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A Critical Literature Review of Defrost Technologies for Heat Pumps and Refrigeration System

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ABSTRACT

When the operating conditions are extremely cold and humid and the surface temperature of the heat exchanger well below the freezing point (lower than the dew point temperature of the air) moisture from the air stream will freeze on the surface after condensation and the frost will start growing. The frost growth degrades the performance of the system considerably. It hinders the airflow and increases the pressure drop through the coil which means more fan power is requires for to maintain the desired flow rate. With reduced flow rate due to the increase of pressure drop, system's capacity drops rapidly. In the case of heat pump the capacity of the evaporator decreases due to the airflow drop, which reduces the overall heating capacity and coefficient of performance of the heat pump. Additionally, the frost layer increases the thermal resistance to the heat transfer between the air and refrigerant. The reduction in airflow and increased thermal resistance reduces the heat energy extracted by the evaporator and decreases the heat pump capacity and efficiency. Similar process is observed for the cooling coils of commercial refrigeration system where the frost growth can dramatically reduce the system capacity. Once the performance reaches its minimum acceptable stage, a defrost process is introduced to remove the frost layer and to achieve the performance at the start of the cycle. The frost defrost process is repeated continuously. Overall the frost growth is highly undesired phenomena which can cause considerable reduction in performance of the system. This study overviews different procedures to counteract the frost growth. Various frost mitigation procedures have been reviewed and compared to access their feasibility. The methods such as air treatment before entering the heat exchanger are used to effectively eliminate or at least minimize the frost growth rate. Such procedures are discussed under two major categories, air treatment processes to mitigate the frost and appropriate system modification to minimize or eliminate the frost growth.

1. INTRODUCTION

Air source heat pump (ASHP) units have found applications worldwide due to their advantages of high efficiency, environmental protection, low cost and easily modification. Studies on ASHPs has become a critical research and development subject mainly due to improved energy efficiency compared to conventional technologies. However, when an ASHP unit operates for space heating and the ambient air temperature extremely low (-7 to 5ºC) and the relative humidity is relative high (greater than 65%), frost will form and accumulate on the outdoor coil of the ASHP, which becomes a major obstacle to achieving sustained performance. Over time, the frost accumulation on the coil becomes sufficient to both impede heat transfer and to dramatically increase the air-pressure drop, leading to a decrease in system performance. To counter the effect, a defrost process is mandatory to remove the frost from the

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surface. Similarly, retail food stores and supermarkets operate their refrigeration systems continuously to maintain proper food storage conditions within their refrigerated display cases and storage areas. For obvious reasons, moist air becomes entrained within the refrigerated display cases and storage areas. Since the temperatures of the evaporators within the display cases and storage areas are well below the freezing temperature (lower than the dew point of the entrained air), water vapor within the air will condense and freeze on the evaporator surfaces, forming frost. Thus, in order to maintain system performance and proper storage temperatures within the display cases and storage areas, evaporators require periodic heating to melt and remove the frost (Tassou, Datta and Marriott 2001).

Defrosting of outdoor coils for heat pumps and the display case evaporators for refrigeration systems can be achieved by several methods. Often times, the operation is stopped, and the frost then melts naturally as the evaporator fans blow air over the evaporator surfaces. To facilitate faster defrost, electrical resistance heaters are commonly deployed to heat the evaporator surfaces. In another defrost technique known as hot gas defrost, high temperature refrigerant vapor from the compressor discharge is routed through the frosted coil via a series of valves and piping. The high temperature vapor provides the required heating to melt the frost which has accumulated on the evaporator coils. Defrosting of supermarket display case evaporators is commonly controlled by a preset time cycle. Defrosts are typically scheduled to occur every six or eight hours, with a duration of 20 to 30 minutes. This method has the advantage of simplicity, reliability and low cost. However, a time-based defrosting strategy is determined from worst case conditions to ensure complete defrosting under extreme conditions. Thus, unnecessary defrost cycles will likely occur, thereby reducing the energy efficiency of the refrigeration system (Tassou, Datta and Marriott 2001). A significant amount of energy is required to defrost the evaporators in refrigerated display cases. Mei et al. (2002) report that electric defrost heaters can account for up to 25% of the total electrical energy consumption of refrigerated display cases. A review of manufacturers' data indicates that electric defrost energy consumption can range from 10% to 30% of the total display case energy consumption, with an average of approximately 20%. Furthermore, defrosting adds heat to the refrigerated display cases, which must be removed by the refrigeration system after termination of the defrost cycle, thereby increasing compressor operation and energy use.

2. FROST GROWTH MITIGATION MEASURES

Frosting duration accounts more than 80% of operation time in a frosting-defrosting cycle, and thus exploration of frost retarding measures plays an important role in designing ASHP and commercial refrigeration units. To improve their operating performance, frost retarding measures attract more and more attention. Previous studies on developing frost retarding measures are broadly classified into three major types: upstream treatment of air, coil design adjustments and system adjustment.

2.1. Upstream Air Treatment

Frost formation and growth on the cold surface is depends on the ambient air conditions. Parameters such air temperature, RH, and airflow rate directly impact the frost density, growth rate on the heat exchanger surface. Following section briefly describes the various parameters which can influence the frost growth rate and proposes techniques which can potentially considerably reduce the phenomena.

2.1.1. Reducing inlet air humidity

Since frost forms due to solidification of water vapors, any measures of reducing inlet air humidity (such as using solid/liquid desiccants) can assist to mitigate the frost growth. Such techniques seem more applicable for a closed environment (display cases for a refrigeration system) rather for an open environment (outdoor coil of an ASHP) (Tassou et al., 2001). Several investigators have evaluated procedures to dehumidify the air-stream and methods such as applications of desiccants have been implemented. Wang et al. (2005) proposed the deployment of an adsorbent bed to dehumidify the air to effectively reduce the frost formation on heat exchangers. Wang et al. (2015) conducted an experimental study for a novel heat pump water heater and observed that the evaporator remained frost-free for 32, 34, 36 min during heating mode at the ambient temperatures of -3°C, 0°C and 3°C, respectively, for 85% RH. Su and Zhang (2017) evaluated the performance of a novel frost-free ASHP system combined with membrane-based liquid desiccant dehumidification. In another study, Jiang et al. (2014) introduced a novel non-frosting ASHP system, in which a glycerol solution spray system was employed to the outdoor heat exchanger to avoid frosting. The ambient relative humidity greatly affects the amount of frost formation (Tassou, Datta and Marriott 2001). Thus, relative humidity is directly related to the required defrosting frequency and associated energy use. Several studies have reported on the energy use associated with defrost heaters as a function of relative humidity. Other factors which influence the rate of frost formation on evaporator coils include ambient air temperature, heat exchanger's fin spacing, and air flow rate (Bullard and Chandrasekharan 2004). Fig. 1 shows the relationship between frost accumulation, air velocity and air pressure drop across an evaporator coil. The data shown in Fig. 1 is for a heat exchanger with a fin spacing of 4 fins per inch (1.6 fins per cm) and entering air conditions of 32°F (0°C) and 72% relative humidity. It can be seen that the pressure drop across the heat exchanger increases with increasing frost accumulation and with increasing air velocity. As frost accumulates, the size of the air passages through the coil are reduced, resulting in an increase in the pressure drop through the coil and an increase in the air velocity through coil. Thus, it has been suggested that defrost initiation can be based either on the increase in pressure drop across the evaporator or on the increase in air velocity through the evaporator, both of which accompany an increase in frost accumulation.

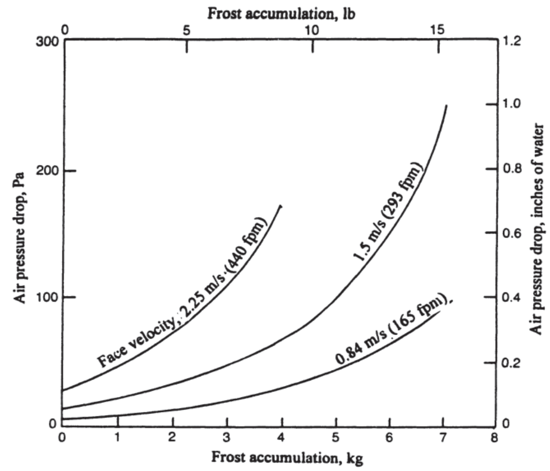

Fig. 1: Effect of frost accumulation and air velocity on air pressure drop across an evaporator coil (Stoecker 1998)

Regardless of the potential benefits of the above described processes, it important to account for the increase in capital and operational costs. Additionally, the desiccant regeneration process requires energy, and thus, makes the process more energy intensive. However, since during the dehumidification process, air temperature is increased due to the heat of adsorption, the process provides a secondary benefit which helps to minimize the frost growth as described in the following section.

2.1.2. Preheating inlet air

Another obvious choice to mitigate the frost is preheating inlet air which is a simple and effective technique. However, it is not easy to implement and requires high energy, particularly in relatively cold regions. Using waste heat in preheating inlet air is a feasible option where for example, heat recovered from exhausted indoor air, can be effectively utilized. Conventionally heating elements are placed in the inlet air duct so that when outdoor air temperature drops below the frosting point, the heating elements can preheat the air to avoid frost growth. Rafati et al. (2014) reported that to prevent frost formation, the inlet air temperature upstream of an outdoor coil must always be higher than the frosting point.

Figure 2 and 3 present the frost formation conditions for a heat exchanger and for an energy exchanger. Kwak and Bai (2010) conducted an experimental study to increase the heating capacity and COP of a small capacity heat pump using the air as a heat source under frosting conditions, deploying an electric heater at the entrance of outdoor unit of heat pump. They concluded that when the outdoor temperature was 2°C/1°C (DB/WB), the heating capacity and COP were increased by 38.0% and 57.0%, respectively, compared to the performance of a conventional heat pump.

Several studies have focused on the heat recovery process as a frost retarding measure (Rafati et al., 2014; Kragh et al., 2005). The process relies on the heat transfer between the exhausted indoor air and ambient air to reduce the frost growth rate. Song (2014) compared different frost mitigation measures and showed that preheating inlet air is not feasible in regions with long periods of very low outdoor air temperatures, from −54 to 10°C. Thus, for such situations the source for preheating inlet air should be waste heat, such as heat recovered from exhausted indoor air or waste water.

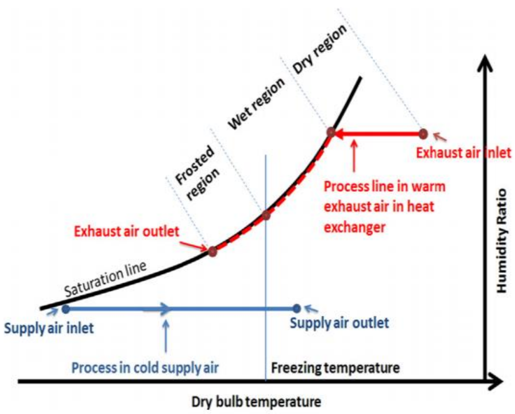

Fig. 2: Psychometric chart showing the processes in the exhaust and supply air streams in heat exchangers

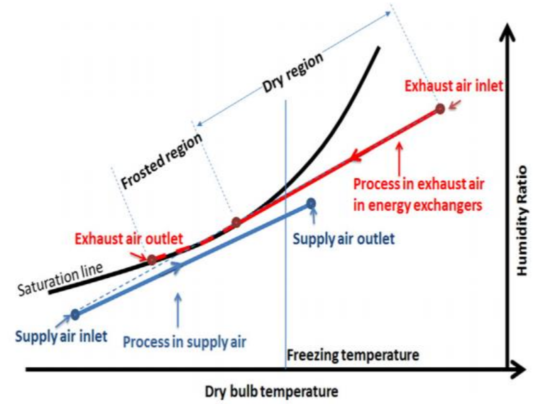

Fig. 3: Psychometric chart showing the processes in the exhaust and supply air streams in energy exchangers

2.1.3. Increasing inlet airflow rate

Increasing inlet airflow rate is another potential technique to minimize the frost growth, but this results in increased fan power and noise level, both of which are major disadvantages. Da Silva et al. (2011) conducted an experimental study to investigate the effect of frost accumulation on the thermo-hydraulic performance of tube-fin evaporator coils. They observed that the frost accumulation rate increased with the air flow rate, supercooling value and fin density. They concluded that airflow rate reduction was a dominant factor for the drop in the capacity of evaporator. To predict the performance of an outdoor coil considering airflow reduction due to frost growth, a numerical model was developed and validated by Ye and Lee (2013). They concluded that convective thermal resistance between the frost surface and air results in 90% of the total thermal resistance; the conductive thermal resistance from the tube wall to the frost surface is only 2–5% of the total resistance. In addition, the increase in the convective thermal resistance from the air to the frost surface varies the most as a function of the blockage ratio due to the growth of the frost layer. Moallem et al. (2013) studied the frost formation on louvered folded fins in outdoor microchannel heat exchangers used in air source heat pump systems. They found that for louver fin variation of the fin width did not improve the frosting performance of the fins significantly, but increasing the fin depth seemed to increase the fin capacity (39%) with some penalization of the frosting time (6%). Additionally, increasing air velocity from 0.8 m/s (157 fpm) to 1.6 m/s (315 fpm) improved the capacity of the fins up to 53%.

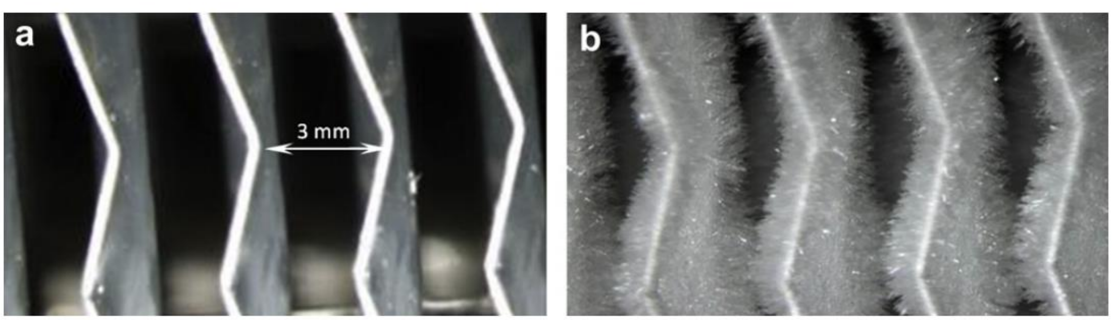

Fig. 4: Visualization of the fin surfaces before (a) and after (b) the frost formation process

2.2. Heat Exchanger Modifications

Passive procedures rely on the modification of the equipment to reduce the frost growth on the heat exchanger surface. Such methods include adjusting the fin design, coil circuiting and system design.

2.2.1. Adjusting fin and tube geometry

Fin density, often measured in fins per inch (FPI), is a critical parameter for heat exchanger design. Due to the requirements of compact design and reduction in manufacturing cost, there has been a trend of increasing the fin density which has led to a reduction in space between two adjacent fins. Yang (2003) conducted a detailed study to investigate the effects of the staging fin on the frost/defrost performance of heat pump outdoor coils under different operating conditions. A series of frosting tests was conducted on an off-the-shelf heat pump system with five (three two-row and two three-row) evaporators over a range of outdoor temperatures and relative humidity and a range of airflow rates typical of those found in residential sized heat pumps. Yan et al. (2003) reported that the rate of pressure drop increases rapidly as the relative humidity increases when a heat exchanger is operating under frosting conditions and the performance of the heat exchanger is not impacted significantly by the fin pitch provided the fin spacing is large. Yang et al. (2006) proposed optimal values of design parameters for a fin-tube heat exchanger of a household refrigerator under frosting conditions to improve its thermal performance (5.5% increment) and to extend its operating time (12.9% improvement). Lee et al. (2010) measured and analyzed the air-side heat transfer characteristics of flat finned-tube heat exchangers at different fin pitches, numbers of tube rows and tube alignment under frosting conditions, and found that the air flow rate of the heat exchangers decreased with time because of frost growth. However, the effect of the number of tube rows on the reduction in the air flow rate was relatively smaller than that of the fin pitch. The staggered tube alignment showed more rapid air flow reduction with time than the inline tube alignment due to the higher flow restriction in the staggered tube alignment. The heat transfer rate increased with the decrease of the fin pitch and increase of the number of tube rows. Equation (1) and (2) present the Colburn *j* factor for inline and staggered tube arrangement.

$$j_{inline} = 0.0066 \times \mathrm{Re}_{D_h}^{0.0526} \times \left(\frac{D_h}{F_p}\right)^{0.4513} \times Fo^{-0.0210} \tag{1}$$

$$j_{staggered} = 0.0006 \times \mathrm{Re}_{D_h}^{0.3734} \times \left(\frac{D_h}{F_p}\right)^{0.2134} \times Fo^{-0.0777} \times N^{0.0545} \tag{2}$$

Park et al. (2016), recently demonstrated that the frost blocking of the spaces between louvers at the front side of an evaporator can be delayed and the thermal performance can be improved by 21% when unequal louver pitch design was used compared to the equal louver pitch case. Sommers and Jacobi (2005) investigated the performance of a vortex generator deployed on plain fin and tube heat exchangers and concluded that vortex generation exhibits reasonable tolerance to frost, incurs only a small penalty in pressure drop, and significantly reduces the air-side thermal resistance.

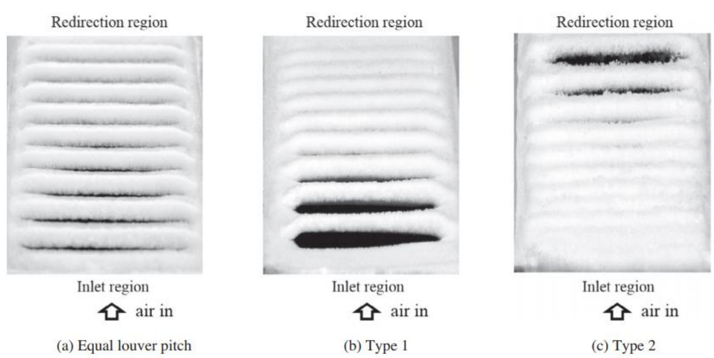

Fig. 5: Frost behavior according to the types of louvered fin used on the front side of the evaporator: (a) equal louver pitch, (b) Type 1, and (c) Type 2 designs

2.2.2. Fin type selection

Fin type can considerably impact the heat transfer and pressure drop of heat exchangers and, for obvious reasons, the heat exchanger performance is highly impacted by the type of fin design deployed. Yan et al. (2005) experimentally investigated the operating performance of frosted finned-tube heat exchangers with flat plate fins, one-sided louver fins and re-direction louver fins. For comparable conditions, the heat exchanger with re-direction louver fins performed worst compared to the other two types of heat exchangers. Huang et al. (2014) experimentally compared the effects of periodic frosting-defrosting performance by using three fin types in an outdoor coil of a residential ASHP unit. The outdoor coil with flat fins demonstrated the best thermal performance in the periodic frosting/defrosting cycles of the ASHP unit, followed by the outdoor coils with wavy and louver fins, respectively. Zhang and Hrnjak (2009) experimentally studied three types of heat exchangers with louver fin geometry under dry, wet and frost conditions. The configurations included: (1) parallel flow serpentine fins with extruded flat tubes, (2) parallel flow parallel fins with extruded flat tubes, and (3) round tube wave plate fins. Under frosting conditions, the heat exchanger with round tube wave plate fin showed the longest refrigeration time due to its largest surface area. The increase in air-side pressure drop for the parallel flow parallel fins with extruded flat tubes heat exchanger was the lowest.

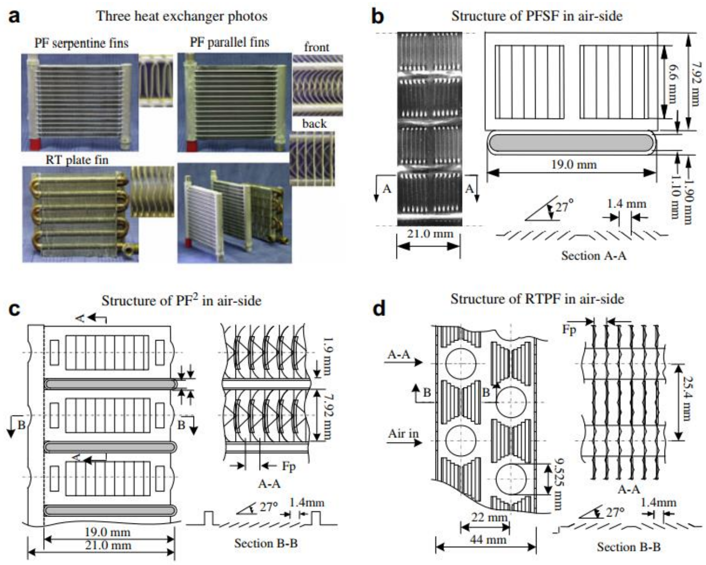

Fig. 6: Structures of three heat exchanger types

2.2.3. Coating treatment on fin surface

Frost growth rate and density highly depend on the surface characteristics. Parameters such as liquid-solid contact angle is perhaps mostly widely used to describe the surface morphology. Several researchers have investigated the impact of surface type and associated frost growth rate. Often times, the surface morphology has been modified and the influence has been evaluated. Such studies include mostly small-scale studies where a relatively small metal piece represented the fin surface. However, recently several researchers have tested full heat exchangers with modified surfaces and the appropriateness of such procedures have been discussed for ASHP and refrigeration systems.

Okoroafor and Newborough (2000) found that frost growth on cold surfaces exposed to warm humid air streams could be reduced significantly by the presence of cross linked hydrophilic polymeric coatings. The frost thickness was decreased in the range of 10–30% when compared to using an uncoated metallic surface. In another study, Wu and Webb (2001) investigated both frosting and defrosting processes on hydrophilic and hydrophobic surfaces, showing a hydrophilic coating was preferable for operation under frosting conditions. Cai et al. (2011) experimentally studied the frosting conditions on a normal copper surface, a hydrophobic coating (car wax coating) surface and a hygroscopic coating (glycerol coating) surface. Based on the distribution of ice crystals and time of frost appearance, the hygroscopic coating performed better than the hydrophobic coating; however, based on parameters such as coating thickness, thermal resistance and expansion defect of the hygroscopic coating, the hydrophobic coating was found to be superior to the hygroscopic coating.

Jhee et al. (2002) conducted an experimental study on hydrophilic and hydrophobic treated heat exchangers and reported that a relatively higher density formed on a hydrophilic surface during frosting, and the water draining rate during defrosting was higher. On the other hand, for a hydrophobic surface the frost density was lower and the draining water rate during the frost melting process was increased mainly due to large chunks of incompletely melted frost. They concluded that the hydrophilic treatment influences the behavior of frosting while the hydrophobic treatment becomes more important during defrosting.

Liu et al. (2006) deployed a novel anti-frost paint on a cold metal surface and observed that the onset of frost formation was delayed by at least 15 min. The thickness and the mass of the deposited frost layer was reduced by at least 40% compared with that on the uncoated copper surface. While evaluating the long-term performance, they found that the growth of frost crystals on the surface of the paint coating was similar to that of a hydrophobic surface. The frost growth exhibited strong dendritical characteristics, and the frost layer formed had a very loose, weak, and fragile structure that could be easily removed by external force. It is important to note that the deployment of a polymer layer introduced a thermal resistance due to its lower thermal conductivity.

Several researchers have investigated the influence of surface morphology at micro or nano-scale to understand the processes such as nucleation of droplets and merging of droplets which dramatically impacts the frost density and adhesion to the surface. Chen et al. (2013) reported a hierarchical surface which allows for inter droplet freezing wave propagation suppression and efficient frost removal. It was demonstrated that the enhanced performance is mainly due to the activation of the microscale edge effect in the hierarchical surface, which increases the energy barrier for ice bridging as well as engendering the liquid lubrication during the defrosting process.

Zuo (2017) prepared a superhydrophobic surface where ZnO (Zinc Oxide) nanorods were deployed through radio frequency magneton sputtering method. They found that the frost formation on the as-prepared SHP ZnO surface was effectively delayed for over 140 min even at -10°C. The superhydrophobic surface exhibited an excellent durability against repetitive frosting/defrosting. Wu (2017) conducted a study to investigate the condensation, frost crystal growth, frost melting and meltwater drainage characteristics on aluminum surfaces with parallel and crossed grooves. They found the parallel grooved surface had better drainage than the flat surface with a smaller meltwater retention ratio, while the surface with crossed grooves had worse drainage.

Sommer et al., (2016) noted that existing frost density correlations found do not include surface wettability (i.e. contact angle) as a parameter in the model. However, surface wettability is important in accurately determining the properties of the frost layer and thus should be included in future frost correlation development efforts. They evaluated the effect of surface energy on the frost thickness and density for both a hydrophobic substrate and a hydrophilic substrate and found that the frost layer on the hydrophobic surface was ‘‘thicker and fluffier” resulting in a less dense frost than the frost on the baseline surface. Liang et al., (2015) designed a frosting/defrosting experiment to study the effects of surface characteristics on defrosting behaviors of a fin. The characteristics of frost melting and molten water retention were analyzed and compared. It was concluded that effects of the surface characteristics on the melting time and melting process were significant.

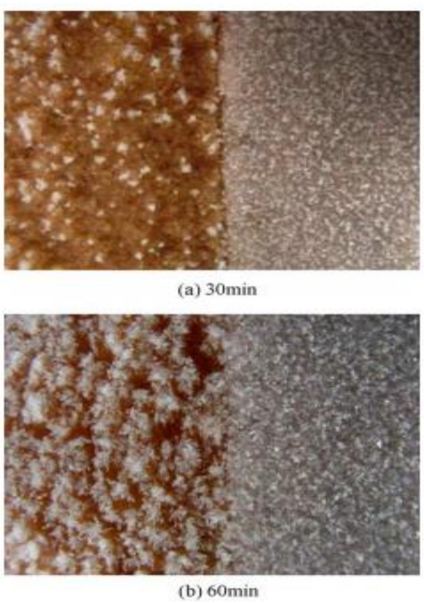

Fig. 7: Comparison of frost growth on the coated (left, thickness = 0.3 mm) and the uncoated (right) surfaces

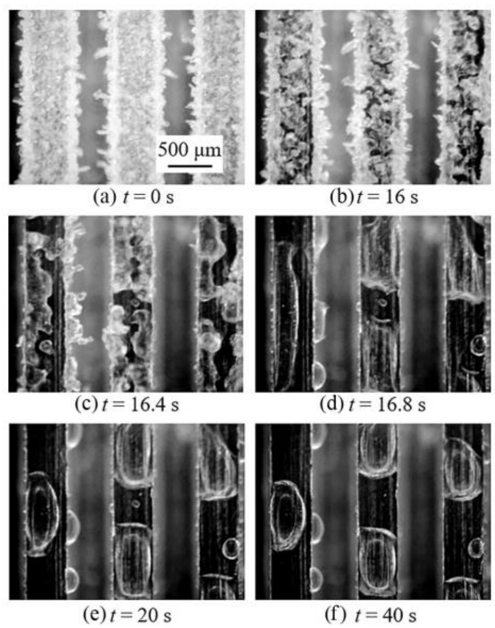

Fig. 8: Frost melting on the surface with parallel grooves after frosting for 30 min (T_w = 16°C, T_{in} = 2°C, RH = 75%, u = 1.16 m/s

2.3. System Modification

There are also some outside of system type frost retarding measures for ASHP units, which have been undertaken through adjusting and optimizing the structure of the system. In these measures, all the energy consumed on frost retarding comes from heat transferred from the refrigerant inside the system to the tube and fins.

2.3.1. Vapor-injection technique

The vapor-injection technique has been used mainly for room air conditioner applications since the 1980s, but its applications to heat pump units received more attention recently, since the process can mitigate frosting in cold climates. Zhnder et al. (2002) conducted an experimental study for an air-water vapor-injection heat pump unit at an inlet air temperature of −7°C. They observed an increase in heat output of 28% and a COP improvement of 15%, respectively, when compared to the performance without injection. Similarly, Nguyen et al. (2007) evaluated the thermal performances of a flash tank vapor injection cycle and a sub-cooler vapor injection cycle using R407C, reporting their heating COPs 24% and 10% higher compared to a single-stage cycle, respectively. Shao et al. (2002) concluded that a vapor-injection heat pump unit could provide enough heating capacity even when the outdoor temperature is in range of −20 to −15°C. In another study, Ma and Zhao (2008) experimentally investigated the operating performance of an ASHP unit with a flash-tank coupled using scroll compressor with an ambient temperature of −25°C. They found that the ASHP unit was more efficient than the system with a sub-cooler at −25 to −7°C.

2.3.2. Two-stage technique

Similar to the vapor-injection technique, the two-stage technique can result in considerably improved performance for a heat pump. Wang et al. (2005) experimentally investigated a double-stage heat pump heating system, which coupled an ASHP unit and a water source heat pump unit. They showed that the proposed system offered an average energy efficiency ratio up to 3.2 and the average indoor temperature exceeded 19.5°C, minimum at 18°C in test period. In another study, Li et al. (2011) proposed and experimentally tested a new frost-free ASHP system, indicating the novel system could operate more efficiently than a conventional ASHP unit in winter. Heo et al. (2010) reported that that the COP and heating capacity of a two-stage vapor injection cycle were enhanced by 10% and 25%, respectively, when the ambient temperature was −15°C. Similarly, Wang et al. (2009) demonstrated that a COP improvement of 23% for a two-stage heat pump system can be achieved when the ambient temperature was −17.8°C. Bertsch and Groll (2008) tested a specially designed R410A two-stage ASHP unit with a heating COP of 2.1 at an ambient temperature of −30°C.

2.3.3. Adding outside heating source

Adding an outside heat source could improve the system operating performance under frosting conditions. Mei et al. (2002) reported that the heating capacity of an ASHP unit could be increased, and the frost accumulation on its outdoor coil can be reduced by heating up the liquid refrigerant in its accumulator. By heating liquid refrigerant, the frequency of defrosting cycles was reduced by a factor of 5 and indoor supply air temperature raised by 2 to 3°C because of the increased compressor suction pressure. It is important to distinguish that this is different from heating the inlet air of the outdoor coil (discussed in Section 0) since the heat is add directly to the refrigerant loop. Regardless, both processes are energy intensive and to improve the economy of the ASHP units. The heating source should be waste heat, such as heat recovered from exhausted indoor air or waste water. This type of frost retarding measure is limited in application, due to its disadvantages of high operating cost and additional infrastructure.

2.3.4. Adjusting refrigerant distribution

For an outdoor coil used in an ASHP unit, multiple refrigerant circuits are deployed to minimize the refrigerant pressure drop and to achieve an enhanced heat transfer rate. Interestingly, the frost accumulation is mostly uneven on the surface of a multi-circuit heat exchanger, a phenomenon known as mal-defrost.

Wang et al., (2012) conducted a field test to quantify the performance drop of an air source heat pump (ASHP) system under a special kind of mal-defrost phenomenon appearing in moderate climate conditions. The mal-defrost was found with the more than 60% frosted area of the outdoor heat exchanger after the system running 5 days. Comparing the test data before and after frosting, it was found that the mal-defrost decreased the COP up to 40.4% and the heating capacity to 43.4%. Qu et al., (2012) conducted an experimental study to analyze the reverse cycle defrost performance for a four-circuit outdoor coil in an ASHP unit. It was observed that defrosting was quicker on the airside of upper circuits than that on the lower circuits. The effects of downward flowing melted frost along a multi-circuit outdoor coil surface had a significant impact on overall performance and the defrosting efficiency of 34.5% was reported for system.

In another study Song et al., (2016a,2016b) reported that when a vertically installed multi-circuit outdoor coil in an ASHP unit was changed to a horizontally installed coil, the defrosting efficiency increased from 43.5% to 53.3%, or an increase of 9.8%. Additionally, the negative effects of melted frost flowing downward due to gravity were eliminated. They defined the parameter frosting evenness value (FEV) as the ratio of the minimum frost accumulation among three circuits to the maximum value. In another study to investigate the relationship of FEV and frost retarding effect, Song et al., (2016c) found that as FEV increased from 75.7% to 90.5%, the average COP was increased from 4.10 to 4.26 for a 3600 s frosting process, and increased from 3.18 to 4.00 during the last 600 s.

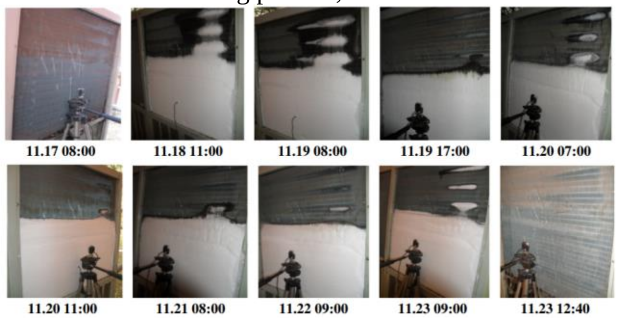

Fig. 9: Images of the frosting process

In Table 1, a relative comparison of various frost mitigation processes is provided. It is important to note that nearly all the measures would increase the initial cost and/or the operational cost. System adjustment would increase the system complexity and decrease system stability. Additional thermal energy is required for the measures of preheating inlet air and adding an outside heat source. Among all the measures, reducing inlet air humidity and preheating inlet air have the best frost mitigation effect. Considering the comprehensive values of listed measures, preheating inlet air with waste heat and coating treatment on fin surface with new materials are highly recommended for further study.

Table 1: Frost mitigation methods

Method	System complexity	System stability	Frost Mitigation	Scalability	Increase in capital cost	Increase in operational cost
Reducing air humidity	High	High	High	Moderate	High	High
Preheating the air stream	High	High	High	Moderate	High	High
Increasing air flow rate	High	High	Moderate	Moderate	High	High
adjusting fin geometry	Low	High	Moderate	High	Moderate	Low
Fin type selection	Low	High	Low	High	Moderate	Low
Surface morphology for fin surface	Moderate	High	Moderate	Moderate	Moderate	Low
Vapor injection technique	High	Low	Moderate	Low	High	Moderate
Two stage technique	High	Low	Moderate	Low	High	Moderate
Adding outside heat source	Moderate	Moderate	Moderate	Moderate	Moderate	High
Adjusting refrigerant distribution	Low	High	Moderate	Moderate	High	Low

3.CONCLUSIONS

Frost growth on the heat exchanger surface can significantly alter the system performance. Various frost mitigation strategies have been reviewed and compared for the deployment of heat pump and commercial refrigeration systems. While this has been an active area of research for many years, there is no agreement on what technique is most effective to mitigate the frost.

1- The air treatment approaches seem most promising for commercial refrigeration applications and not viable options for cold climate heat pump.
2- Passive techniques such altering the fin geometry or modifying the surface morphology has been seen as major developments, however their application is limited by unacceptable durability, scalability and manufacturing challenges.
3- System level modification techniques have been successfully deployed in a range of system with varying level of impact. Most of such modification are most appropriate for heat pump application, although several have been considered for commercial refrigeration systems as well.

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