APPLICATION OF THERMOELECTRICITY TO THE PROCESS OF CRYOCONCENTRATION OF ORANGE JUICE

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Abstract

The majority of current industry dedicated to the production of concentrated fruit juices uses conventional refrigeration cycles based on gases such as NH_3, CO_2 or CFC. These technologies have been consolidated throughout an important number of years of experience with successful results. However, the requirements of maintenance of the equipment involved, the replacement and the use of gases, etc. induce to study and propose new ways of cooling.

This paper describes the main features of a prototype of a "cryoconcentration cell" for orange juice. This development is being supported by a R&D project within the program of the CICYT, a Spanish Government Agency to promote R&D activities. A set of elemental cells working together can be conceived as an alternative to substitute the current method of cryoconcentration using the aforementioned conventional techniques.

The cryoconcentration cell uses thermoelectric elements to produce the cooling able to convert the water excess in the juice into ice that is possible to eliminate later and to concentrate the juice. The orange juice will be the hot sink in our application. The heat extracted from the orange juice will be transferred to water in circulation, which will be the cool sink.

A first prototype of this cell has been constructed in aluminium, using 16 thermoelectric elements on both main sides of the recipient that temporarily contains the juice. One of the three dimensions of this recipient is very thin compared to the other two and there are no thermoelectric elements. The thermoelectric elements are in contact with the recipient that contains the orange juice and also, are in contact with a heater interchanger with cool water in circulation.

A detailed description of this prototype, its design and some initial results obtained will be included in the paper.

Cryoconcentration of fruit juices

The contents of water in the natural fruit juices is between 85 and 90 per cent of their total volume. This high content of water suggests its elimination by the concentration of the juice. This process will save important costs of packaging, transport and storage.

The most part of these concentrated juices are type "three plus one", that is, they require the addition of three volumes of water to one volume of juice for the restoration of the original product. The degree of concentration is measured in Brix degrees. This unit indicates the contents of soluble solids of the concentrated product. For example, if three volumes of water are added to a concentrate juice of 45 ° Brix a new product of 15 ° Brix results.

Two main industrial methods exist to concentrate natural juices:

- Evaporation
  Different versions of the evaporation method exist, but in any case the water is eliminated by the addition of heat.

- Cryoconcentration
  This is the process of juice cooling till -8°C to obtain ice and fruit juice because the freezing point of this is around -12°C. The next step will be a mechanical separation of the ice from the juice.

The cryoconcentration of fruit juices has several advantages in respect to other methods, some of them are the following:

- Volatile substances are not lost like in the evaporation process. This is important to keep the taste and aroma of the juice intact.

- The fermentation and growing of patogen microorganisms is disminished.

- This process is cheaper than evaporation.

Investigation on the use of the thermoelectricity in the cryoconcentration process.

The knowledge gained concerning the cryoconcentration process of fruit juices suggested the idea to investigate the possible application of thermoelectricity. A research project with this objective was developed by the Instituto de Investigación Tecnológica (IIT) belonging to the Pontificia Comillas University. The project was a subproject within another bigger project in which the objetive was the study of new fruit concentration techniques. Three Spanich research centers collaborated: Instituto del Frío, Complutense University and IIT. IIT was in charge of the investigation concerning the application of thermoelectrical techniques. The project was supported by the CICYT, a Spanish Government Agency to promote R&D activities. This paper describes the main results of the activities developed by IIT.

The main reference of our work was obtained from the real industrial world. We visited an industry of orange juice concentration that used the cryoconcentration

technique and the process observed was used as a pattern for our investigation. The main features of this process follow.

Once the juice is obtained from the oranges, it is processed to eliminate microorganisms and put to cool. The cooling system is based on a typical NH_3 circuit with severe requirements of maintenance for its components. This system is able to cool the juice till -10° C obtaining ice and juice in the ice. The thickness of the ice is 10 mm. The next step to obtain the concentrated juice is a mechanical separation of the orange juice from the ice, using a press.

The objective of our work is the investigation of the possible substitution of the cooling system by a thermoelectric system.

Description of the cryoconcentration cell

A prototype able to demonstrate the feasibility of the thermoelectricity application was designed and built. This prototype, named cryoconcentratation cell (in short CC), was designed according to the main parameters that define the real process. They are:

- Thickness of ice produced:10 mm
- Temperature in the ice between -8° C and -11° C
- Recipient containing the juice suitable for human consumption

Additionally required to the prototype were:

- Design thinking toward an industrial use
- Modularity and interchangeability of CC
- Low cost

The CC objective is to extract heat from the orange juice till freezing its water content (not the juice) and to transfer this heat to another fluid, in the present prototype water, using a set of thermoelectric elements.

The CC operation is like a heat pump where the orange juice is the hot sink and the water used to take the heat extracted from the juice is the cool sink.

According to these requirements the CC prototype consists of three main parts: recipient to contain the orange juice, module of thermoelectric elements and heat interchanger. A descripcion of each one follows.

Recipient to contain the orange juice

This recipient has two squared parallel sides separated 10 mm to keep the orange juice there to concentrate. This separation corresponds to the thickness of ice necessary to obtain. A representation of the recipient is shown in figure 1.

The recipient was made of aluminium. This material permits a good heat transfer and is suitable to keep feeding products. The orange juice is introduced in the side A (figure 1) open to the environment and is collected moving the cover in side B by the elimination of its pressing mechanism. The aluminium plates C_1 and C_2 permit the heat transferring from the juice to the heat interchanger using the module of thermoelectric elements.

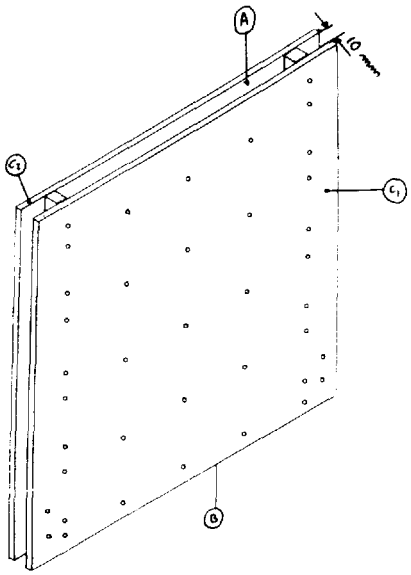

Figure 1

Module of thermoelectric elements

The CC has two modules of thermoelectric elements attached outside the recipient containing the orange juice, one to the surface of the side C_1 (figure 1) and another one to the side C_2.

These modules consist of 16 thermoelectric elements each. The physical disposition of the elements is a squared matrix of 4x4 elements equally spaced. This is shown in figure 2.

The elements are type Marlow model DT-1089. They are connected in parallel.

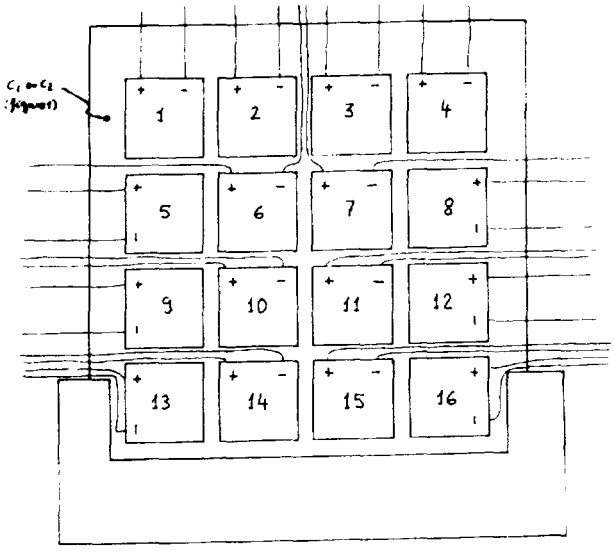

Figure 2

Heat interchanger

The heat interchanger permits the circulation of water coming from an external water network. It is made of aluminium and put in contact with the hot side of the matrix of thermoelectric elements to transfer the heat to the water.

The water flows forced and guided inside the interchanger through several channels. Although the original idea was to build these channels using aluminium bars, as shown in figure 3, the heat interchanger was finally built by mechanization of a thicker plate obtaining the same effect.

The interchanger dimension is that of the matrix of thermoelectric elements and this is fixed covering them. There are two interchangers, one for each thermoelectric module.

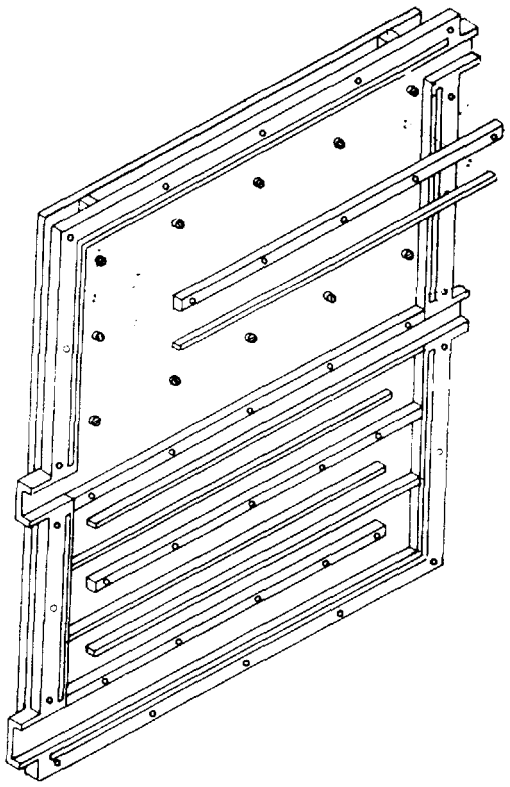

Figure 3

Several CC can be used in an industrial process working in parallel. The modular construction of the CC allows the easy change of the thermoelectric elements if it should be necessary.

The complete assembly of the CC components is shown in figure 4

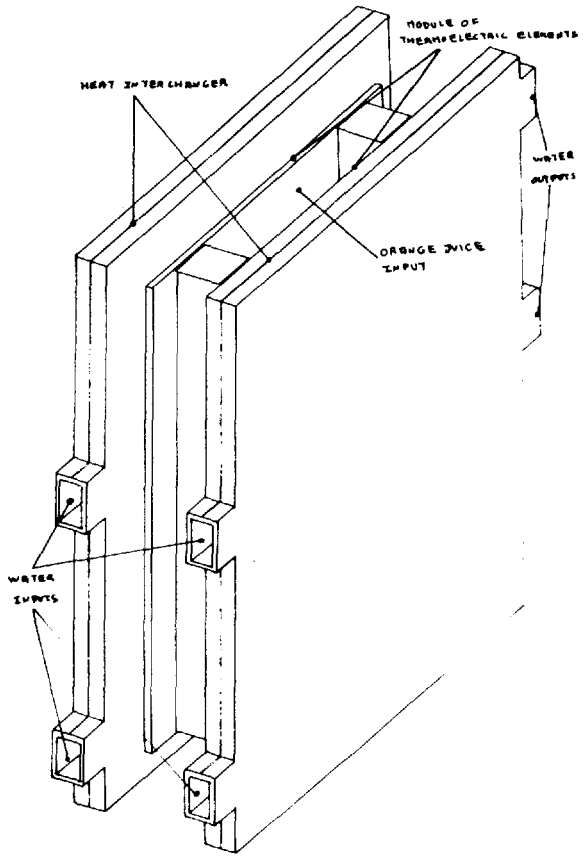

Figure 4

Electric supply and testing of the cryoconcentration cell

For the purposes of our investigation, three DC power sources of 40, 40 and 120 A supplied the 32 thermoelectric elements included in the CC. The distribution of power to the thermoelectric elements is according to the scheme presented in figure 5.

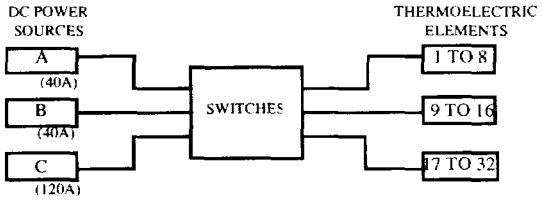

Figure 5

A complete set of computations was obtained before the construction of the CC in order to know its theoretical performance and to design it. After the construction, intensive tests were done to compare the real and calculated performance of the CC. For this objective, several sensors were intalled in the CC. These sensors measure temperatures in some of the design key points. Thermocouples type K of 2 mm thickness were used in the tests. The distribution of the sensors in the CC is shown in figure 6.

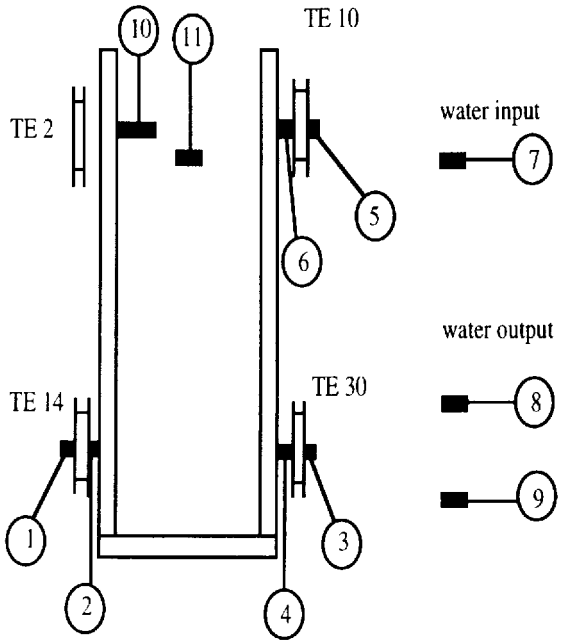

Figure 6

The description of the measurements indicated in figure 6 follows:

Thermocouple	Description
1	Hot side TE 14
2	Cool side TE 14
3	Hot side TE 30
4	Cool side TE 30
5	Hot side TE 10
6	Cool side TE 10
7	Water input
8	Water output
9	Water output (b)
10	Juice in contact wall
11	Juice in the middle

The TE (Thermoelectric Element) number 14 and 30 are on the same horizontal level on opposite sides of the recipient containing the juice. The TE 10 and 30 are on the same vertical level on the same side of the recipient containing the juice.

The thermocouples were connected to a datalogger and this to a PC. A programme running in the PC was able to automatically collect the data from the sensors.

The flow of the water circulating inside the heat interchanger was measured using a counter not connected to the datalogger.

The electrical power used was noted reading the external panel of each DC power source.

Performance tests of the cryoconcentration cell

Intensive testing has been done to know the CC performance and to compare it with the design.

The parameter most easy to change for the different tests was the DC current supplied to the thermoelectric elements.

The temperature of the water circulating inside the interchanger is fixed by the water network. The flow of the water was also difficult to control because very small flows were required in the testing and a precission flowmeter of low flow was not available.

According to these restrictions only the DC current was possible to change easily. Tests were done using 2, 2.5, 3, 4 and 5 A. A complete study and documentation of results obtained were issued. A very short description of the performance observed is shown through the use of the following figures. This example uses 3A for each thermoelectric element.

Figure 7 shows the evolution of the temperature in the hot and cool side of the element 14. Similar evolution was found for the element 10 and 30. The difference between the hot and cool side is approximately 25°C. The conditions in the minute 15 can be considered acceptable for the cryoconcentration objectives.

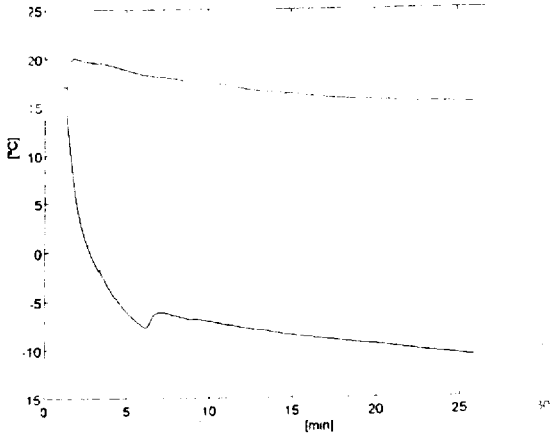

Figure 7

Figure 8 shows the evolution of the water input temperature to the interchanger and the two temperatures of water output from the interchanger. The difference of temperatures input/output is 1.6 °C. The decreasing in the input temperature and its correspondence to the output temperature is caused by cooler flowing of water coming from the water network. The output temperatures are very similar. This indicates that the interchanger is in an uniform operation in all its surface.

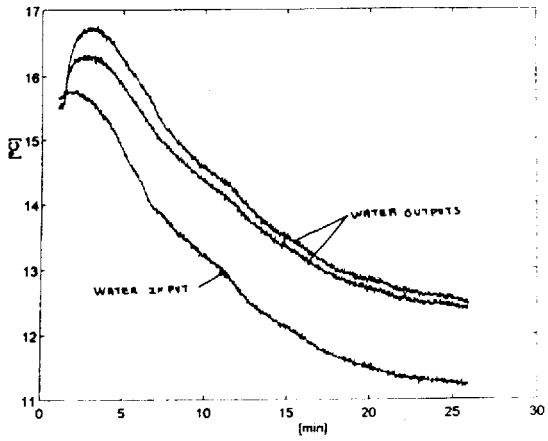

Figure 8

Figure 9 presents the evolution of the heat extracted by the interchanger through the time of test using the water input and output temperatures and the flow of water . Its stabilization point is around 900 W.

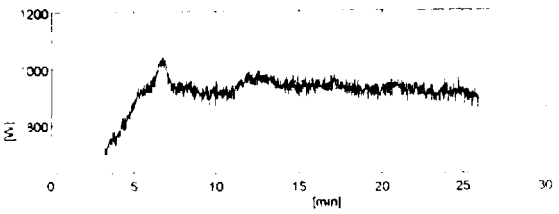

Figure 9

It is impossible to include the results of this testing phase in this paper. However, a general idea about of the CC performance could be obtained from Table 1.

This Table shows data from 4 different tests using 2, 2.5, 3 and 4 A as it is indicated in the first column. The mean of the other columns are the following:

T_{amb}: ambient temperature
F_w: water flow circulating in the interchanger
T_j: orange juice temperature in the middle of the recipient in the minute 30
T_H: average temperature in the hot side of the thermoelectric module
ΔT: average difference of temperatures between hot and cool sides of the thermoelectric module
Q_C: cooling power calculated using T_H and ΔT of the thermoelectric module
P_E: electrical power supplied
Q_H: heating power of the thermoelectric module. ($Q_H = Q_C + P_E$)
Q_I: heat extracted by the interchanger. It is calculated using input and output temperatures and flow of the circulating water
Q_J: cooling power in the juice. It is calculated by measurement of temperatures inside the juice
COP_{TE}: calculated using Q_C and P_E
COP_{CC}: calculated using Q_J and P_E

From the table can be deduced an important difference between the columns Q_J and Q_C. This is the reason of the difference between the two COP. There are several possible causes: important leakeages of juice in the recipient in the bottom side and continuous reposition of juice, not good transmission of cool to the juice and leakeages of water in the interchanger. Also, some measurement point can be unreliable. Despite these problems detected, the performance is closed to the expected and the investigation is in progress improvening mechanical aspects of the design. Now, a new prototype has been built preventing all the problems detected. Intesive testing is being done obtaining better results.

The conclussion that can be deduced of this study is that the application of thermoelectric effect in an industrial process of juice cryoconcentration is possible and positive, but more investigation is necessary to do in order to compete with the current technology.

Conclusions and future work

In this paper the investigation of a new method of cooling for the cryoconcentration of fruit juices, in this case orange juice, using thermoelectricity has been presented.

For the purpose of this investigation a prototype of "Cryoconcentration Cell" able to reach the cryoconcentration objectives has been described. Design criteria, component description, test facility and performance results have also been shown.

The performance tests have been acceptable, but more investigation must be done to transfer this technology to the industry.

At present, a new prototype of CC has been built using copper and correcting some design characteristics. Performance tests are being done obtaining good results. They will be informed in an upcoming publication.

The new prototype will use part of the DC power required for the thermoelectric elements from the sun by the use of photovoltaic modules.

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Current	Tamb	F_w	T_j	T_H	ΔT	Q_C	P_E	Q_H	Q_I	Q_J	COP_{TE}	COP_{CC}
A	°C	m/s	(min 30) °C	°C	°C	W	W	W	W	W	%	%
2	20,6	0,68	-5	16	22	200	367	567	700	137	55	37
2,5	22	0,687	-6,5	16,5	25	250	575	825	800	150,5	45	26
3	18,2	0,726	-8	16,5	29	280	836	1016	900	162	35	19,3
4	17,2	0,747	-9	19	30	460	1492	1952	1450	172	30	11,5

Table 1