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## ABSTRACT

Heat pumps are an energy efficient way to provide adequate heating to an indoor space. In contrast to electric or gas heating, a heat pump works to draw the "free" heat from the cold outdoor ambient and transfer thermal energy to the heated space. When the outdoor ambient is cold and humidity conditions are right, however, frost will start to develop on the heat pump's outdoor coil. Frost on the coil surface blocks air flow through the coil thus reducing the heat pump's efficiency and overall performance. Control of frosting and defrosting is particularly important to the successful use of heat pumps in cold climates.

To restore the unit's heating capacity and efficiency, a defrost cycle is needed to remove the accumulated frost developed on the coil. While defrosting restores heat pump efficiency, this period of operation itself requires additional power and ultimately results in an energy penalty. Improving defrost performance and/or reducing the number and duration of required defrost periods would significantly improve heat pump operation.

Heat pump researchers and manufacturers have spent a great amount of effort on the topic of defrosting. A comprehensive review of efforts within the last 15 years was conducted to summarize existing defrosting technologies and identify those solutions that may be more feasible or readily commercialized to reduce the defrost penalty. This summary highlights technologies that may reduce or eliminate the negative impacts of the defrosting period including approaches using hot gas bypass, coil coatings and advanced control strategies. The potential impact of the identified technologies is energy and demand savings, improved performance for comfort, and removal of a significant barrier to widespread adoption of air-source heat pumps in all climates.

## 1. INTRODUCTION

While heat pumps offer an energy-efficient and cost-effective solution for residential and commercial heating and cooling applications, outdoor coils can accumulate frost during the winter months, which can significantly degrade performance. To remove frost, conventional heat pumps reverse the refrigerant cycle to heat the outdoor coil and melt away the frost. This approach has the undesirable consequence of cooling the indoor space intended to be heated such that backup heaters are used to provide temporary heating during the defrost period. Past research has found that the defrost penalty results in a reduction of heat pump efficiency of approximately 10-15% (Kruse, 2006). Demonstrations in the field resulted in a degradation in coefficient of performance (COP) of as much as 40% and heating capacity reduction by as much as 43% (Wang et al., 2013a). Consider, for example, a 10-15% penalty for a 3-ton heat pump running at an average 50% duty cycle during frost-forming outdoor temperatures (32°F – 41°F). In a city such as Seattle, Washington, which is within the frost-forming temperature band approximately 1,310 hours per year, or 15% of the year, this heat pump would use 200-300 kWh of additional energy consumption per year due to the defrost penalty.

This practice not only increases the overall electrical consumption, it results in irregular spikes in electricity demand. Assume, for example, a group of 70,000 residents with heat pumps, which are in defrost mode for 5% of each hour during the 15% of the year when frosting temperatures occur. Each heat pump is equipped with a 10kW heater to provide heating to the space while the unit runs in reverse cycle to enable defrost. During the winter months, at any given moment, 3,500 heat pumps (5% of 70,000 residents) are in a defrost period, consuming 10kW of electric power, or a total of 35 MW. This occurs for roughly 1,300 hours per year (depending on the location), equating to a total annual consumption of 52.5 GWh. With improvements in defrost performance and/or control, the supplemental electric power can be significantly reduced or eliminated, avoiding this additional energy requirement. At a cost of $80/MWh to add grid capacity, this results in a savings of $4.2 million for this sample population alone.

The industry currently uses a few common methods for initiating defrost. These include the timer method, differential temperature system, differential pressure system or some combination of these. These technologies have the advantage of providing a relatively low-cost approach to initiating and implementing defrost control. Their main disadvantages, however, include the inability to directly measure or detect the accumulation of frost, which can thus lead to initiating defrost when it may not be required. A heat pump system capable of eliminating or minimizing defrost would benefit the end user by decreasing their electricity consumption and would benefit the utility by minimizing demand spikes due to defrost. Several alternative methods from current industry practice are summarized herein, including advanced control strategies, the use of hot gas bypass, and coil coatings.

## 2. CONTROL STRATEGIES

Control strategies focus on when and how defrosting should be initiated. The timer method is a simple example, one that is cheap and easy to implement, but with this approach, the heat pump may go unnecessarily through a defrost cycle without any frost accumulation, or far too late after frost has started accumulating, significantly degrading heat pump performance. This phenomenon is sometimes referred to as mal-defrost (Wang, 2011) and several good examples are outlined in a series of field tests conducted by Wang, W. et al. (2011, 2013a). In one instance of mal-defrost, three defrost operations occurred in a six-hour period while almost no frost was observed on the heat exchanger. This resulted in a 4.2% decrease in heating efficiency during that time period. Other instances of mal-defrost lead to reductions in COP and heating capacity by 17.4% and 29%, respectively. As can be learned from these case studies and others, significant frost accumulation and ineffective defrost control can be detrimental to heat pump performance and result in considerable additional energy consumption. More advanced control strategies take into account the outdoor temperature and relative humidity, as well as a host of other approaches.

### 2.1 Air and/or Refrigerant Property Control

Based on the results of their field testing, Wang et al. (2013) found that frost formation on a coil depends on six primary parameters: air temperature, air relative humidity, air velocity, air cleanliness, heat exchanger temperature and wettability of the heat exchanger surface. Monitoring all of these parameters simultaneously to effectively implement defrost control would be difficult and expensive for a residential air source heat pump. Hence, researchers have explored various approaches focusing on a small sub-set of these parameters.

Zhu et al. extended the existing temperature control approach by also considering humidity. In two separate studies Zhu et al. (2015a, b) research teams developed a Temperature-Humidity-Time (T-H-T) defrosting control method based on a frosting “map”. A field test was conducted for two heating seasons comparing the

T-H-T method, to the conventional Temperature-Time (T-T) defrosting control method. Defrosting was always initiated when about 90% of the outdoor coil surface was covered by frost. During period of high frost accumulation, the temperature difference between the compressor suction and discharge increased by about 20% and the heating capacity decreased by about 30%. Under non-frosting conditions, the T-T method initiated defrost operation 31 times within 24 hours (mal-defrost). No defrosting operations were conducted for the T-H-T method. For consecutive and variable frosting conditions, the T-T method resulted in mal-defrost for 63% of the defrosting processes while all of the defrost cycles conducted under the T-H-T method were found to be necessary.

In addition to using the refrigerant cycle or air/coil properties directly, researchers have also identified the potential for sensing and/or measuring frost accumulation on the outdoor coil directly. Multiple patents (Reedy and Eplett, 1977; Levine, 1990; Bahel et al., 1994) have been filed to this affect. Based on observations in the general market, however, advanced sensing technologies for measuring frost levels are not currently utilized in commercially-available residential heat pumps.

Further work was then done by the Zhu et al. (2015a, b) team to develop a frosting map guiding defrosting control. The frosting map divided the coil into three regions, non-frosting, condensing, and frosting. The frosting region was further divided into three zones: severe, moderate, and mild. Lab and field tests were carried out to verify the zoning. Defrosting intervals were proposed for different frosting zones to reduce defrost times and improve overall performance.

Similar to the concept of utilizing “regional” or mapped control, Qu and Hrejsa (2015) observed the potential impact of geographic location and filed a patent for a method of defrost using a controller configured to operate at least two defrost cycles. The method comprises receiving, at the controller, weather data for a defined geographic area proximate to an installed location of the heat pump system; and selecting, based on said weather data, one of the at least two defrost cycles.

Zhiyi et al. (2008) evaluated a new heat pump defrost system with a refrigerant charge compensator, instead of an accumulator. Results showed that the improved frost system with the compensator worked as expected, and its suction and discharge pressures and the power of the compressor during the defrosting were much larger than before.

Kim and Lee (2015) used an effective mass-flow fraction (EMF) to detect heat transfer rate based on temperature measurements, which was then used to determine the defrosting start-time of the defrost cycle. The performance of the EMF control was compared with time control under varied frosting conditions of an experimental system. The time control method determined the defrosting start-time with an error of ±50%, whereas the EMF control determined the defrosting start-time with an error of ±10%.

Other methods of defrost relying on heat pump refrigeration cycle parameters or coil properties have also been evaluated. Jiang et al. (2013) developed a novel method using refrigerant superheat, Watters (2002) considered fin spacing on the coil itself, and Huang et al. (2004) experimentally evaluated the effects of fan starting methods. Another study explored the possibility of electrostatic prevention and high-velocity air flow on frost formation (EPRI, 2010). Results suggested that the time between defrost cycles could be increased, reducing overall defrost power, by blowing high-velocity air over a heat exchanger coil during the defrost period. This work was extended in a second study, which found that applying such high air velocity during the defrost period could reduce the number of required defrost cycles by as much as 60% (for defrost periods of 30 seconds or less). This translated to a 40% energy savings (EPRI, 2014).

## 2.2 Self-Learning Controls

Another method is to apply self-learning control capability. An early concept was patented by Sulfstede et al. (1985) with more recent research conducted by Liang et al. (2010), who developed a control algorithm with self-learning function based on the cardinal fuzzy control algorithm. Experimental results showed reduced shock to the refrigeration cycle, good control of the reverse cycle function, better oil flow control and improved thermal comfort.

### 2.3 Photo-Coupler Control

Byun et al. (2006) investigated the reliability and effectiveness of using a photo-coupler for detecting frost formation in an air source heat pump with the ultimate goal to determine the most efficient initiation point of the defrost cycle. Using a photo-coupler as a frost sensing device was evaluated by comparing its performance with a conventional time control defrost system in which the defrost cycle is set to start at a pre-determined interval (every 1–1.5 hours). Results indicated that the overall heating capacity using the photo-coupler detection method is 5.5% higher than that of the time control method. It is also shown that for maximum efficiency, the defrost cycle must be initiated before the frost build-up area exceeds 45% of total front surface of the outdoor coil.

### 2.4 Integrating Thermal Storage

Several researchers have considered various control strategies utilizing thermal storage integrated with the heat pump. One such concept recovered energy from the heat pump system by sub-cooling the refrigerant and storing it in a cold-water tank (Byrne, 2009). Minglu et al. (2010) evaluated a thermal energy storage (TES) concept in which a reverse-cycle defrosting method was developed to improve occupants' thermal comfort. Yet another prototype heat pump unit using a novel TES developed by Wenju et al. (2011). Results showed that the novel reverse-cycle hot gas defrosting method was able to shorten defrosting time by approximately three minutes, or 38%, and minimize the risk of shutting down the heat pump unit due to low suction pressure. In addition, the indoor coil surface temperature during defrosting was warmer than when a traditional standard reverse-cycle hot gas defrosting method was used.

## 3. DEFROST USING HOT GAS BYPASS

The hot gas bypass defrost (HGBD) method enables a heat pump to defrost the outdoor coil by bypassing hot gas from the compressor discharge line through individual circuits of the outdoor coil. Patents for integration of a HGBD method were awarded to Hayes in 1981 and Gavula in 2007, among others. Research conducted by Byun et al. (2008) considered the feasibility of the HGBD method as compared to that of a normal, 1.12 kW (0.3 ton) capacity air-source heat pump system with no defrost equipment, such as an electric resistance heater. Results indicated that the HGBD method is useful for retarding the formation and growth of frost at the outdoor coil. For example, during 210 min of heat pump operation, the HGBD method improved COP and heating capacity an average of 8.5% and 5.7%, respectively, relative to the normal system. Experimental work conducted by Li et al. (2016) found that the HGBD method has the potential to defrost a coil as effectively as a reverse cycle defrost strategy and could deliver heating continuously while defrosting sections of the outdoor coil. Further investigation and engineering, however are needed to reduce defrost times and improve efficiencies.

Variations of the HGBD have also been evaluated. Jang et al. (2013), for example, designed a high temperature and low-pressure HGBD method, deviating from the typical high (discharge) pressure approach. Other researchers have explored a dual hot gas bypass defrosting (DHBD) method, which uses two bypass lines of hot gas from the compressor. One hot gas line is connected to the inlet of the outdoor coil, and the other is connected to the outlet of the outdoor coil. The purpose of the DHBD method is to prevent a decrease in the compressor outlet temperature after the HGBD process begins. Research conducted by Cho et al. (2011) found that the DHBD method sustained a higher compressor outlet pressure and reduced the defrosting time by 36% compared to the HGBD method.

DHBD variations evaluated by Kim et al. (2015) on a 16.4 kW (4.6 tons) heat pump further showed the effectiveness of a DHBD method compared to a traditional reverse cycle method, but only above 0°C. The DHBD method was not as effective below 0°C due to a decrease in refrigerant temperature followed by lower hot-gas bypass temperature. To overcome lower discharge temperature of compressor, a combined defrosting cycle with DHBD and an induction heater (IH) was developed. This method had higher discharge temperature and reduced the defrosting time by 15% as compared to that of the traditional reverse cycle method with nonstop indoor heating operation at an outdoor temperature of -5°C.

## 4. COIL COATINGS AND SURFACE TREATMENTS

Superhydrophobic and icephobic materials have been identified and preliminary research suggests that coating the outdoor coil of the heat pump with such materials will lead to reduced (or delayed) frost accumulation and/or faster shedding of ice, shortening the defrost duration. As an alternate to coating materials, it is possible to achieve similar results from surface treatments (e.g. etching and other techniques to produce micro/nano structures on surfaces). A major advantage of coatings or surface treatments is that they do not alter the refrigeration cycle or circuitry in any way; there are no required additional components and the fundamental cycle behavior remains unchanged. While a significant amount of research has been conducted, a majority of it is in evaluation of a new coating approach itself, rather than its application to a heat pump coil.

Superhydrophobic coatings are commercially available products. The majority of these coatings work based on the principles of water contact angle (CA). Contact angles with the surface that are above 150° are superhydrophobic. In addition, a low sliding angle (SA) is needed. The sliding angle is the critical angle where a water droplet with a certain weight begins to slide down an inclined plane. Because of the ready availability of superhydrophobic coatings to repel water, a natural evolution is to use this technical base to develop icephobic surfaces. The many applications of icephobic surfaces include deicing air plane wings, preventing ice formation on roads and bridges, and preventing or delaying frost formation on the outdoor section of an air source heat pump in the winter time. Recently, Sommers et al. (2018) evaluated surface wettability specifically in regard to frost growth, which is dependent on a number of environmental conditions. In addition to conducting experimental tests complete with video imagery, modeling work is underway to accurately represent frost growth behavior. This capability is needed for future development work, particularly in regard to the design of refrigeration evaporators.

There are at least three different approaches to characterizing surface icephobicity. First, icephobicity implies low adhesion force between ice and a solid surface. In some cases, ‘‘icephobic’’ surfaces are defined with a shear strength between 150 kPa and 500 kPa. Second, icephobicity can be described as the ability to prevent ice formation on the surface. Third, an impact test for bouncing-off droplets was suggested implying that icephobic surfaces repel incoming small droplets (e.g., of rain or fog) at the temperatures below the freezing point. These three definitions of icephobicity correspond to three different properties of anti-icing surfaces: they should (i) prevent freezing of water condensing on the surface (ii) prevent freezing of incoming water (iii) if ice formed, it should have weak adhesion strength with the solid, so that it can be easily removed (Hejazi et al., 2013).

There are significant technical challenges to develop a surface coating that will prevent frosting on a heat pump while not impacting coil heat transfer and maintaining the integrity of the coating. In addition, once a droplet freezes, a surface that is hydrophobic is not necessarily icephobic. The detachment of ice from a surface occurs through a fracture and is different from the dewetting mechanism created by CA (Nosonovsky and Hejazi, 2012). Water can withstand pressure, either positive (compressive) or negative (tensile), but it cannot support shear stress since the stress tensor of liquid is spherical in the static limit. The mechanical forces that act upon a water droplet and a piece of ice on a rough solid surface is the difference between de-wetting and ice fracture. The force needed to detach a water droplet depends on CA hysteresis and can be reduced significantly in the case of a superhydrophobic surface. The force needed to detach a piece of ice depends on the receding CA and the initial size of interfacial cracks. Therefore, even surfaces with very high receding CA may have strong adhesion to ice if the size of the cracks is small.

In addition to evaluating coating technologies in the lab, a number of researchers are working to effectively model frost growth

### 4.1 Heat Exchanger Coating Research

While a majority of coatings research has been conducted on the technologies themselves, several researchers have evaluated their application for heat exchangers in particular, intended for heat pump or other HVAC&R applications. Yang (2003) evaluated the performance of a heat pump unit with baseline or fin-staged outdoor coils at either frosting or steady-state test conditions. Their study did not consider the addition of a coating specifically, it does call on the impact of varying fin densities on frost accumulation and defrost. Experimental data showed that for a given two-row heat pump outdoor coil operating at 35°F (1.7°C) under frosting conditions, fin staging increased cycle time and COP. There was a small decrease in peak capacity at lower initial airflow rates. At a lower temperature of 28°F (2.2°C), cycle time continued to be enhanced with fin staging, and cyclic COP was within 5% of the base case when fin staging was used.

Moallem et al. (2012) evaluated frost formation on louvered fin microchannel heat exchangers with the aim of studying the effect of hydrophilic and hydrophobic surface coatings. Specifically, the research evaluated water retention on coil frosting performance and frost growth rates. Frost mass and thickness growth rates, corresponding coil heat transfer rates, capacity degradation, and air-side pressure drop for five microchannel coils with different surface coatings were measured. The experimental data showed that the hydrophilic and hydrophobic surface coated coils accumulated frost on the heat transfer surfaces with visible difference in the type, appearance, and patterns of the frost. The duration of the frosting cycle, the heat transfer rate, and air-side pressure drop were similar to the ones of a louvered aluminum fin microchannel heat exchanger with uncoated surfaces. For the operating conditions tested in this work, hydrophobic and hydrophilic coatings on microchannel coils affected the heat transfer capacity in frosting conditions by up to 15%.

Shah, et al. (2013) received a patent for a military application in which they applied an icephobic coating to the condenser of an environmental control unit supplying cooling for equipment on an aircraft. For this particular application, the coating was helpful in not only reducing frost accumulation, but the vibration of the aircraft provided an added aggravation to shake ice off of the heat exchanger.

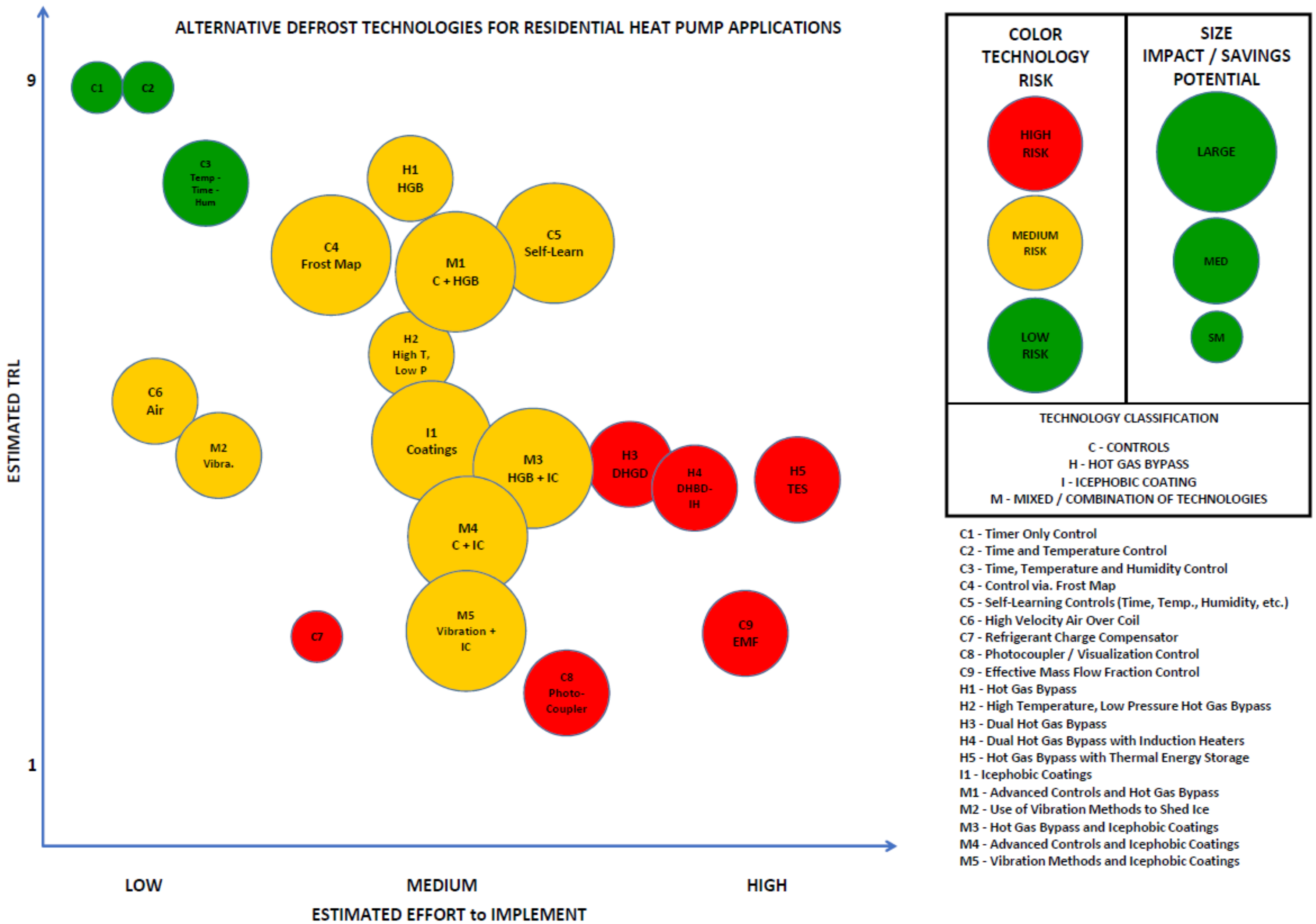
The use of vibration itself, has also been a topic of study for the purposes of shedding water on heat exchangers. Huber, et al. (2018) investigated the effects of vibrations produced by an eccentric mass motor on Teflon sheets for cases of drop-wise condensation (vertical orientations) and further outlined other past work in this area.

A study conducted by Wang et al. (2015) considered that if initial frost that accumulates on a coil is removed quickly, the frosting process can be curtailed. Thus, a comprehensive defrosting method, which combines the surface characteristic of a superhydrophobic fin and high-speed hot airflow was evaluated for heat pump applications. When the high-speed hot airflow acted on the fin surface, most of the initial frost was instantaneously blown away by the airflow due to the weak adhesion of the superhydrophobic surface.

Experimental testing of prototype heat pumps were constructed using outdoor coils coated with a commercially available icephobic coating product. These units were tested for comparison against an unmodified baseline system (Martin et al., 2017). The study found that the coated coils accumulated less frost or delayed the rate of frost accumulation, but also indicated an increased air-side pressure drop due to increased fin thickness and performance inconsistencies due to limitations in coating uniformity.

## 5. TECHNOLOGY POTENTIAL

A number of technologies have been identified for the purpose of reducing frost accumulation and improving defrost performance in heat pumps. Based on the findings reported in the literature, these technologies were evaluated and assigned a relative ranking for their potential energy savings, Technology Readiness Level (TRL) and estimated effort to implement, thus generating a technology roadmap for future development (Figure 1). Technologies already in use, including variations of timer control, are the lowest risk (and lowest cost) options, hence their wide-adoption by the industry. Advanced control options are perhaps the most promising of new technologies in that they generally have a higher technology readiness level and are relatively easy to implement. The challenge, of course, is finding the right mix of sensors to not only produce an effective control strategy but meet cost demands. As such, those technologies that not only require advanced controls, but may also require additional parts and/or design changes, are tagged as higher risk options. These include some of the advanced hot gas bypass methods, use of thermal storage, and visualization techniques. More research is needed to better understand the potential of the breadth of coatings available, in particular, not only to assess their ability to reduce frost formation, but also their durability.




NOTE: Placement of technology bubbles is subjective and estimated based on current understanding of technology development and standard practices for the heat pump industry. Some technologies will have very siimlar TRL and effort levels, but are not overlaid on this graph for the purposes of readibility.

**Figure 1:** Alternative Defrost Technologies for Residential Heat Pump Applications

## 6. CONCLUSIONS

Industry currently uses time and temperature, differential temperature, differential pressure, and demand defrost to control the defrost cycle. An advantage of all these methods is that the cost to implement them is low. A disadvantage is that none of the methods directly sense frost, resulting in occurrences of defrost when there is no frost present or conversely, not initiating defrost under heavy frost conditions.

Using additional parameters, such as time, temperature *and* humidity as the control mechanism for defrost initiation shows promise. These approaches incorporated additional sensors for site-specific measurement and control, but research may be warranted to control from a connected thermostat with access to local weather data. A frost probability map can be created using temperature and humidity information. Defrost is then initiated using this data, elapsed time, and current temperature and humidity.

Numerous coatings have been identified with the potential to reduce frost accumulation. In order to be considered for heat pump applications, such coatings must be durable, low cost and not impact the heat transfer of the coil. Optimum surface roughness can be obtained with stamping, etching with acid, etching with lasers, sand blasting and anodization. This nanostructured surface combined with a highly repellent chemistry is how icephobic surfaces are achieved.

Further research is needed to identify the next generation of defrost control. Other than simple timers, which tend to contribute to unnecessary energy consumption through cases of mal-defrost, there are few or no commercially-ready, cost effective solutions available today. In the continued quest for efficient heat pump solutions, particularly for cold climates, it is imperative that adequate time is spent considering the best possible approach for limiting frost formation, quickly shedding any frost that does develop, and preventing cases of mal-defrost.

### ABBREVIATIONS

| | |
|---|---|
| CA | Contact Angle |
| COP | Coefficient of Performance |
| EMF | Effective Mass Flow |
| DHBD | Dual Hot Gas Bypass Defrost |
| H | Humidity |
| HGBD | Hot Gas Bypass Defrost |
| HVAC&R | Heating, Ventilation, Air-Conditioning and Refrigeration |
| IH | Induction Heater |
| SA | Sliding Angle |
| T | Temperature, Time |
| TES | Thermal Energy Storage |
| T-H-T | Temperature-Humidity-Time |
| TRL | Technology Readiness Level |
| T-T | Temperature-Time |

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