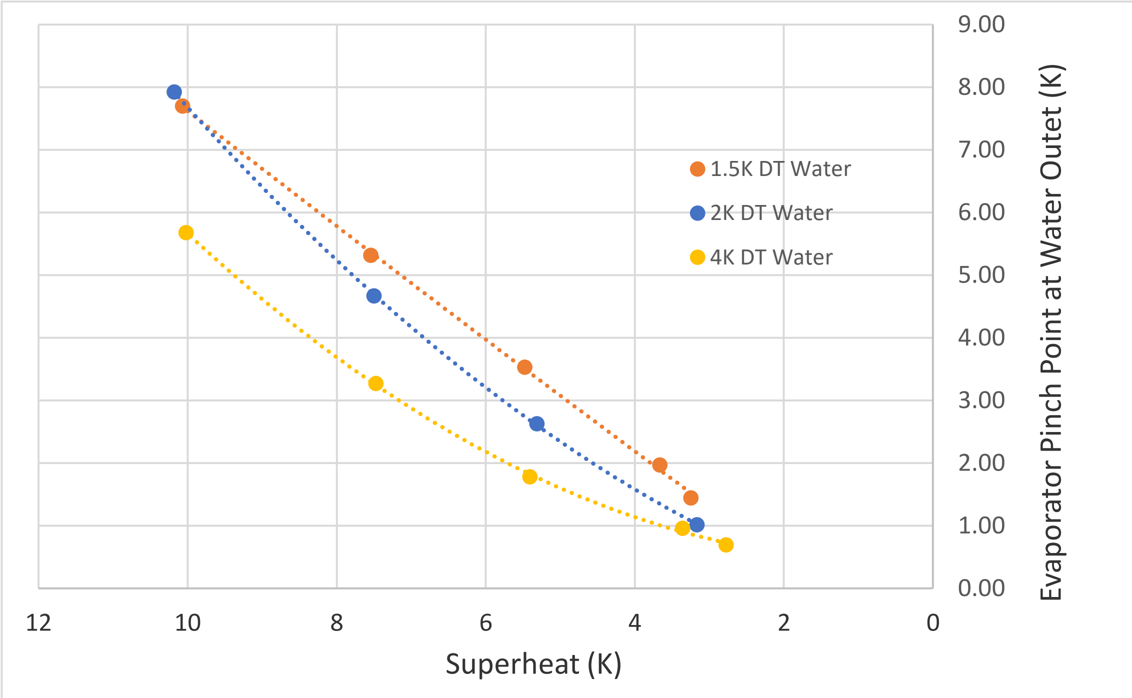

Figure 8: Pinch point temperatures at the evaporator outlet as a function of Superheat for water-side temperature differences of 1.5K, 2K and 4K

Figure 8 shows the pinch temperature at the evaporator outlet as a function of the superheat. Put differently, this is the difference between the refrigerant and water temperatures at the water-side outlet. The trend clearly shows closer approach temperatures as the superheat decreases. In essence, this is indicative of better heat exchanger performance for lower superheats. Furthermore, it also evident that pinch temperatures are closer (and thereby heat exchanger performance better) for larger water-side temperature differences.

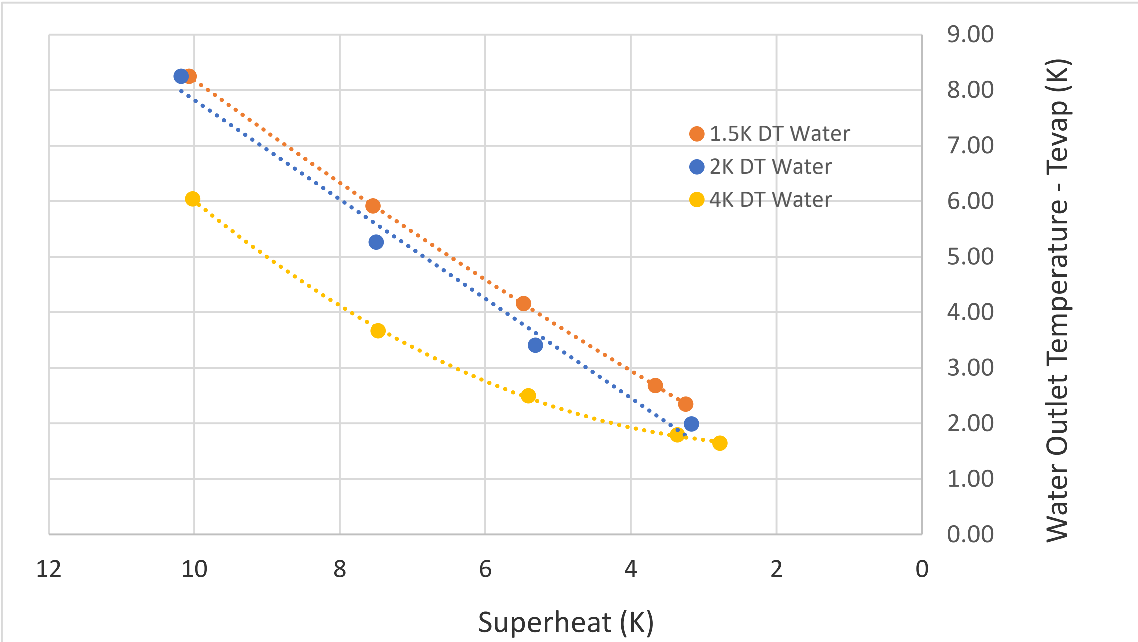

Figure 9: Water Outlet Temperature minus Evaporating Temperature for water-side temperature differences of 1.5K, 2K and 4K.

Figure 9 shows the difference between the water outlet temperature and the evaporating temperature of the refrigerant as a function of the superheat. Principally, this illustrates that the evaporating temperature is increased as the superheat decreases. A higher evaporating temperature entails a higher capacity for a given work input, or conversely, that for a given capacity delivered on the water side, the work input needed is lower because in effect, the pressure ratio across the system is smaller. Furthermore, larger water-side temperature differences show higher evaporating temperatures; this is due to the fact that the average temperature of heat transfer is higher as the water side temperature difference is larger. This also explains why the pinch temperatures are closer for larger water-side temperature differences as seen in Figure 8.

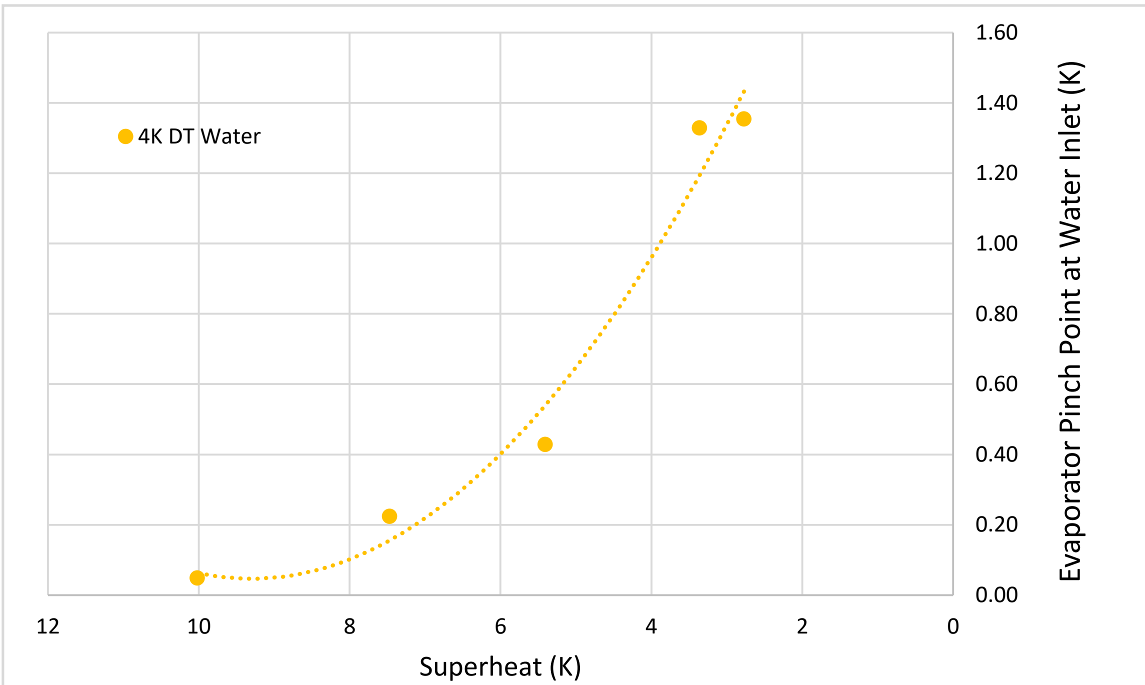

Figure 10: Pinch point temperatures at the evaporator inlet as a function of Superheat for a water-side temperature difference of 4K

Figure 10 shows the pinch temperature at the evaporator inlet as a function of the superheat. This is the difference between the refrigerant and water temperatures at the water-side inlet. The trend shows that the heat exchanger is “pinched” at the inlet located at higher superheats. When compared with Figure 8, it leads to the interesting observation that the pinch point moves from the inlet location to the outlet location as the superheat decreases. This is again indicative of better heat exchanger performance for lower superheats.

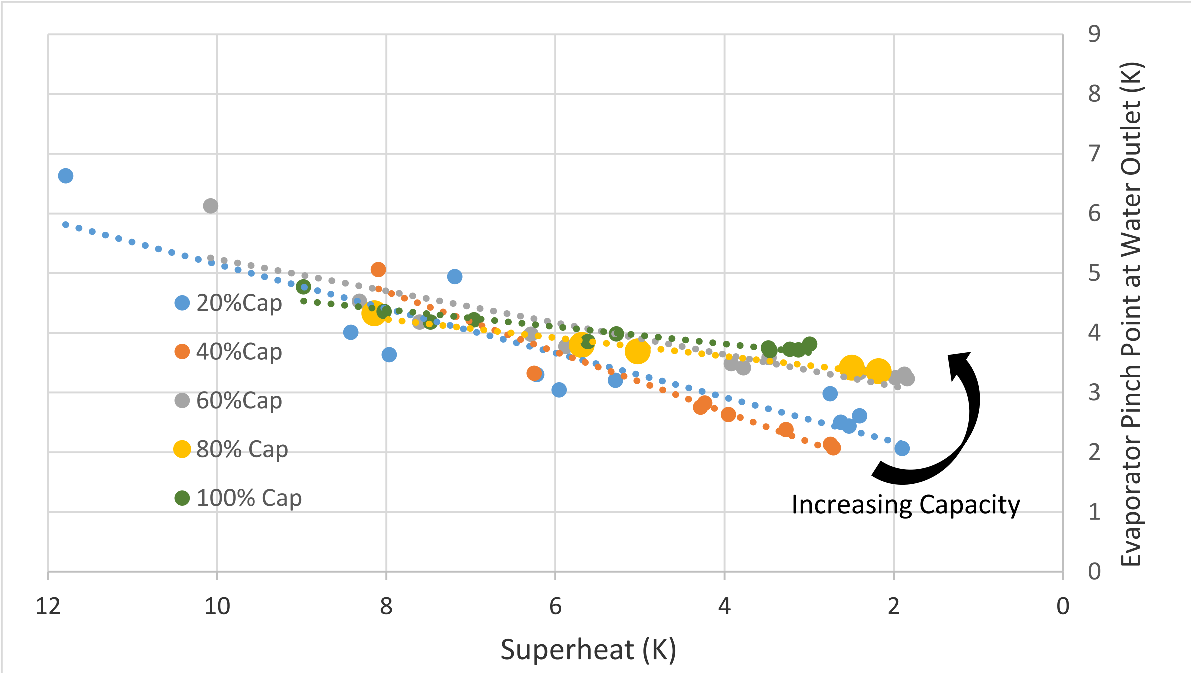

Figure 11: Pinch point temperatures at the evaporator outlet as a function of Superheat for various capacities, performed on a chiller with a variable speed compressor

Figure 11 shows the pinch temperature at the evaporator outlet as a function of the superheat from a further test campaign. In this campaign, the chiller capacity was modulated in order to further understand the benefits of low superheat operation. It is clear from the results that lower capacities benefit more from low superheat operation:
pinch temperatures are closer (and thereby heat exchanger performance better) for lower capacities. This is logical: a heat exchanger sized for 100% capacity has spare surface area at lower capacities that may be used to improve heat transfer performance. However, a pinch point at the heat exchanger inlet would not fully capture this benefit. Minimizing the superheat has the effect of moving the pinch point to the outlet location, and thereby utilizing the surface area for efficient heat transfer (at a higher average evaporating temperature). The improved heat exchanger performance at lower capacities in turn leads to better performance at these operating points. This is significant, because the vast majority of operating hours of a chiller system are at part load operation, and having better performance at the points has a disproportionate effect on improving the seasonal energy performance ratio (SEER).

6. CONCLUSIONS

A comprehensive framework designed to enable low-superheat operation to optimize the performance of a commercial-scale chiller has been presented. Implications for controller management as well as compressor reliability are addressed, and a customized test rig was constructed in order to investigate performance improvements experimentally. Results show that EER performance can be improved by up to 10%. The performance improvement is largely derived from an improvement in capacity for the same compressor input power. This in turn is derived from better heat exchanger performance due to better approach temperatures (smaller pinch points) at lower superheats. Further results show that the performance improvements are magnified at part load operation: this has a significant impact on improving the seasonal energy performance ratio (SEER) because the vast majority of operating hours on a chiller system are at part load.

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