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Continuous, High Efficiency Defrosting of Air-to-Air Heat Pumps

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Abstract: This study aims to realize continuous, high efficiency defrosting of air-to-air heat pumps using the effect of outdoor warm air recycling, trying to improve the coefficient of performance (COP) and total heat capacity of traditional defrosting methods like hot bypass and Joule heating. The proposed patented method recovers heat from the air change system by mixing the warm discarded air with the incoming air of the external heat exchanger. The fan of the external unit sucks the indoor air with the depression obtained by a Venturi. The warm air is ducted to the Venturi through a hole in the wall. The amount of warm air mixed to the outside air is regulated by a butterfly valve installed on the pipe from the hole to the Venturi. In this way, the air entering the external coil is warm enough to avoid frost. The energy efficiency of the system is assured, for the warm indoor air is heated with the high COP of the heat pump. Our system can achieve defrosting with a limited amount of warm air, and realize a higher overall COP than the best traditional defrosting systems. Finally, the defrosting device can be added as an option to any existing split systems.

Keywords: Heat pump; Frost; Warm air bypass; Coefficient of performance (COP); Heating capacity

1. Introduction

A heat pump is an environmental-friendly technology for room and water heating. It extracts heat from low-temperature sources like wells or outside air, and transfers it to warm up the target space. Moving the heat instead of creating it through the Joule effect or by burning fossil fuels uses substantially less energy. For this reason, heat pumps are more practical than traditional resistance heating and more cost-effective than burning fossil fuels.

Unfortunately, water vapor freezing at low outside temperatures restricts the heat pump's ability to heat effectively in practically all climates. In conventional applications, electric resistance heating raises the temperature of the heat pump's air source during the coldest weather to stop the "cold blow." The energy efficiency of heat pumps is typically 1.5 to 3 times greater than that of electric or fossil fuel heating without resistance heating. The refrigerant in the exterior coil evaporates in the open air. When the air temperature drops close to or below 0°C, frost accumulates on the coil, obstructing airflow and decreasing heat-exchanger efficiency. The frost also insulates the fins and reduces the heat transfer rate, further suppressing the coil efficiency. As a result, heat pumps without an auxiliary source of heat can only function in very mild local climates. In cold regions, the evaporator's frost is periodically removed to prevent a decline in heat exchange efficiency. Frosting and defrosting have a substantial negative impact on heat pump reliability and the time between overhauls (TBO), which lowers overall efficiency. Frosting also raises the price of the equipment and uses more energy. Therefore, engineers and researchers must focus heavily on frosting prevention.

The outdoor coil is mainly defrosted by heating, reverse-cycle and hot gas bypass. Heating and reverse cycle defrosting have been the most common method. The reverse cycle inverts the roles of a condenser and an evaporator, using a four way-valve. In this way, the indoor coil sends heat to the outdoor coil, thus melting the ice on the external heat exchanger. This operation allows the heat pump to extract heat to the warm side. During defrosting, an indoor auxiliary heater keeps the room temperature at the set point at the cost of efficiency. Electric heat defrosting is even worse: the defrosting time is longer and energy efficiency is poorer than the reverse cycle.

Recent years has seen the hot gas hypass become a popular defrosting tool. Hot refrigerant from the compressor outlet is required to bring hot fluid to the external heat exchanger. Thus, the function of the internal and external heat exchangers can remain unchanged. The technique, however, is crucial in preventing the system-wide invasion of the bypass refrigerant. The defrost cycle should begin before the frost buildup area exceeds 45% of the total exchange surface of the outdoor coil. The optimum method for increasing compressor discharge temperature is hot gas bypass injection directly into the compressor suction. Even though the compressor motor requires more power, the hot-gas bypass defrosting demonstrates a higher refrigerating capacity and better temperature control than reverse cycling.

2. Methodology

The proposed method, which is patented, begins with the premise that the COP rises as the temperature difference decreases (Figure 1) [1].

This is the obvious cost to transfer energy from a lower to an upper level. Therefore, it is practical to generate the energy when the temperature difference ΔT between inside and outdoor air is small. To put it another way, energy generated at a small ΔT requires less electric energy. Additionally, it is essential to have a suitable air change per hour (ACPH). The minimum recommended rate for a few different room types is shown in Table 1.

In most business and industrial heating systems, the heat is recycled by a recuperator that cools down warm used air and heats up the incoming fresh air. This paper intends to use this warm air to defrost the outdoor heat exchanger. In this way, the used air heat is recovered and the heat pump works with a smaller ΔT. Essentially, the air heating the outdoor heat exchanger is a mix of the outdoor air and the used warm air. Figure 2 shows the effect of the proposed method in a small split system.

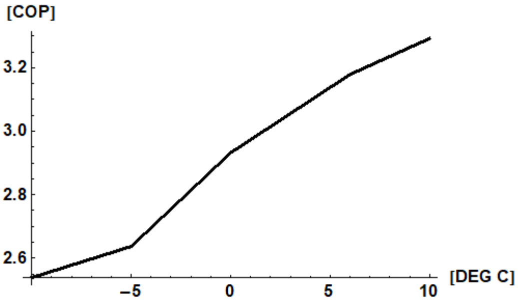

Figure 1. Measured COP without defrosting of a commercial split heat pump (max TC=12 kW) with the internal temperature of 24°C

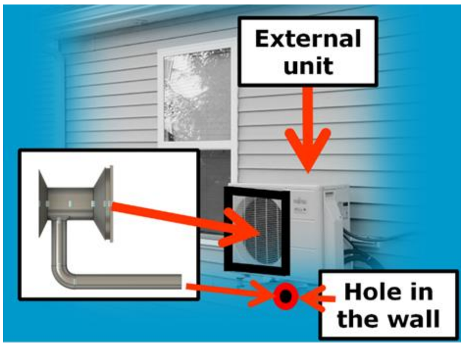

Figure 2. Conceptual installation of the new device

Table 1. Typical ACPHs

Room or space	ACPH
Basement	3-4
Bedroom	5-6
Laundry	8-9
Kitchen	7-8
Living room	6-8
Office	6-8
Restaurant	8-10
Restaurant bar	15-20
Auditorium	12-14

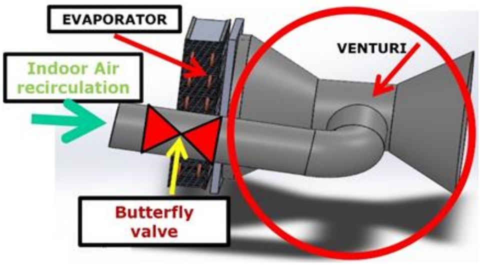

Figure 3. Conceptual drawing of the new device

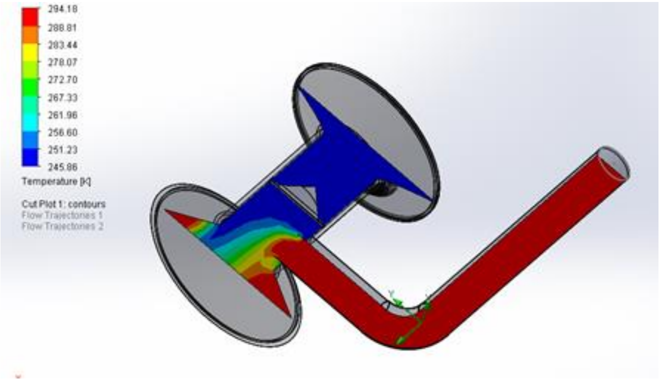

Figure 4. CFD of the mixing device (Temperature [K])

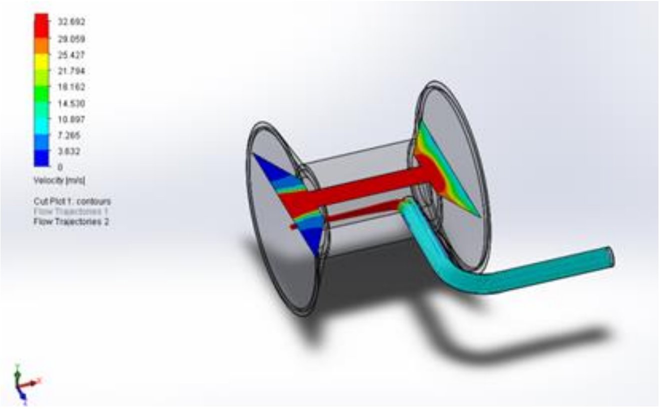

Figure 5. Cavity geometry

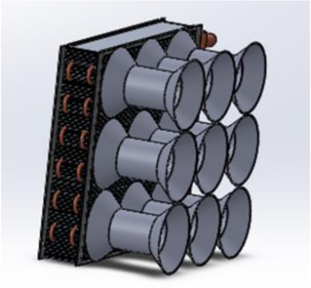

Figure 6. Multi-venturi compact arrangement

A Venturi duct is mounted on the air intake of the external coil. The air is sucked into the Venturi by the external coil fan. The Venturi is connected to the indoor space via a hole in the wall and a pipe. As the air flows into the Venturi, the depression sucks the indoor air into the external coil heating/cooling duct. Then, the warm air at indoor temperature is mixed with the outdoor air. The temperature at the inlet of the external coil is higher that the outdoor temperature.

Theoretically, frosting should not form if this inlet temperature is higher than 0°C. Practically speaking, the temperature at the inlet should be higher due to mixing and turbulence. The input temperature is fixed at 2°C in the example of the following paragraph to prevent frost. In the low-pressure pipe of the Venturi, a butterfly valve is added so that it is possible to set the minimum inlet temperature. The valve is managed by the heat pump's electronic control unit (ECU) (Figure 3).

The external coil inlet may include an additional temperature sensor, or the ECU may determine the value of this temperature. The mixing of the warm air from the indoor and the cold external air can be improved by mixing devices like the reverse cone in Figure 4. The mixing device is required to enhance the inadequate warm (inside) and cold (outside) air mixing onto the external coil (Figure 5). As seen in Figure 6, the additional Venturi system may have a very compact design. This multiple-Venturi configuration is comparable to those found in military vehicle desert air filters. The patented system is an optional addition that may be made to the current outdoor unit.

Compared with the existing defrost systems, the proposed system has a unique advantage: the heat for defrosting is obtained with a high COP, given by the difference between air-inlet-external-coil temperature and indoor air temperature [2-17]. Another advantage is that the heat pump does not stop working during defrosting. As a result, the defrosting process can be continuous, enabling the outdoor heat exchanger to operate at the optimal level. A third advantage is the heat recovery of air exchanged. The high efficiency of the proposed new system is demonstrated in the next section.

3. COP Comparison

This section uses a practical example to evaluate the benefits of indoor-outdoor air mixing for defrosting. The mixing device in Figure 2 is mounted on the heat pump of Figure 1. The outdoor air temperature is T_{out}=263.15 K (-10℃) and the internal air temperature is T_{in}=291.15 K (18℃), putting the ΔT at 28 K. The minimum air temperature at the inlet of the external coil is set to T_{inlet}=275.15 K (2℃) to avoid frosting. In this condition, the heat pump works with a ΔT_{heat_pump}=16 K. At this ΔT, the total thermal capacity for the internal coil of a commerical split heat pump stands at TC=8.62 kW. The electric power required is P_{el}=2.97 kW for a COP_{true} of 2.9:

$$COP_{true} = \frac{TC}{P_{el}} = 2.9 \tag{1}$$

The maximum airflow rate of the internal unit is A_{flow}=500 lt/s. The outdoor air should be heated by mixing indoor and outdoor air with a $\Delta T_{defrost}$=12 K from T_{out} to T_{inlet}:

$$\Delta T_{defrost} = T_{inlet} - T_{out} = 12[K] \tag{2}$$

The fraction of heating power for defrosting is $F_{defrost}$=3.69 kW:

$$F_{defrost} = TC\frac{\Delta T_{defrost}}{\Delta T} = 3.69[kW] \tag{3}$$

Therefore, the fraction of thermal power to be used for defrosting is 43% of the total available energy:

$$F_{defrost\%} = 100\frac{F_{defrost}}{TC} = 43[\%] \tag{4}$$

The fraction of inlet air-flow to be transferred outdoor to warm up the external unit air is $A_{defrost}$=15 lt/s:

$$A_{defrost} = \frac{F_{defrost}}{C_p \Delta T_{defrost}} = 15[lt/s] \tag{5}$$

The residual air flow for heating is A_{heat}=485 lt/s:

$$A_{heat} = A_{flow} - A_{defros} = 485[lt/s] \tag{6}$$

This corresponds to the $A_{heat\%}$=97% of the total available air flow of the indoor unit:

$$A_{heat\%} = 100\frac{A_{flow} - A_{defros}}{A_{flow}} = 97[\%] \tag{7}$$

Therefore, the effective total capacity of the heat pump in defrosting is $TC_{defrost}$=3.87 kW:

$$TC_{defrost} = \frac{A_{heat\%}TC}{100} = 3.87[kW] \tag{8}$$

Thence, the COP during defrosting is $COP_{defrost}$=2.81:

$$COP_{defrost} = \frac{TC_{defrost}}{P_{el}} = 2.81 \tag{9}$$

This value is far better than the COP (1.5) for defrosting with hot-gas bypass [17].

4. Conclusions

Frosting is a major problem for the air conditioning (AC) system of air-to-air heat pumps. Numerous approaches have been used throughout the years without genuinely yielding good outcomes. Defrosting has a significant impact on the COP, and in a few instances, it may be necessary to install an extra heating system when the heat pump is rendered inoperable by the defrost phase of the cycle.

The patented technique described in this work warms the chilly outside air that enters the external heat exchanger by recovering heat from the air that was discharged (for air change). Even though heat recovery is frequently used in big heating systems, our technique can be used with tiny units with thermal capacities as little as a few kW. The warm air passes through a hole in the wall. The fan of the external unit sucks it with the depression obtained by a Venturi positioned in front of the air-venting hole. A butterfly valve is mounted on the pipe from the hole to the Venturi, and responsible for regulating the amount of warm air sucked and mixed to the cool, outside air. In this way, the air entering the external coil is warm enough to avoid frost.

The proposed system is energetically efficient, for the warm indoor air is heated with the high COP of the heat pump. In addition, the heat pump works with a reduced temperature difference, thanks to the variation in the indoor temperature after the mixing of external and (changed) warm indoor air.

Based on the real data at -10°C outdoor temperature, calculations show that a limited amount of warm air is needed by our system for defrosting, and the overall COP of the system is higher than the best traditional defrosting systems. In addition, the heating system continues to work during the defrosting phase, and the external heat exchanger does not accumulate frost at all. Thus, the system maintains the best efficiency possible. The proposed defrosting device can be added to any existing split system.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Nomenclature

T_{out}	Outside temperature, K (263.15)
T_{in}	Inside temperature, K (291.15)
T_{min}	Minimum air temperature of the outdoor heat exchanger to prevent frosting, K (275.15)
ΔT_{heat_pump}	Temperature difference of the heat pump, K (16)
TC	Thermal capacity of the heat pump with ΔT_{heat_pump}, kW (8.62)
P_{el}	Electrical power absorbed by the heat pump with ΔT_{heat_pump}, kW (2.97)
COP_{true}	Dimensionless coefficient of performance of the original commercial heat pump with ΔT_{heat_pump}
$\Delta T_{defrost}$	Temperature difference between outdoor air T_{out} and the incoming air of the external heat exchanger T_{min}, K (12)
$F_{defrost}$	Fraction of heating power used for defrosting, kW (3.69)
$F_{defrost\%}$	Fraction of heating power used for defrosting, % (43)
$A_{defrost}$	Air flow of indoor air for defrosting, lt. s^{-1} (43)
A_{flow}	Max air flow of the indoor unit, lt. s^{-1} (500)
A_{heat}	Max air flow of the indoor unit for heating during defrosting, lt. s^{-1} (485)
$A_{heat\%}$	Fraction of air flow of the indoor unit for heating during defrosting, % (97)
TC_{frost}	Thermal capacity of the heat pump for heating during defrosting with ΔT_{heat_pump}, kW (3.87)