AN EXPERIMENTAL REFRIGERATOR WITH AN INVERSE AIR CYCLE FOR FREEZING IQF FOOD PRODUCTS

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INTRODUCTION

As part of research and tests on new refrigeration technologies for applications in the food industry, this study considered a prototype machine working on an air cycle. Coupled with a closed rotary freezer, this machine is designed for preparing individually quick frozen (IQF) products.
There is nothing new in a refrigerator that uses air as its operational fluid, though the only applications to date have concerned air conditioning systems, particularly in trains and airplanes, which demand compact, safe, low- maintenance systems.
The increasing investments in this type of machine, prompted mainly by the need to safeguard the environment, and advances made in the materials and manufacturing methods used for the heat exchangers (particularly the regenerative types, fundamental for air cycles) and turbo machines, have made it possible to reach the very low working temperatures, even lower than -80°C, needed to freeze foodstuffs.
The purpose of the present study was to characterize the refrigerator so as to assess its performance and potential in a wider context, such as the food industry.

1. THE AIRS 50 REFRIGERATOR

In addition to being extremely safe, the air-type refrigerator is also a cost-effective alternative to the traditional refrigerator used in the commercial setting. Not only does the use of air not only makes the process completely safe (because it does not affect the organoleptic properties of the foods), but air is also a far cheaper refrigerant than those used in cryogenic systems (liquid nitrogen and CO_2), so it has a negligible influence on the final price of the product.
Figure 1 shows the refrigerator installed at the refrigeration technology laboratory of the Department of Energetics at the Polytechnic University of the Marche (Ancona, Italy).

Figure 1 – AIRS 50

The AIRS (Air Cycle Refrigerant System) 50 was built by the Japanese Earthship Co; it uses a Brayton-Joule double-compression inverse air cycle with intermediate refrigeration and inside regeneration. Its main components include:

- 1^{st} stage compressor
- 1^{st} heat exchanger
- 2^{nd} stage compressor
- 2^{nd} heat exchanger
- high-pressure side regenerative heat exchanger
- turbine
- ice trap
- user
- low-pressure side regenerative heat exchanger

The machine has a bypass valve. When it is open, the air circulates only in the machine's circuit and not in the rotary freezer: this keeps the machine constantly at a low temperature (around -75°C), while allowing for the rotary freezer to be inspected, with a rapid return to normal operating conditions. Figure 2 shows the AIRS machine's functional diagram, while figure 3 shows the corresponding cycle on a T-s plane.
With the enthalpy values given in table 1, the thermodynamic COP of the cycle can be calculated:

$$COP_t = \frac{h_8 - h_7}{h_2 - h_1} = 0.718$$

The real COP is a good deal lower, however, since a cooling power of around 15 kW is developed against an electric power absorption of 28 kW.

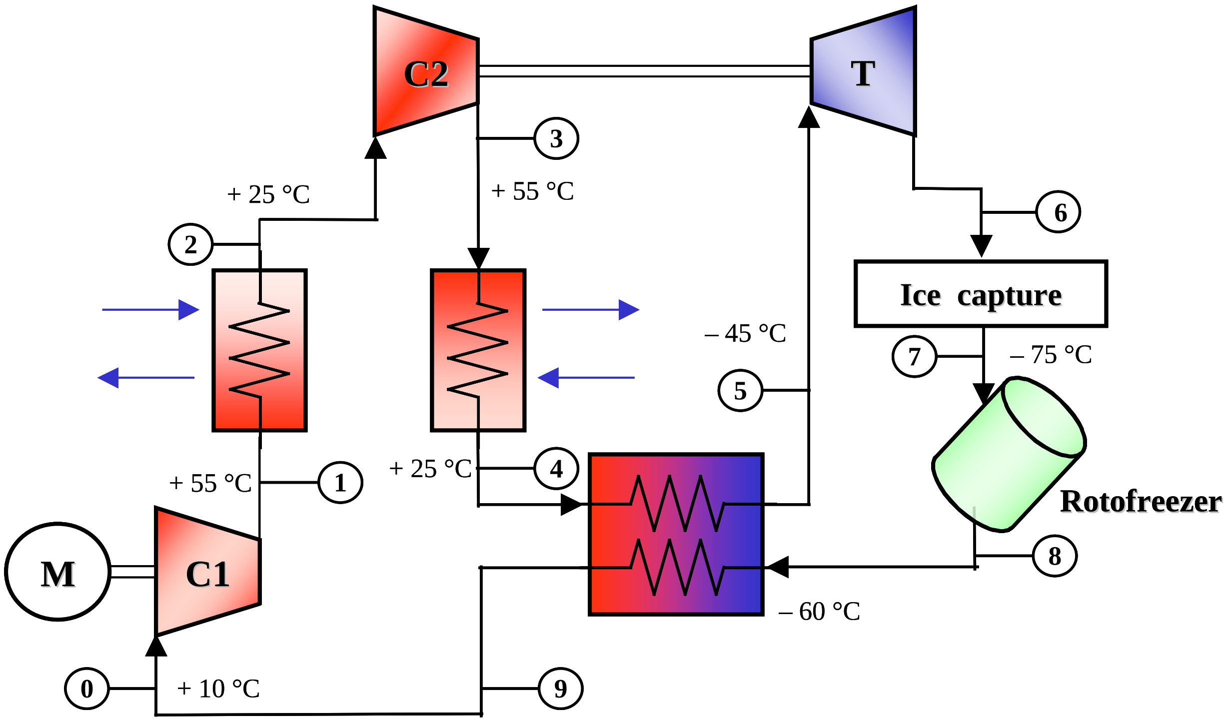

Figure 2 –AIRS functional diagram

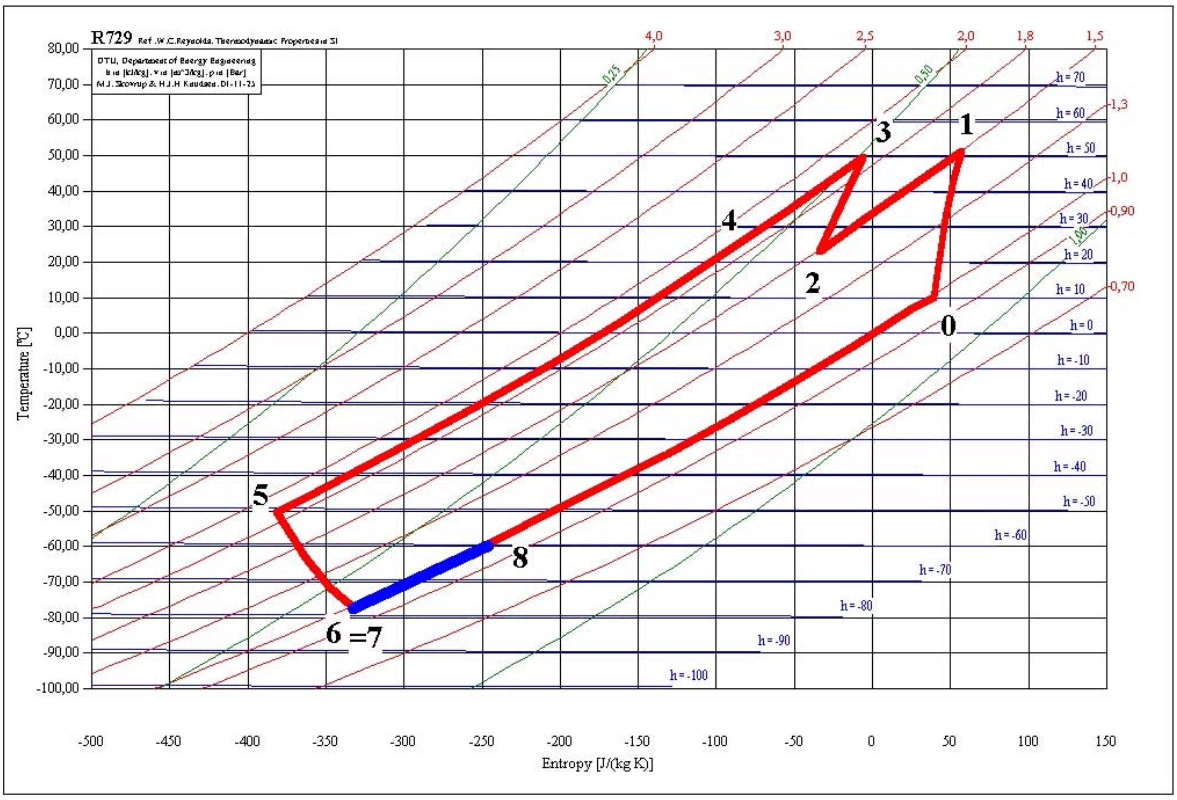

Figure 3 – T-s diagram

Point in cycle	Temperature [°C]	Pressure [MPa]	Enthalpy [kJ kg^{-1}]	Entropy [J kg^{-1} K^{-1}]
1	30	0.1	532.20	3961.46
2	65	0.14	567.48	3975.02
3	40	0.14	542.21	3897.39
4	70	0.18	572.47	3917.52
5	40	0.18	542.13	3825.00
6	-25	0.18	476.46	3589.92
7	-55	0.1	446.36	3629.52
8	-30	0.1	471.68	3739.00

Table 1 – Reference states for the cycle in figure 2

2. PRELIMINARY ASSESSMENTS

Pressure and temperature measurements were taken at each of the points shown in figure 1. A nozzle-type Venturi meter was inserted around 3 m from the machine's delivery outlet, where the flow can be roughly assumed to be non-turbulent, to enable air flow rate measurements. This parameter is one of the most important in that it enables the flow of air into the rotary freezer to be monitored. Figure 4 shows the trend of the air flow rate as a function of the temperature.

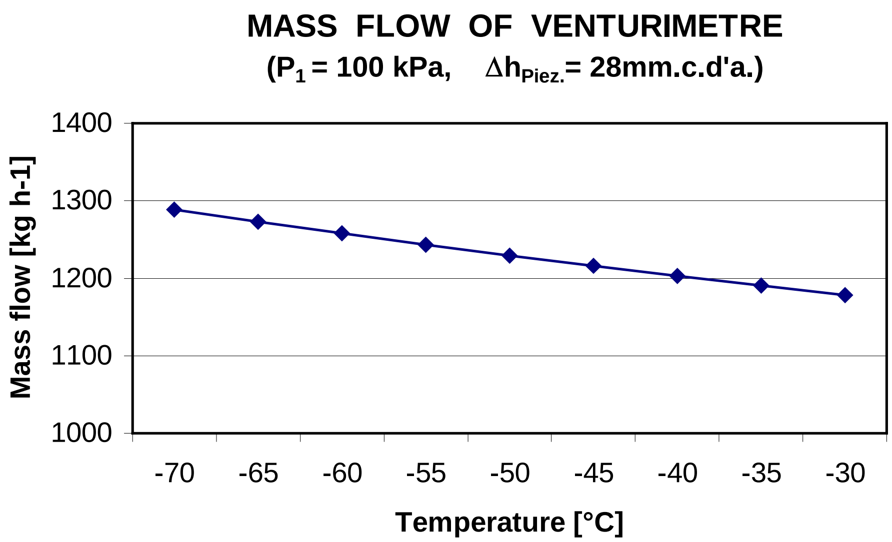

Figure 4 – Air flow rate in relation to temperature

The temperatures at the rotary freezer's inlet and outlet were also measured, revealing the trends shown in figure 5.

Heat gains were assessed through the connection circuit and in the rotary freezer since they constitute an additional thermal load that the air has to remove (figure 6).

The thermal loads were determined assuming a constant temperature of the air inside the ducts (amounting to -80°C) and in the outside environment (23°C), and negligible variations in the cross section of the pipes. Tables 2 and 3 show the thermal loads of all the sections subject to heat gains and the thermal loads for the various components. The sum of the thermal loads considered was around 2.34 kW.

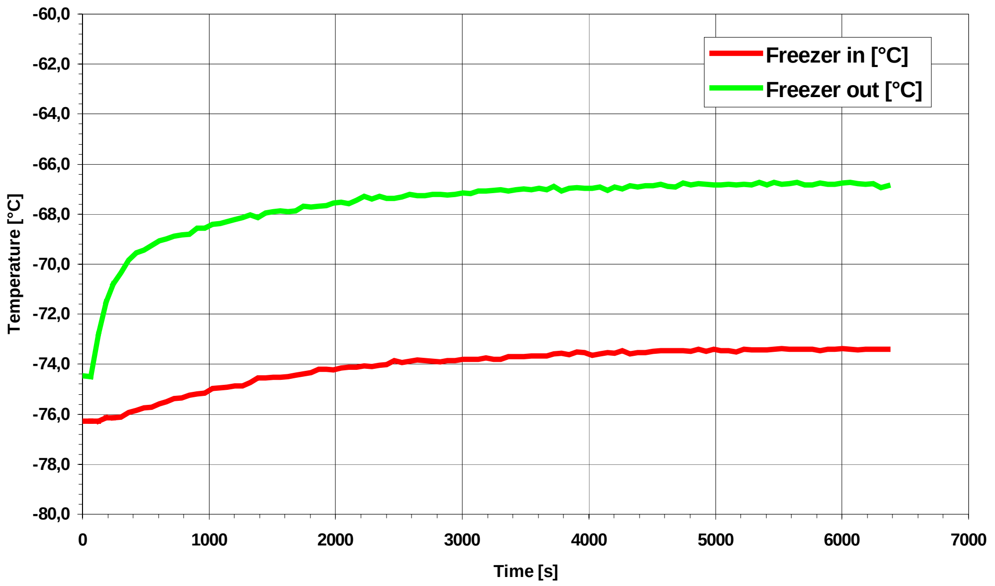

Figure 5 – Trend of temperatures at rotary freezer inlet and outlet

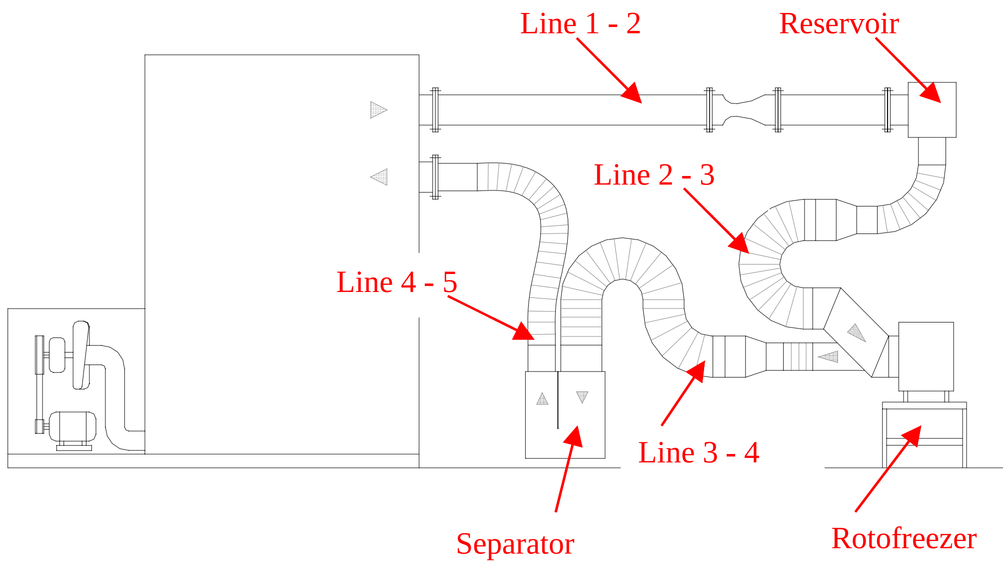

Figure 6 – Sections liable to heat gains

Line	**Length** [mm]	**R$_{in}$** [mm]	**R$_{ext}$** [mm]	**T$_{in}$** [°C]	**T$_{ext}$** [°C]	**Thermal load** [kW]
1 - 2	3460	109	160	-75	23	0.222027986
2 - 3	3560	100	132	-75	23	0.315825232
3 - 4	2700	125	157	-75	23	0.291759005
4 - 5	3300	100	132	-75	23	0.292759344

Table 2 – Thermal loads in the piping

Component	**Length** [mm]	**Side** [mm]	**T$_{in}$** [°C]	**T$_{ext}$** [°C]	**Heat gain** [kW]
Reservoir	500	64	-75	23	0.082
Separator	680	32	-75	23	0.321
Rotary freezer	410	275	-75	23	0.696

Table 3 – Thermal loads in various components

3. TESTS CONDUCTED

3.1 Tests with no thermal loads

The machine's temperature reductions are shown in figure 7. The lowest temperature was reached to the turbine's outlet, where it went from ambient temperature to -82°C in 2.6 hours.

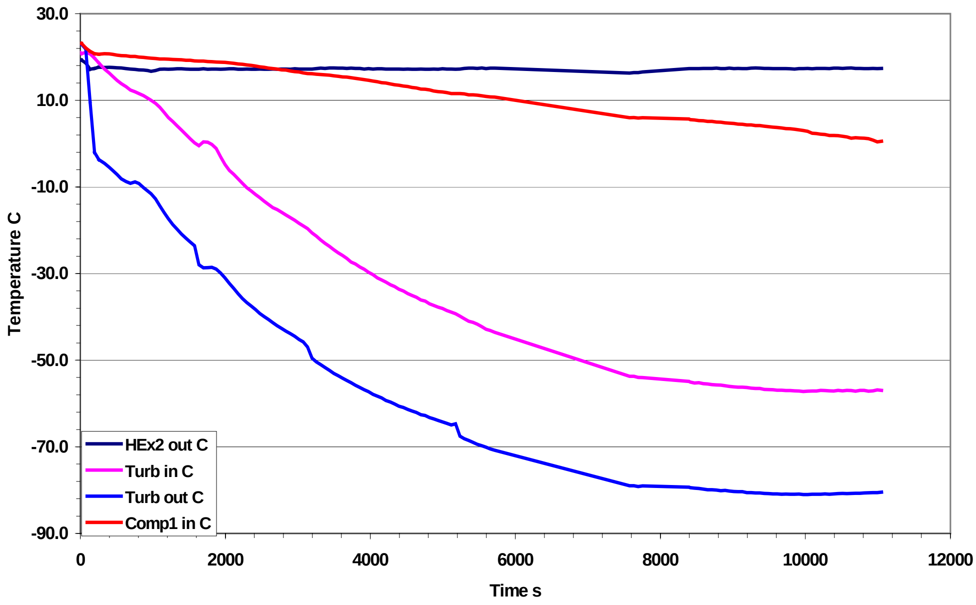

Figure 7 – Temperature reduction in the machine

The compression ratio was 1.8 for most of the test, reaching a maximum of 1.84 after 1.2 h.
Figure 8 shows the trend of the temperatures until static conditions were reached at the machine outlet (around -80°C) with the bypass open, i.e. the air was only circulating in the machine's circuit, not in the rotary freezer. After 1.7 h (6200 sec), the bypass was closed to allow the air to circulate through the rotary freezer, so the air temperature increased as a result of the thermal loads (due to the warmth of the rotary freezer and the machine's piping). From this point onwards, the air temperature began to drop again, becoming stationary 4 h after starting the system.

3.2 Tests with a sensitive load

The machine was brought from ambient temperature down to the ice capture outlet temperature, around -80°C, which is the design temperature in that it is generally the ideal condition for quick freezing food products). Then the bypass was closed to make the air circulate inside the rotary freezer.

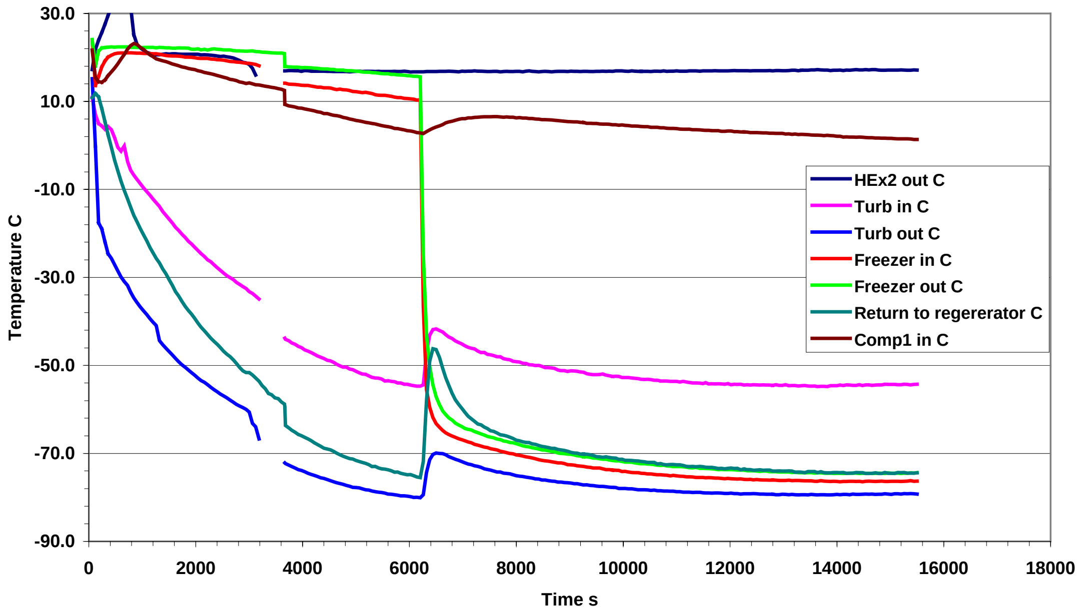

Figure 8 – Temperature trends during tests with no thermal loads

To simulate a thermal load, four approximately 1kW heating elements were placed in the rotary freezer (thus varying the thermal load between 0 and 4 kW). The four heating elements were turned on to produce a sensitive load and the temperatures were allowed to become stable. The temperature variation at each point was less than 0.2°C per hour. The thermal load simulated in the rotary freezer was given by the heat produced due to the e Joule effect, or $P_E = V\ I$ [kW]. All the measurements were recorded at 1-minute intervals.

3.3 Tests with latent and sensitive loads

To be able to simulate a genuine thermal load, it was necessary to consider both a sensitive load and a latent load, so a small steam generator was connected to the rotary freezer.
The system was initially brought from ambient temperature down to the required steady state operating temperature under no load conditions. Then the four heating elements and the steam generator were switched on to provide the required thermal load. Table 4 shows the results of one of the tests:

TEST	$\mathbf{P_e}$ [kW]	**Total heat gain** [kW]	$\mathbf{T_6}$ [°C]	$\mathbf{T_7}$ [°C]	$\mathbf{T_8}$ [°C]	$\mathbf{T_9}$ [°C]
c.d.c.	0.00	2.34	– 79.1	– 76.3	– 74.4	– 70.2
c.d.c. + 2R	2.01	4.35	– 76.1	– 73.6	– 66.9	– 62.2
c.d.c. + 3R	2.83	5.17	– 70.7	– 67.5	– 58	– 53
c.d.c. + 4R	3.96	6.30	– 68.9	– 66.2	– 55.1	– 50

Table 4 – Heat gain measurements

where: c.d.c. = thermal load of the empty circuit
P_e = dissipated electric power
T_6 = turbine outlet temperature
T_7 = rotary freezer inlet temperature
T_8 = rotary freezer outlet temperature
T_9 = low-pressure side regenerator outlet temperature

The recorded temperatures represent the steady state test conditions, i.e. the temperature values at which the process is in equilibrium between the heat developed by the heating elements and the heat removed by the air.
Figure 9 shows the trends of the temperature balance in relation to variations in the electric power dissipated in the rotary freezer.

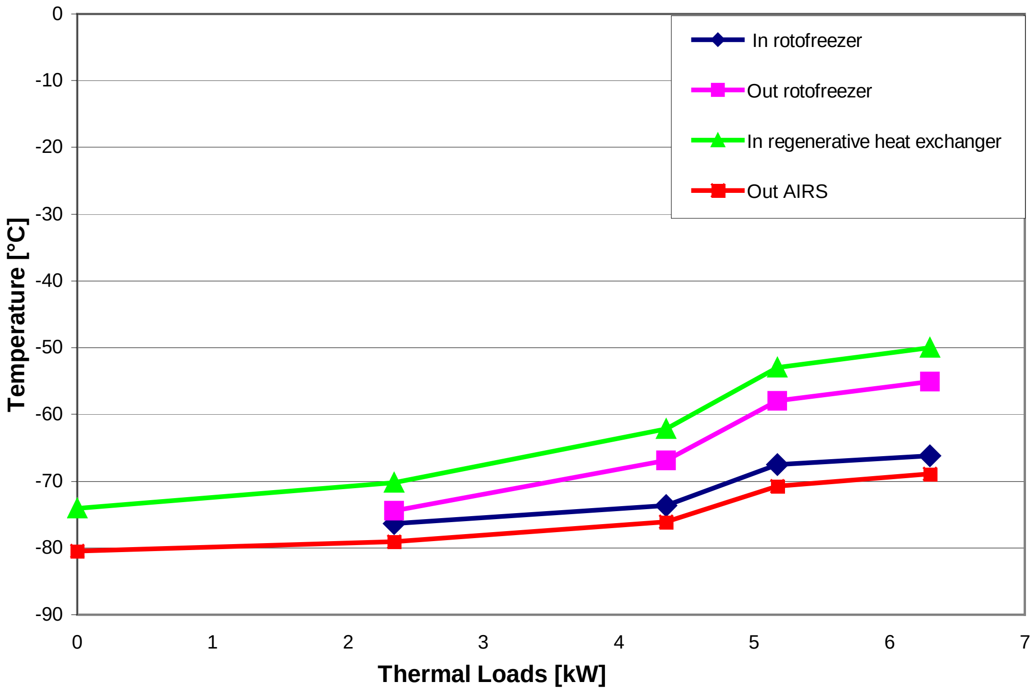

Figure 9 – Trend of the temperatures under varying thermal loads

4. CONCLUSIONS

The present study is a first step towards the development of a new freezer system using air instead of the traditional refrigerant fluids. An important part in the future of air cycle plants will be played by public opinion and, more in general, by the increasing need to use technologies with a lower environmental impact that are not hazardous to living beings.
Being highly reliable and low-maintenance, air cycles have so far been widely used in aeronautical and railway air conditioning, but the quick freezing of food products may represent a new frontier for a sector with interesting prospects.
The changing eating habits of consumers and the consequent increase in the demand for table-ready or frozen foods could prove a decisive factor in orienting more investments into freezing with air cycles, particularly because this freezing method is absolutely safe and keeps the organoleptic and nutritional properties of the products intact.
The tests conducted in this study (reaching temperatures of -80°C in less than 2.6 h) have succeeded in demonstrating the great potential of this system, given the very limited costs of freezing goods this way. The next step will concern optimizing the rotary freezer in order to improve its productivity.
We believe that air cycle systems will mark the dawn of a new food freezing technology, though further tests are needed to definitively dispel the doubts that have discouraged its use in the past.