DOI: 10.21134/8d2deh11

CYTEF
XII Congreso Ibérico
y X Congreso Iberoamericano
de Ciencias y Técnicas del Frio
Universidad Miguel Hernández de Elche
26-06 28-06/2024
UNIVERSITAS Miguel Hernández

EXPERIMENTAL ANALYSIS OF THE INFLUENCE OF FAN SPEED ON FROST GENERATION AND ITS IMPACT ON A HEAT PUMP

David ALARCÓN-GALLÉN[1]*, Emilio NAVARRO-PERIS[1]

1: Instituto Universitario de Investigación de Ingeniería Energética (IUIEE),
Universitat Politécnica de València (UPV). Camino de Vera s/n, 46022, Spain
e-mail: d.alarcon@iie.upv.es

Abstract: *The phenomenon of frost on the heat exchanger surfaces penalizes the performance of the heat pump, one of the operating parameters that influences the evaporation temperature, this is transferred to the formation of frost, and its impact is the amount of air passing through the evaporator, in that sense, an air-water heat pump has been experimented at different fan speeds and environmental conditions inside a climatic chamber. The results allow to obtain different parameters to characterize the frost formation process and to make an effective comparison between them. The lower the fan speed, the lower the air flow rate, the lower the heating time, and the higher the number of defrost cycles required for the same environmental conditions. In this way, some correlations could be developed to predict how the frosting process is affected by the fan speed in more conditions that are not tested. The aim is to determine to what level frost formation can be suppressed by achieving different fan speeds whether it is technically and economically feasible and what implications imposes on the heat pump performance.*

Keywords: heat pump, frost suppression, defrost, energy efficiency

1. INTRODUCTION

The heat pump systems are receiving interest due to their energy efficiency, decarbonization potential, and reduced operation cost [1] in climatization and domestic hot water production, even in colder climates. However, the external coil can be frozen when its operation needs to maintain negative temperatures on the evaporator's surface, and this temperature is lower than the dew temperature of the air. This usually happens in cold climates, also coastal areas and tropical regions tend to have high humidity levels due to evaporation of seawater and frequent rainfall.

The evaporation temperature is influenced, among other variables, by the evaporation temperature (which can be modified by varying the air flow rate) and the amount of water in the air (moist air has more capacity to contain thermal energy than dry air, therefore, it can provide more heat to the refrigerant in the evaporator, which can increase the evaporating temperature.

Frost is a porous medium that reduces thermal conductivity and, due to its accumulation, reduces the airflow rate that flows through the fin-and-tube heat exchanger, by reducing the amount of air, the extractable energy is reduced. As a result, the capacity and the performance of the heat pump decreases during the frost growing. Moreover, the frost layer must be removed, and for this purpose, the heat pump recurs to different strategies of defrost that further penalize the operation and the thermal comfort. In a nutshell, heat pumps present some disadvantages in their operation in cold climates, that reduce their interest and potential just where heat pumps could be most beneficial.

Due to its importance, recently, different researchers have conducted studies on this topic [2, 3]. Since this phenomenon depends on the refrigerant and air-side conditions, it is hard to determine a proper methodology to completely understand it and adequately compare prototypes. The most important advances respect that are the frost maps presented by [4], also in [5] these frosting maps are presented for variable speed heat pumps. These maps are presented as a basis for improving machine operation and for characterizing the state of the evaporator concerning frost.

In this paper, a monobloc air-to-water heat pump is tested and monitored in frosting conditions, for each condition different fan speeds are used to vary the air flow rate through the fin-and-tube heat exchanger whereas the relative humidity is constant, and a specific analysis of the airflow rate reduction along the time is performed. Finally, a comparison is realized.

2. TEST BENCH & MATRIX

A commercial air-to-water heat pump is tested in a climatic chamber, where air conditions can be controlled, and connected to a hydraulic system (dashed line) to maintain a certain return temperature. Exhaust air conditions are measured through a mixing and sampling tree incorporating a fan to overcome pressure drops. Figure 1 shows the test bench and the instrumentation used to monitor the operation of a heat pump in frost conditions.

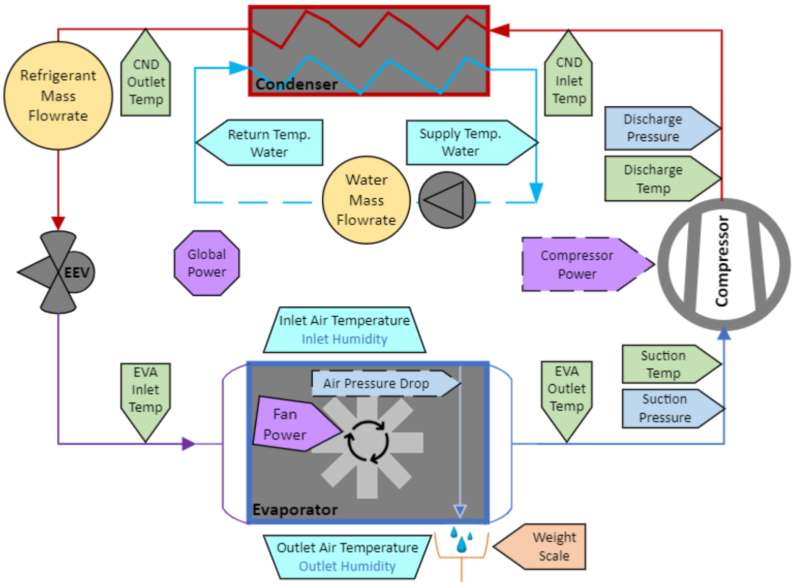

Figure 1. Test Bench and Instrumentation (Heating Mode).

The tested conditions are shown in Table 1. The compressor speed is set at the maximum possible to accelerate the frosting process. These tests aim to evaluate how the fan speed influences the process. However, it should be noted that the lower the compressor speed, the greater the frost suppression.

Table 1. Tested Conditions.

Test	Air Dew-Temperature [°C]	Relative Humidity [%]	Water Supply Temperature [°C]	Compressor Speed [rps]	Fan Speed [rpm]			
					1	2	3	4
A	-3	90%	55 ($\Delta T = 5[K]$)	80 (max)	620	560	500	380
B	-5	90%	35 ($\Delta T = 5[K]$)	80 (max)	620	560	500	440

3. METHODOLOGY

The frost phenomenon takes place in a heat pump working in heating mode, a complete cycle (heating + defrost) could be divided into different stages:

i. Heating Stage: heat is transferred from outside to inside, and frost is accumulated on the evaporator.
ii. Defrost Initial Stage: the compressor stops working in heating mode and the four-way valve changes.
iii. Melting Frost Stage: the unit works in cooling mode, the evaporator is now a condenser, and the released heat is intended to melt the ice (~0°C).
iv. Evaporating Melted Frost Stage: the unit stops working in cooling mode and the four-way valve changes. This water is not calculated.
v. Defrost Last Stage: the compressor stops working and the four-way valve changes.
vi. Heating-Resume Stage: the compressor starts working in heating mode, but the flow temperature has not yet reached the preconditions. It should be noted that in this stage the frosting process can start again.

Due to the frosting phenomenon being a constant process of deposition, first, the heat pump and the climatic chamber work to achieve the desired conditions without the humidity, once the conditions are achieved, the boiler starts to work and injects stream-vapor into the chamber, and when the humidity achieves the desired value, the recording starts.

When the heat pump detects that the amount of frost is penalizing your operation too much, stop the fan and start the defrosting process. Once the defrost last stage finishes, the fan speed is changed, and a new heating cycle starts (the heating-resume stage is considered in the heating period for the next cycle).

Using the acquired data and processing them with REFPROP [6], for refrigerant properties; and CoolProp [7] for air properties, the cycle variables are obtained. Applying an energy balance on the fin-and-tube heat exchanger, the airflow rate is obtained.

4. RESULTS & DISCUSSION

Test B1 (A-5W35R90@80rps_620rpm) is considered not valid due to some instabilities in the relative humidity, the control system was saturated, and the humidity conditions were 100% during the first minutes of the test, this changes the conditions as there is much more extractable water in the air.

Table 2. Time and Mass Results.

Conditions	Fan Speed [rpm]	Defrosted Mass [g]	Heating Time	Defrosting Time	Reduction in Heating Time [%]
A-3W55R90%	380	1272	1:32:10	0:03:40	0.00%
	500	1677	1:52:10	0:04:00	21.70%
	560	1853	2:02:50	0:04:00	33.27%
A-5W35R90%	440	1066	1:02:00	0:04:30	0.00%
	500	1342	1:12:10	0:05:00	16.40%
	560	1559	1:20:30	0:04:40	29.84%
	620	2136	1:54:00	0:05:20	83.87%

As can be seen, there are little differences in the time that the unit requires to perform the defrost cycle, even though the amount of frosted water is reduced with the fan speed.

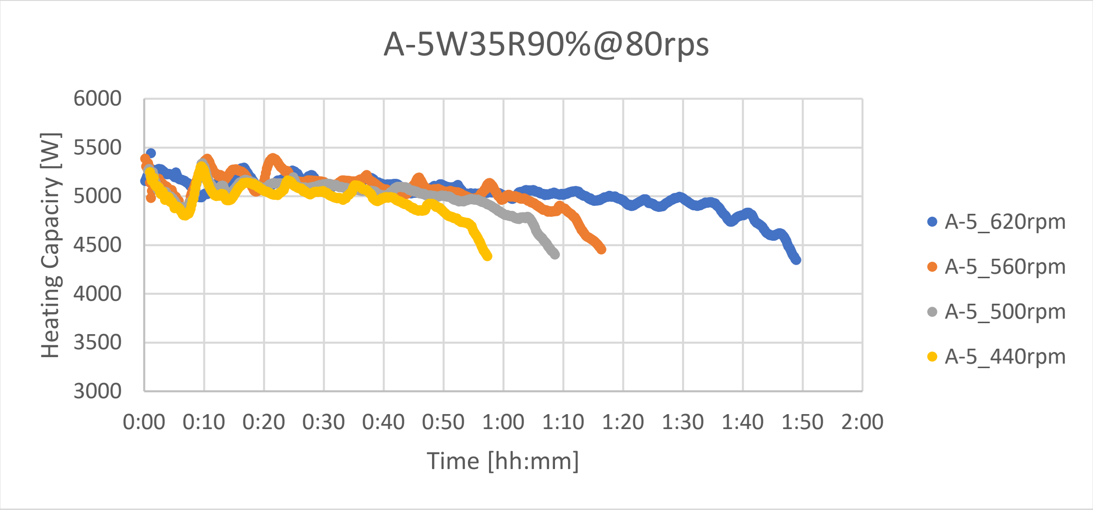

Figure 2. Heating Capacity Evolution A-5W35R90%@80rps.

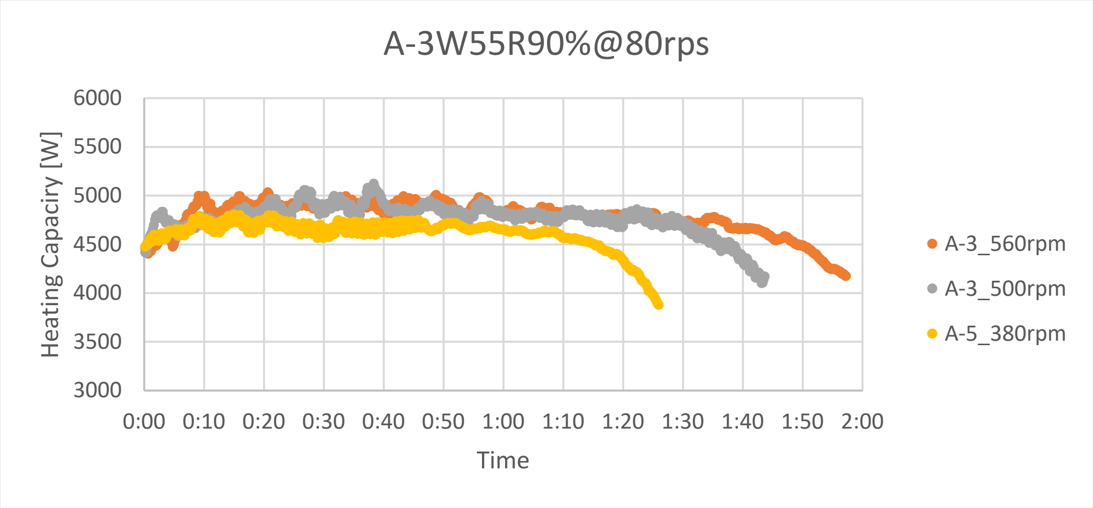

Figure 3. Heating Capacity Evolution A-3W55R90%@80rps.

Fan speed shows little influence on the heating capacity, and on the unit power consumption, therefore, an increase in the fan speed has a limited impact on the performance. The most relevant impact of the fan speed is on the warm-up time; however, it has not been possible to identify a valid linear relationship for the two conditions. As can be seen, the lower the fan speed the lower the heating time. Table 3 shows the energy used to warm up the water, the required compressor work, and the energy required for the defrosting process. The ratio between the heating energy and the heat pump consumption is mainly constant.

Table 3. Energy Analysis Results.

Conditions	Fan Speed [rpm]	Heating			Defrost		
		Energy [kWh]	Work [kWh]	EE [-]	Energy [Wh]	Work [Wh]	Total [Wh]
A-3W55R90%	380	7.01	2.97	2.36	397.63	92.30	489.92
	500	8.85	3.71	2.39	472.98	108.73	581.71
	560	9.65	4.04	2.39	479.71	103.96	583.67
A-5W35R90%	440	5.03	1.45	3.46	314.54	57.27	371.81
	500	6.05	1.75	3.46	335.82	59.85	395.66
	560	6.81	1.96	3.47	362.37	63.42	425.79
	620	9.68	2.80	3.45	464.79	75.45	540.24

Table 4 shows the results if a daily extrapolation is considered, considering the time required to perform a complete cycle (heating + defrost), the number of cycles per day is obtained. An efficiency ratio is proposed, where E_d is the energy extracted from the waterside during a defrost cycle.

Table 4. Daily Extrapolation Results.

Conditions	Fan Speed [rpm]	Complete Cycles per Day	Heating		Defrost			$\frac{E_h - E_d}{W_h + W_d}$
			Energy [kWh]	Work [kWh]	Energy [kWh]	Work [kWh]	Total [kWh]	
A-3W55R90%	380	15.03	105.38	44.64	5.97	1.39	7.36	2.16
	500	12.40	109.65	45.93	5.86	1.35	7.21	2.20
	560	11.35	109.59	45.90	5.45	1.18	6.63	2.21
A-5W35R90%	440	21.65	108.90	31.50	6.81	1.24	8.05	3.12
	500	18.66	112.96	32.64	6.27	1.12	7.38	3.16
	560	16.91	115.13	33.18	6.13	1.07	7.20	3.18
	620	12.07	116.82	33.84	5.61	0.91	6.52	3.20

As can be seen in Table 4, the fan speed influences the number of complete cycles, as the higher the fan speed (the air flow rate), the lower the number of cycles, and the comfort conditions are affected less often by the defrosting process. The heat pump consumption increases slightly, but the improvement in the total heating energy by working for a longer period allows for enhancement of the performance of the heat pump.

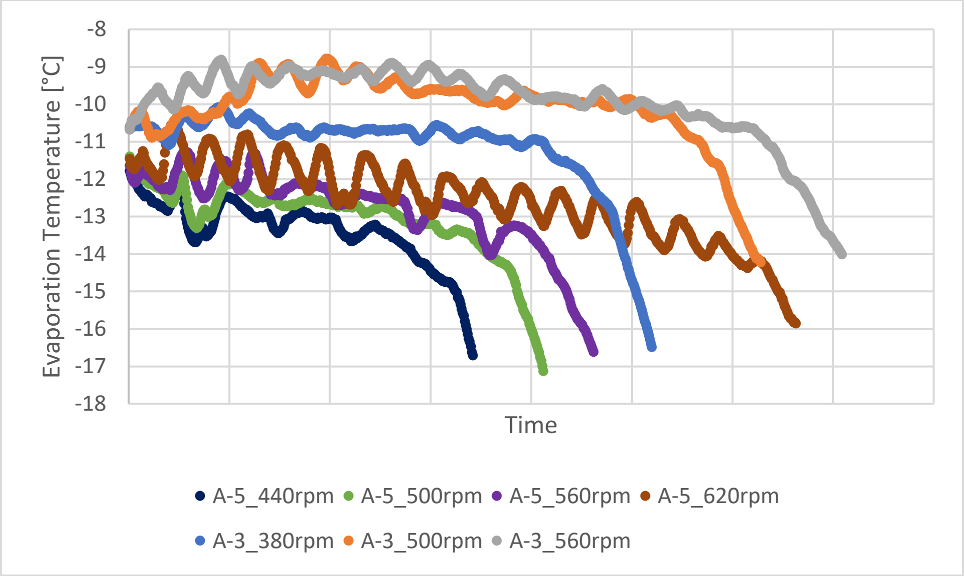

Figure 4. Evolution of Evaporation Temperature with the Frosting Process.

Table 5. Frost Impact Table: Initial 2 Minutes vs Final 2 Minutes.

Conditions	Fan Speed [rpm]	Heating Capacity	COP	Air Flowrate	Pressure Ratio	Mref	ΔTeva [°C]
A-3W55R90%	380	-12.6%	-13.6%	-39.7%	-17.3%	-18.9%	-5.34
	500	-9.1%	-6.5%	-38.0%	-12.1%	-7.8%	-3.65
	560	-5.5%	-11.6%	-46.6%	-12.4%	-12.4%	-3.38
A-5W35R90%	440	-12.5%	-7.5%	-21.7%	-15.8%	-4.5%	-3.99
	500	-13.7%	-15.5%	-35.1%	-18.0%	-14.4%	-4.86
	560	-13.1%	-13.9%	-34.1%	-18.5%	-9.7%	-4.31
	620	-12.5%	-17.2%	-38.2%	-17.6%	-13.6%	-4.07

Table 6. Frost Impact Table: Maximum vs Minimum Values.

Conditions	Fan Speed [rpm]	Heating Capacity	COP	Air Flowrate	Pressure Ratio	$\dot{m}_{ref}$	ΔT_{evap} [°C]
A-3W55R90%	380	-19.3%	-16.0%	-41.4%	23.8%	-19.8%	-6.41
	500	-19.9%	-14.4%	-45.9%	17.8%	-19.0%	-5.45
	560	-17.1%	-15.1%	-45.4%	16.1%	-18.2%	-5.20
A-5W35R90%	440	-17.4%	-18.7%	-32.5%	23.7%	-17.2%	-4.92
	500	-17.6%	-21.2%	-42.2%	27.1%	-22.1%	-5.73
	560	-17.4%	-21.9%	-40.0%	27.3%	-21.0%	-5.38
	620	-16.3%	-23.5%	-44.4%	24.9%	-24.5%	-5.32

Figure 4, shows how the evaporation temperature is reduced as the frost grows, this is the main effect of the frost and causes the other ones: reduction in suction conditions, reduction in the mass flowrate, reduction in the heating capacity, increase in the pressure ratio, and a global decrease in the performance. It should be noted that the compressor work is reducing due to the reduction in the mass flow rate. These changes in the main parameters are tabulated in Table 5 which compares the two first minutes with the two lasts, and in Table 6 which compares the maximum and minimum values. The second table is proposed because to first instants could be not representative of the cycle due to the heating-resume period.

5. CONCLUSIONS

In this paper, an experimental parametric study of the airflow in a heat pump under frost conditions is carried out. The results show that, from an energy and comfort point of view, it is always going to be more interesting to increase airflow for better frost suppression. Respect the lower fan speed, the maximum can enlarge the heating period by 33.27% in A-3 $(380 \rightarrow 560)$ and by 83.87% in A-5 $(440 \rightarrow 620)$. Even though, to increase the fan speed increases the power consumption, the efficiency of the complete cycle is higher for the longest heating period. In this regard, to improve the efficiency of heat pumps in cold environments it would be interesting to explore alternatives to increase the airflow: more powerful fans, wider fin pitch, etc. While in terms of instantaneous performance, this will not be a major improvement, for a seasonal period the gains can be significant.

REFERENCES

[1] Zhang Q., et al., Techno-economic analysis of air source heat pump applied for space heating in northern China, Applied Energy, 2017, 207: 533-542.

[2] Zhang G., et al. Review of experimentation and modeling of heat and mass transfer performance of fin-and-tube heat exchangers with dehumidification. Applied Thermal Engineering, 2019, 146: 701-717.

[3] Song M., et al., An experimental study on even frosting performance of an air source heat pump unit with a multi-circuit outdoor coil, Appl. Energy, 2016, 164: 36–44.

[4] Zhu, J.H., et al., Developing a new frosting map to guide defrosting control for air-source heat pump units, Applied Thermal Engineering, 2015, 90: 782-791.

[5] Liu S., et al., Developing condensing-frosting performance maps for a variable speed air source heat pump (ASHP) for frosting suppression, Applied Thermal Engineering, 2022, 211: 118397.

[6] Lemmon, E.W., et al., NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2018.

[7] Bell, I., et al., Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp, Ind. Eng. Chem. Res.2014, 53: 2498−2508