2004 ASME International Mechanical Engineering Congress and Exposition
November 13-20, 2004, Anaheim, California USA

IMECE2004-60096

DEVELOPMENT OF AN INNOVATIVE DEFROSTING SYSTEM FOR COMMERCIAL CHILLER EVAPORATORS THROUGH PIEZOELECTRIC ELEMENTS APPLICATION

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ABSTRACT

The present study relates to the design of an innovative defrosting system for commercial chiller evaporators. This system is based on piezoelectric plates connected to the evaporator fins and driven at ultrasonic frequencies by a suitable electronic circuit.

The operational frequency of piezoelectric elements is chosen to be close to the first harmonics of the fin resonance frequency in the ultrasonic range. The electronic driving system supplies the electric voltage required at the operational frequency starting from the PVM 0-5V signal output of a microcontroller. Moreover, the measurement of the absorbed current is acquired by the microcontroller as feedback to tune the operational frequency at the variation of the fin mass due to frost deposit and detachment.

Experimental results show that the approach inhibits the frost deposit during chiller operation, increasing the period between two consecutive defrosting phases which currently is typically no greater than 6 hours. This is an important result considering that while defrosting the chiller must be shut off, depending on the defrosting methods applied, with negative effects on the goods being preserved. The system was developed in collaboration of ISA S.p.A and patented [1].

NOMENCLATURE

f	Frequency
t	Thickness of the frost deposit
ΔV	Voltage
I	Electric current
W_e	Electric Absorption

SUBSCRIPTS

0	Resonance conditions
p	Piezoelectric

INTRODUCTION

The evaporator is the chiller component in which "cold" is produced through the evaporation of refrigerant at low temperature.

In ventilated refrigerators, such as those produced by ISA S.p.A., air is forced by fans through the evaporator and then in to the cooled vane. Figure 1 shows a section of a refrigerator for pastry shop and a scheme of the refrigeration plant.

The evaporator pipes are equipped with plate fins. As the moist air is cooled across the evaporator, the moisture condenses and ices over the fin surfaces. The frost deposit causes an air mass flow rate reduction across the evaporator and consequently degrading the chiller performances.

In commercial refrigerators, defrosting is usually achieved automatically at a pre-set time nowadays no greater than 6 hours. The hot gas, reverse cycle and electric heating defrosting are the methods currently applied [2, 3]. Such methods need the compressor chiller to be shut down at any defrosting phase, causing the temperature increase inside the cooled vane with negative effects on the state of preservation of goods. Moreover, in case of hot gas and reverse cycle defrosting an excessive compressor stress occurs.

The aim of the research is to develop an innovative system which inhibits the frost deposit during chiller operation allowing to increase the time between two consecutive traditional defrosting phases at 12 hours. The object of the present study is to design an innovative evaporator defrosting system by applying piezoelectric elements connected to the evaporator fins. These elements, if driven by an alternative voltage, vibrate at the frequency of the driving signal [4,5,6] inducing the frost to separate. Moreover further deposits are hindered. To maximize the mechanical energy transmission to the fins, the driving signal frequency must be equal to fins resonance frequency or to its harmonics.

As a first step, experimental tests were carried out to evaluate the resonance frequency of the frosted fin and the operational ultrasonic frequency optimal range. The latter, in fact, must be determined in order to maximize the device effect in compliance with the refrigerator noise limits.

The second phase was focused on the design of both the electronic driving system and control system to produce a signal at suitable voltage and frequency variable in agreement with the fins resonance frequency. The latter in fact varies as the mass of the frost deposit varies.

The developed innovative defrosting system promotes the separation of the frost and inhibits further deposits on fin surfaces during normal chiller operation, as demonstrated during some experimental tests. Consequently, it is possible to increase time between two consecutive traditional defrosting phases with a significant improvement in performances of ventilated commercial and industrial chillers.

Furthermore the system does not entail any modification in the chiller design. The acoustic insulation of the evaporator is, in fact, not required because of the operational ultrasonic frequency of the device.

The experimental results also led to determination of the piezoelectric elements typology and the best location for their installation. The optimization of the electronic circuit will be done in the future.

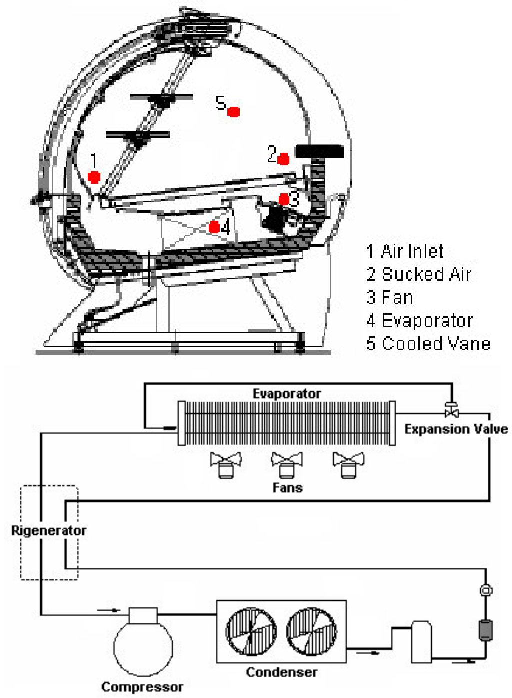


Figure 1: section of a refrigerator for pastry shop and scheme of the refrigeration plant

TEST BENCH SETUP AND PRELIMINARY EXPERIMENTAL RESULTS

Preliminary experimental tests were carried out in order to verify the efficiency of the innovative defrosting method and evaluate both the resonance frequency of the frosted fin and the optimal range of the operational ultrasonic frequency. To this aim, an evaporator characterized by a fin spacing of 4 cm for the first fin and 2 cm for the others, was designed and installed on a particular refrigerator in order to simplify the piezoelectric installation.

The refrigerator is a rectangular box completely open in the upper side to guarantee better accessibility. The evaporator is placed inside the box while the other components of the refrigeration plant are located under it. Air circulation across the evaporator is guaranteed by natural convection; consequently frost deposits are expected mainly in the fins' s upper side, because the ambient air enters in the evaporator' s upper side and leaves the evaporator from the lower side.

Therefore piezoelectric elements, for a global electric absorption of 1 Watt, were attached on the upper part of some evaporator fins and electrically connected to the supply system.

The supply system is constituted by a function generator and a driving piezoelectric amplifier (Trek model 603). The supply voltage was 300 V with the possibility to tune frequency.

During refrigerator operation at frequencies below 16 kHz, continuous frost separation was observed from the evaporator part enhanced by the piezoelectric elements, resulting in a very small frost deposit thickness after five hours of operation. These results verified the effectiveness of the defrosting method.

Moreover it was possible to observe that the reduction in frost formation is improved by varying the driving signal frequency. In fact, in the case of driving signal frequency equal to the frosted fin resonance frequency or its harmonics a greater mechanical power was transmitted, with resulting greater electric current absorption.

Therefore to have resonance conditions throughout all the operation time, a particular control system becomes necessary to regulate the driving signal frequency by means of the feed-back of the current absorbed by piezoelectric load.

Furthermore a high noise level, due to the low operational driving frequencies, was evidenced. Consequently it is necessary to find suitable operational ultrasonic frequencies.

Experimental determination of the frosted fin resonance frequency

In this phase an experimental test was carried out in order to determine the frosted fin resonance frequency f_0 and its harmonics over 20 kHz by measuring the electric current absorption.

During the test a function generator, a driving piezoelectric amplifier and an oscilloscope were used to generate driving signal at variable frequency, increase the voltage generator output to 300V necessary for the piezoelectric elements and monitor the electric absorption respectively.

Table 1: evaluation of the frosted fin resonance frequency

f (kHz)	f/2	f/3	f/4	f/5	f/6	f/7	f/8	ΔV (V)
5	2.5	1.67	1.25	1	0.83	0.71	0.63	14.32
5.5	**2.75**	1.83	1.38	1.1	0.92	0.79	0.69	14.24
6.2	**3.1**	2.07	1.55	1.24	1.03	0.89	0.78	14.24
8	4	**2.67**	2	1.6	1.33	1.14	1.00	14.16
9.3	4.65	**3.1**	2.33	1.86	1.55	1.33	1.16	14.08
10	5	3.33	2.5	2	1.67	1.43	1.25	14.08
11.2	5.6	3.73	**2.8**	2.24	1.87	1.6	1.40	14.32
12.8	6.4	4.27	**3.2**	2.56	2.13	1.83	1.60	14.16
13.5	6.75	4.5	3.38	**2.7**	2.25	1.93	1.69	14.16
15.3	7.65	5.1	3.83	**3.06**	**2.55**	2.19	1.91	13.2
20	10	6.67	5	4	**3.33**	**2.86**	2.5	13.12
25.6	12.8	8.53	6.4	5.12	4.27	3.66	**3.2**	11.44

The test was carried out before increasing the driving signal frequency from 0 to about 25 kHz and after diminishing it until 0.

Particular frequencies were detected in correspondence to the electric absorption peaks, measured as the voltage peaks between the 100Ω impedance of the current oscilloscope output.

The voltage peak values are reported in the 9th column of table 1, while the corresponding operational frequencies in the 1st column.

Dividing these frequency values by 2, 3, …, 8, all the possible values correspondent to the same fundamental frequency were found and evidenced in table 1. The resonance frequency was determined as the mean of those values equal to 3 kHz.

Furthermore observing the voltage values in table 1, it can be seen how the peak values, each correspondent to resonance conditions, decrease starting from the fundamental frequency. Therefore, the range of operational frequency between the first two ultrasonic harmonics (21-24 kHz) was chosen to obtain a significant transmission of mechanical power.

DESIGN OF THE PIEZOELECTRIC DRIVING CIRCUIT

Piezoelectric elements specifications

The resonance frequency of the piezoelectric elements must be in the range 21 – 24 kHz previously found, in order to maximize the vibration of the fins at frequency close to the 7^{th} – 8^{th} harmonic of their resonance frequency. Moreover the piezoelectric elements must be rectangular plates with maximum dimensions of 75×15mm, in agreement with the geometry of the evaporators chosen for the device implementation (figure 2). Finally a small electric absorption of each plate is required in order to limit the global absorption of the device which must be constituted by a number of piezoelectric elements appropriate to the number of fins.

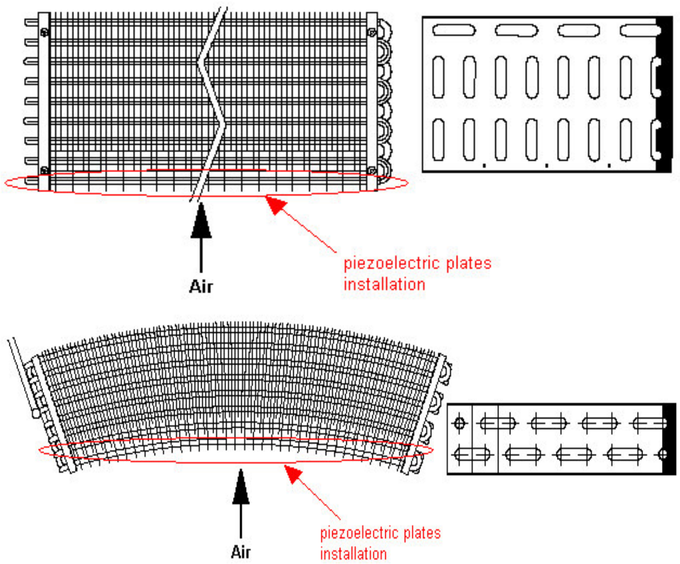


Figure 2: evaporators geometry

According to these specifications, two different typologies of commercial piezoelectric plates were found.

The first typology (Phisyk Instrumente Ceramic PIC 181) is characterized by a 4 nF capacity and 70×20×4 mm dimensions. The supplier advices to determine experimentally the optimal voltage level of the driving signal in the range 200-1000V_{pp}.

The second typology (Morgan Electric Ceramics PC8) is characterized by a 2.4 nF capacity and 66×10×3 mm dimensions and required a sinusoidal +/- 600 V driving signal.

Due to the variability of the piezoelectric driving conditions, the prototype driving circuit must guarantee their tuning in order to determine the suitable piezoelectric elements and their optimal driving voltage. Therefore the attention was initially focused on the piezoelectric driving circuit.

Preliminary design indications

In reference to the main specifications of the driving circuit, the range of the operational frequency was already noted along with the need of voltage level tuning and limited electric absorption. Furthermore the need of driving frequency tuning in the range 21-24 kHz arises. As previously detailed, the driving frequency of piezoelectric elements must be equal to the frosted fin resonance frequency or its harmonics, in order to maximize fins vibration. In this case, the frosted fin resonance frequency changes during chiller operation because of the continuous variation of the frost deposit mass.

Therefore a control circuit for operational frequency tuning by means of the feed-back of the piezoelectric electric absorption W_e is necessary. To this aim a microcontroller was chosen as signal generator. The microcontroller, in fact, allows to vary the signal frequency, receiving in input the value of the current absorption. Figure 3 shows the block diagram of the driving electronic circuit. The main sections are:

- (A) Driving signal generator, producing the piezoelectric driving signal at variable frequency in the range of 21-24 kHz. Moreover the block evaluates at fixed time the resonance frequency of the frosted fin as the frequency value corresponding to the maximum current absorption. A microcontroller PIC 16F84A was chosen as generator. This device has an A/D converter constituted by a quartz working at 4MHz and allows to generate a PVM 0-5V signal at 21-24 kHz. Moreover the device can acquire an analogous input. It is supposed that in the interval time T_1 (for example T_1=1s) the microcontroller generates a driving signal at frequency variable from the minimum to the maximum value of the operational range. In this time the microcontroller acquires the measurement of the current absorption and finds the frequency corresponding to the current peak. For the next interval time T_2 (for example T_2=9 s) the microcontroller generates the driving signal at that frequency value.
- (B) Driving signal amplification section, producing the driving signal amplification to the desired voltage level.
- (C) Electric absorption probe, consisting of Hall's probe for the current absorption measure.
- (D) Signal elaboration circuit, producing an analogous output for block A starting from the signal produced by block C. On the basis of that signal, block A detects the resonance frequency of the frosted fin and modifies the driving signal frequency at fixed time.
- (E) Piezoelectric load.

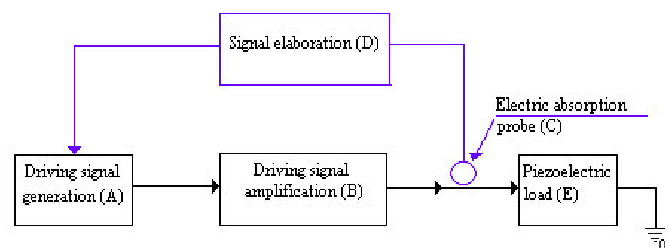


Figure 3: driving electronic circuit block diagram

Electric absorption probe and signal elaboration circuit

Hall' s probe was chosen for the measure of the electric current absorption. Figure 4 shows Hall' s probe and the scheme of the signal elaboration and amplification circuit. The circuits supplies a voltage varying linearly with the magnetic field measured by Hall' s effect. After the system calibration it is possible to determine the magnetic field and the current that flows in the circuit according with Biot-Savart' s law.

The operational characteristics of Hall' s probe are:

- Operational voltage: 4.5-6 V
- Current absorption: 9-10 mA
- Sensibility: about 1 mV per Gauss
- Operational temperature: -20°C - + 85°C.

The probe is not influenced by the evaporator temperature, but it is extremely sensitive to magnetic field variations, so it will be shielded by an aluminium box.

The trimmer R5 allows the probe zero calibration. Hall' s voltage is measured between R5 and the pin U of Hall' s probe.

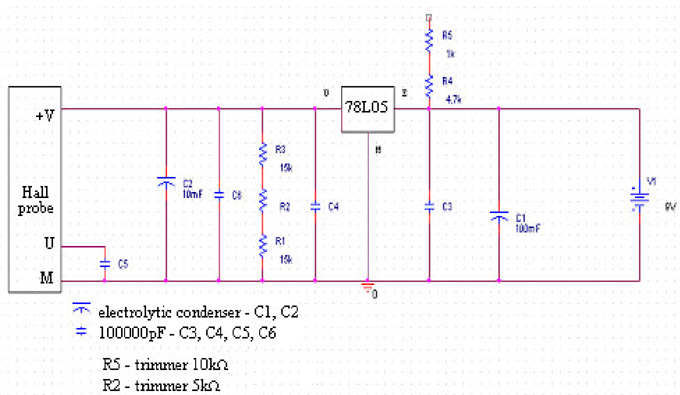


Figure 4: Hall' s probe and signal elaboration circuit

Amplification circuit of the driving signal

This electronic circuit must amplify the PVM 0-5V signal, produced by the microcontroller at the operational frequencies, to the voltage level (1200 V_{pp} maximum) necessary to drive piezoelectric elements.

In order to find the typology of the piezoelectric plates and the optimal voltage of the driving signal, the prototype circuit must also allow to vary the voltage level supplied to the piezoelectric load. Figure 5 shows the scheme of the designed circuit.

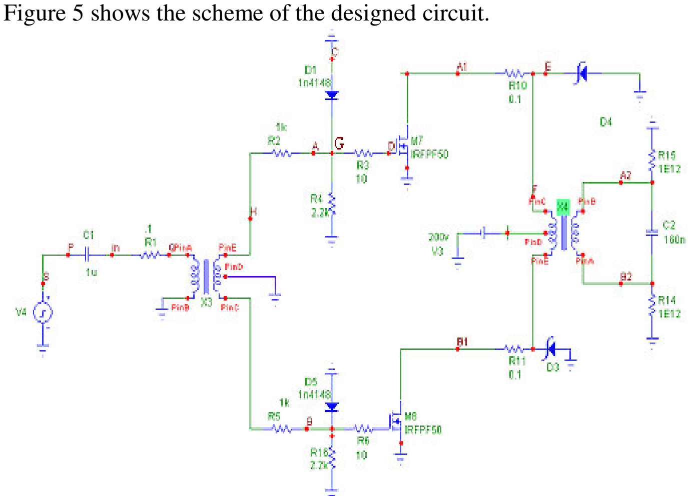


Figure 5: amplification circuit of the piezoelectric driving signal

The PVM 0-5V input signal is shifted by a capacity in order to bring the signal' s mean value to 0. The transformer on the left has two secondary windings with a center tap. It amplifies, according to the ratio 1:3, the input signal in order to produce the voltage level necessary to turn on the mosfets through their gates. Moreover the transformer creates the galvanic isolation between the low voltage and high voltage circuit sections. Two mosfets n-channel with 500V voltage drain source are used. Because two identical mosfets are installed, the same polarization voltage (+200Vcc maximum) is supplied to the mosfets drains through the central tap of the transformer on the right and its primary windings. This transformer was built for this application: a ratio of transformation equal to 3 characterizes the transformer at the operational frequencies.

The electronic circuit was made and tested. A particular attention was focused on dimensioning the resistive net placed at the mosfet gate node and the Zener diodes for circuit protection against possible voltage feed ripples.

TEST OF THE DEFROSTING DEVICE

Preliminary test

The test bench described above was also used to test the defrosting device. The piezoelectric plates were installed on some fins, and in particular:

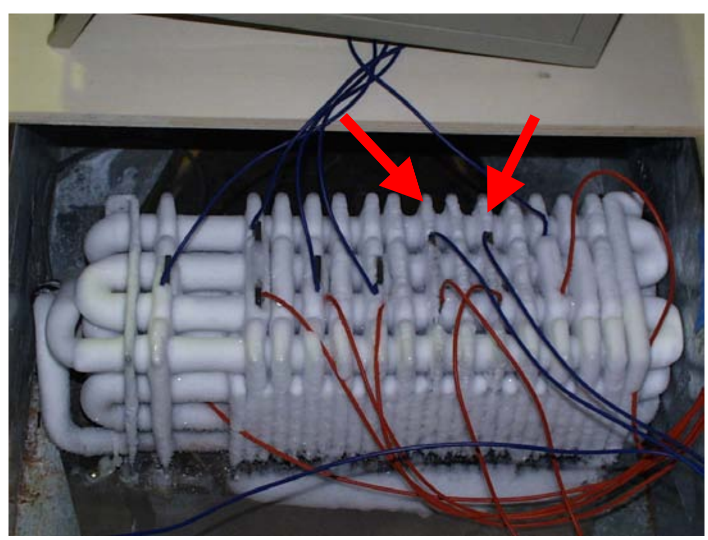
- Phisyk Instrumente PIC 181 plate installed horizontally on the upper part of the fin surface (configuration *a*);
- Phisyk Instrumente PIC 181 plate installed vertically on the upper part of the fin surface (configuration *b*);
- Morgan Electric Ceramics PC8 plate installed horizontally on the upper part of the fin surface (configuration *c*).

In this phase a function generator was used for the PVM 0-5V generation and a 64 Vcc feed (400W_e maximum electric power supplying) was provided at the center tap of the high voltage transformer. The device must be tested in such conditions with all the piezoelectric configurations described. Next, after determining the best configuration, a variac will be used to vary the supplying voltage in the range 0 - 220 Vcc for the voltage feed optimization.

For the system test two piezoelectric plates, installed according to configuration *c*, were connected in parallel to the device. To avoid mosfet overheating a fan was placed in front of the electronic circuit and a thermocouple was used to monitor the temperature.

This test demonstrated the correct device operation and the effectiveness of the defrosting method proposed. Figure 6 shows the frosted evaporator: the arrows indicate fins with piezoelectric elements in operation.

As it can be seen, the thickness of the frost deposit on those fins is halved compared to the fins without the piezoelectric plates. Moreover, as it can be noted, this effect concerns also the fins close to those with piezoelectric elements installed.



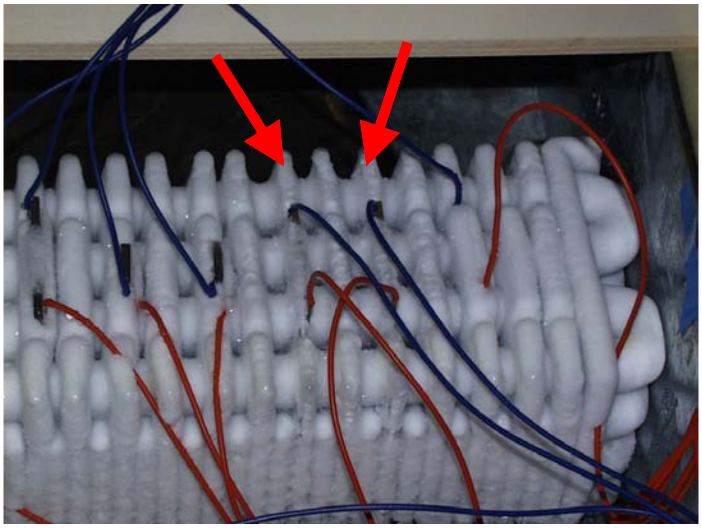


Figure 6: frosted evaporator with piezoelectric elements in operation

Furthermore it must be evidenced that the operational conditions were extremely critical. The test, in fact, was carried out in June 13th 2003 with 80% air moisture. Moreover the evaporator was completely open in the upper side, with no cooled air recirculation. Therefore the good results led to optimize the device. In the following phase, the better configuration of the piezoelectric actuator was determined.

Determination of the piezoelectric elements configuration

In this phase, tests relative to the piezoelectric configurations *a*, *b* and *c* were carried out, in order to determine the one characterized by better performances. During each test, the following parameters were measured every half hour:

- frost thickness on the fins far from the piezoelectric elements - t
- frost thickness on fin with piezoelectric element installed (*piezo-fin*) - t_p
- air moisture
- voltage ΔV, current I and electric power absorption W_e measured by means of a Microvip net analyzer. The electric power globally absorbed by the piezoelectric load, the electronic circuit and the power supply is measured.

Table 2: test results of configuration *c*

	Date: June 18th 2003							
hour	8:30am	9:00am	9:30am	10:00am	10:30am	11:00am	11:30am	12:00pm
We [W]	57	64	63	66	64	62	65	62
I [A]	0.34	0.38	0.38	0.39	0.39	0.38	0.39	0.37
ΔV [V]	231	229	225	229	229	229	231	228
Air Moisture	83%	80%	77,6%	79,2%	79,3%	77%	76,4%	75,6%
t_p [mm]	0	1.5	2	3	4.5	6	8	9
t [mm]	0	3	5	7	8	8.5	10	11

In the first test, configuration *c* was tested. In table 2 the results are summarized. As it can be noted, the ratio between the thickness of the frost deposit on the *piezo-fin* and the one on the other fins is about 2. In particular it is greater than 2 in the first part of the test, then it decreases. The several operational ambient conditions must be evidenced.

The second test trials configuration *a*. The results were in this case worse than the previous ones, as can be seen in table 3.

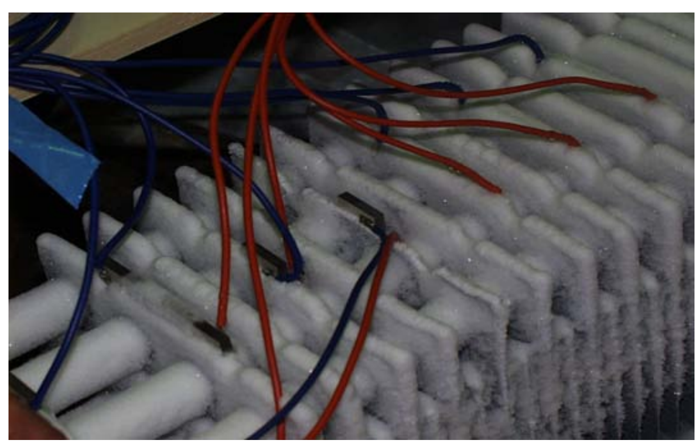
Table 3: test results of configuration *a*

	Date: June 19th 2003						
hour	9:00am	9:36am	10:10am	10:32am	11:07am	11:30am	12:14pm
We [W]	19	19	19	18	19	19	20
I [A]	0.14	0.13	0.13	0.13	0.14	0.14	0.14
ΔV [V]	229	225	225	225	229	228	228
Air Moisture	83%	73%	63%	63%	61.5%	62%	62%
t_p [mm]	0	2	3	3.5	4	5	6
t [mm]	0	3	5	6	7	8	9

Finally configuration *b* was tested. The experimental data gathered during the test are summarized in table 4. The results obtained were better than in the previous tests. The frost thickness $\mathbf{t_p}$ is in fact less than half of **t**. Moreover the reduction of the thickness frost deposit is all along the fin, as it can be seen in figure 7.

Table 4: test results of configuration *b*

	Date: June 20th 2003							
hour	8:40am	9:10am	9:40am	10:10am	10:40am	11:10am	11:40am	12:10pm
We [W]	42	44	44	44	45	45	44	44
I [A]	0.27	0.28	0.28	0.28	0.28	0.29	0.28	0.28
ΔV [V]	227	229	229	229	231	232	230	229
Air Moisture	66%	64%	63,6%	63%	62.5%	62%	61,5%	61,2%
t_p [mm]	0	1	2	2.5	3	3.5	4	4.5
t [mm]	0	3	4	5	6	6.5	7	8



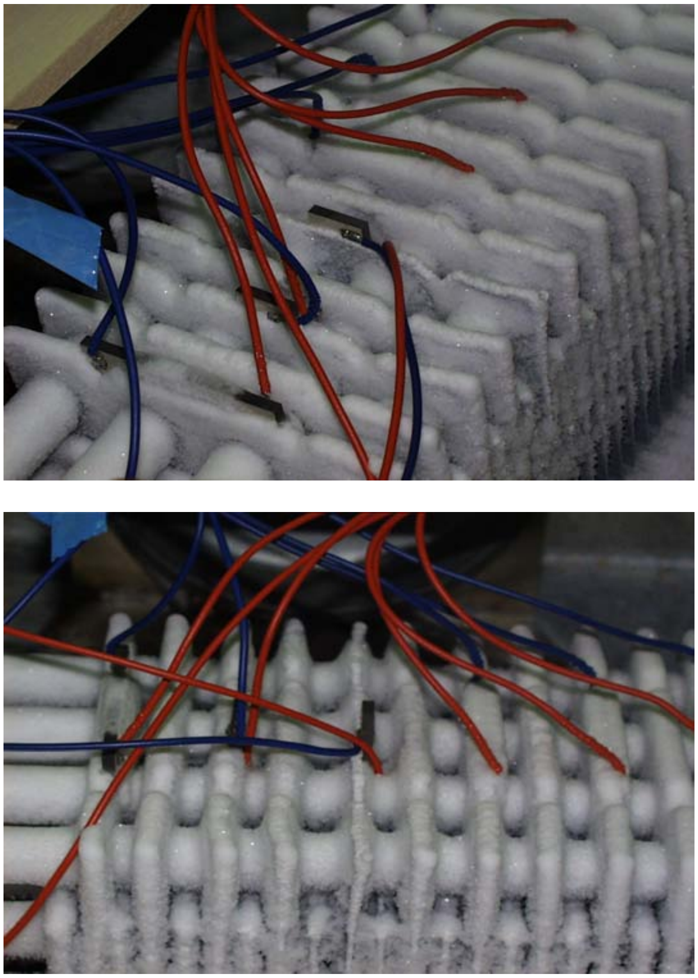


Figure 7: defrosting device with configuration *b* piezoelectric elements

CONCLUSIONS

The present study proposes an innovative ultrasonic defrosting system for ventilated commercial chiller. The device was designed, realized and tested, confirming its effectiveness particularly in the case of piezoelectric elements in configuration *b*. That system, in fact, inhibits the frost deposit on evaporator fins during chiller operation and consequently allows to increase the period between two consecutive traditional defrosting phases, currently no greater than 6 hours. Therefore a significant improvement in the state of preservation of goods can be obtained; it must be noted, in fact, that at every traditional defrosting phase the chiller compressor is shut down with an increase in temperature inside the cooled vane. Moreover the defrosting system is compatible with all refrigerator characteristic; in particular the device does not produce audible noise and does not affect the quality of the air forced in the cooled vane.

Furthermore the defrosting effect is optimized by tuning the operational frequency according to the frost deposit mass.

In the next future the optimal supply voltage level for the mosfet drains will be determined and consequently the supply circuit will be implemented. The last step will be the microcontroller programming.

ACKNOWLEDGMENTS

The present study was realized in collaboration with ISA S.p.A.. In particular the authors would like to thank Ing. Stefano Menghini and Ing. Stefano Musto.

Prof. Luca Roselli – Dipartimento di Ingegneria Elettronica e dell'Informazione – and Prof. Federico Rossi – Dipartimento di Ingegneria Industriale – for their great contribution to this work are also acknowledged.

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