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INDUSTRIAL THERMOELECTRIC COOLING IN THE KILOWATT RANGE

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ABSTRACT

A new technology using the experience obtained in the field of much larger systems, with pieces of thermoelectric material integrated into the heat exchangers, has been developed. It is based on polarised modules of type N and type P that are substitutes for the pieces of thermoelectric material of 1.5 cm^2. The principle of the polarised module is described, with its interfacing. Measured characteristics are given. A prototype unit with pieces of thermoelectric material and an analogous prototype containing polarised modules are tested and compared. Thermoelectric cooling for electronic cabinets and for air conditioning with heat rejection to water are described and performances are given.

Thermoelectric cooling in the kilowatt range for operation at 110 or 220 volts AC rectified to DC requires that the electrical current goes through small pieces of thermoelectric material with an area of a few mm^2. Thermoelectric modules containing many such couples of thermoelectric material are available commercially. The technologies used to assemble several of these large modules are not suited when more than about 4 modules are required.

Two types of thermoelectric air cooling units, one for electronic cooling, the other for air conditioning with heat rejection to water are described and performances are given. The case of water cooling for electronics with heat rejection to air is also examined.

1. THERMOELECTRIC COOLING TECHNOLOGIES

Thermoelectric cooling can be divided into 3 ranges :

- small : below several hundred watts
- medium : from several hundred watts to several kilowatts
- large : above several kilowatts.

1.1. Small range

The great majority of applications are in the small range. Modules consist of many thermoelectric couples, that are in series electrically and parallel thermally, are placed between two electrical insulators, the most common being alumina. A photograph of module CP5.31.06L manufactured by Melcor of Trenton N.J. is shown.

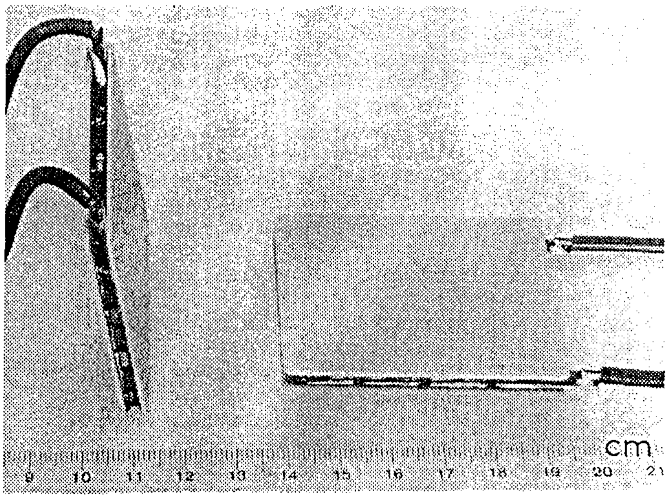


Fig1 Photograph of Melcor Module CP_5.31.06L

There are many types of modules available commercially from very small ones of fraction of a watt for cooling laser diodes, to modules with an area of 55x55 mm or more used for many cooling applications in the 30 W to 300 W range. They are used in many scientific apparatus, in air cooling units for electronic cabinets and in water coolers installed in train and picnic type coolers The technology consists of compressing the ceramic modules between flat surfaces that are part of the heat exchangers.

This technology is ideal for small units because of its simplicity. Difficulties arise when one needs to assemble more than 4 modules between 2 plates because the modules must have parallel surfaces and they must be of the same height, otherwise the ceramic and the module will be deteriorated during the tightening. It is difficult with this technique to reach pressures of 1MPa (10 atmospheres, 150 psi). Many papers have been presented on equipments using this technology[1,2,3].

1.2. Large range

Over the past 20 years three companies have studied technologies for large cooling systems with cooling powers in the range of ten kilowatts.

-York Corporation built several units for military applications, several patents were obtained but no papers were published. This activity stopped in the early 1970's.

-Westinghouse Corporation filed and obtained many patents, prototypes were built and several have been in operation for many years in the US Navy. Several papers were published on these equipments[4,5,6].
-Air Industrie in 1973 started up an important research and development program for the specific application of air conditioning passenger railway coaches[7,8,9] for units in the 5 to 30 kw range. A technology was developed that has been proven by a thermoelectric air conditioning unit on a passenger railway coach in daily operation since 1978. Since 1980 a technology for water cooling with heat rejection to water has been developed. A prototype unit with a cooling power of 15 kW (4 tons of refrigeration) has been under industrial testing since the begining of 1985[10,11]. Air conditioning with heat rejection to water is being developed[12]. The technology consists of integrating large pieces of thermoelectric material into the heat exchangers. The water circuits consist of 700 mm long tubes that are insulated from the electrical circuit and are grounded. This technology based on thermoelectric material of 1,5 cm^2 cross section operates around 150A. So it is well suited for cooling powers in excess of 15 kW, with COP (Coefficient fo Performances = cooling in W/electrical power in W) of the order of 1; The electrical power is of 15 kW and the voltage is of 100 V. This technology is not suited at all for the medium range requiring 3 kW because the voltages would be of the order of 20 V.To obtain such voltages from mains at 110 V or much more requires voluminous and heavy transformers which would have a non negligible volume compared to that of the thermoelectric unit.

1.3. Medium range

This range untill recently has not been developed for lack of a technology because neither of the 2 above technologies are suited. Air Industrie since 1981 has been developing for this range a new technology; the objective is to use small pieces of thermoelectric material of a few millimeters of cross section so that the electrical current is of several amperes (the average current density through thermoelectric material is of 1 A/mm^2). The classical way of assembling several modules between 2 flat plates is not well suited when many modules are necessary. The main problem is that it is very difficult to put sufficient pressure on the ceramic so as to have a highly reliable thermal conductance between the ceramic and the flat plat. A second problem is that of the electrical lead wires that must withstand shock and vibration tests which are a prerequisite for reliable material. In the next paragraph, a new technology will be described that solves these 2 problems. We have called it high compression module technology.

2. HIGH COMPRESSION MODULE

2.1. High Compression of ceramic thermoelectric modules

The commercially available thermoelectric modules constitute a remarkable structure. An outstanding study done at the Draper Laboratories in Cambridge Mass, was the objet of a paper by Leong and Martorana[13]. It showed how a module would tend to warp under a temperature gradient if no pressure was applied to the upper face. Experimental compression tests were done in our laboratory on thermoelectric material and on ceramic modules, where the compression force was well centered by using a spherical interface as shown below.

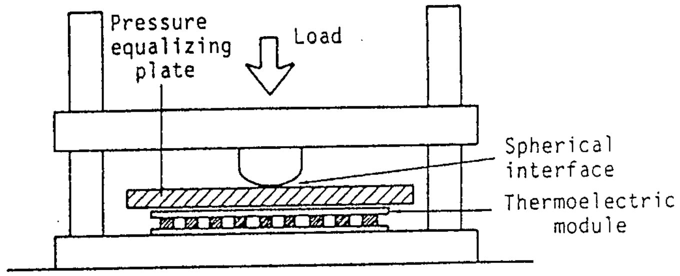


Fig. 2 Schematic of compression module

The compression results are given in Fig.3 as a function of the area of the individual pieces of thermoelectric material used in the modules. There are also other parameters that affect the maximum pressure such as :
-ratio of total thermoelectric material area to ceramic area, in general about 0.3 to 0.5.
-height of the pieces of thermoelectric material in general 1.5 mm
-structure of the module
.copper connectors between the couples
.ceramic

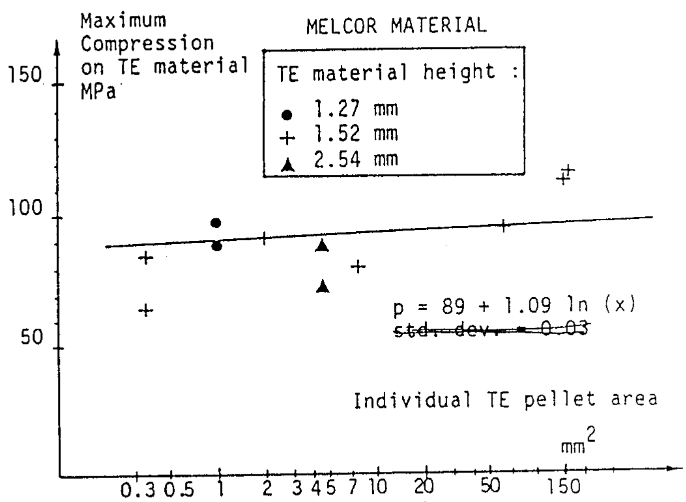


Fig.3 Maximum compression on MELCOR thermoelectric material

These tests correspond to the degradation values so a safety factor of 2 must be included which would reduce the maximum recommanded pressure on the themoelectric material to about 30 MPa. This would correspond to about 10 MPa on the ceramic external surface of the module. In practice when thightening one or more modules between flat surfaces, one only obtains pressures on the ceramics of 0.3 to 1 MPa (3 to 10 atmospheres, 45 to 150 psi).

2.2. Thermal interface resistance as a function of pressure

The thermal resistance at a flat interface between 2 materials with a thermal grease such as Dow Corning 340 or in the case of an electrically and thermally conducting silver based grease such as Elecolit 495 varies as a function of pressure.

Below 1 MPa there is considerable dispersion as shown by the striped area. Therefore pressures on the ceramic in excess of I MPa are necessary to have a stable thermal interface resistance and for structural reasons as indicated below.

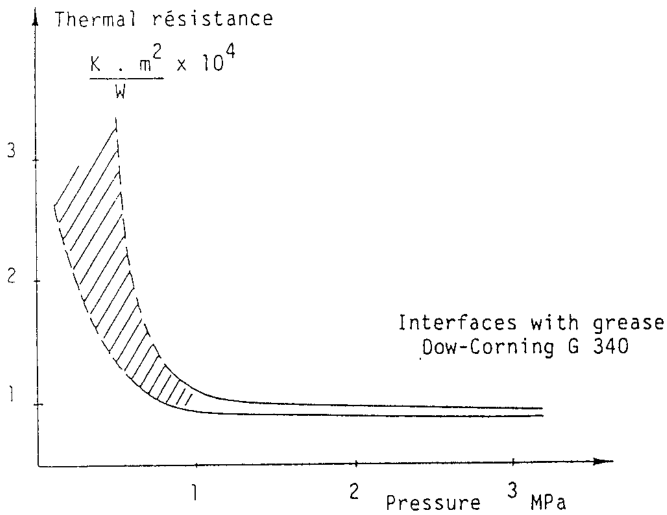


Fig.4 Thermal resistance of interface

2.3. Module structure reliability

A module under a compression of 5 to 10 MPa on the ceramic withstands well to shock and vibration tests. Prolonged thermal cycling tests are underway at the moment, to check this.

3. POLARISED MODULE

We have just shown the advantages of using modules under high compression.
We have already developed a proven technology with pieces of thermoelectric material that are integrated into the heat exchangers. Along the electrical circuit the pieces of thermoelectric material are alternately of type N and type P. A N or P type module is obtained by having an extra piece N or P in the module.

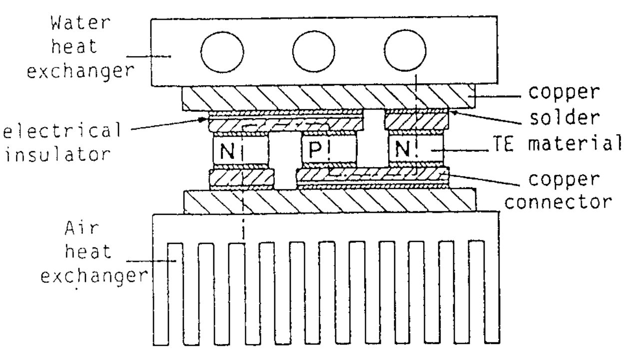
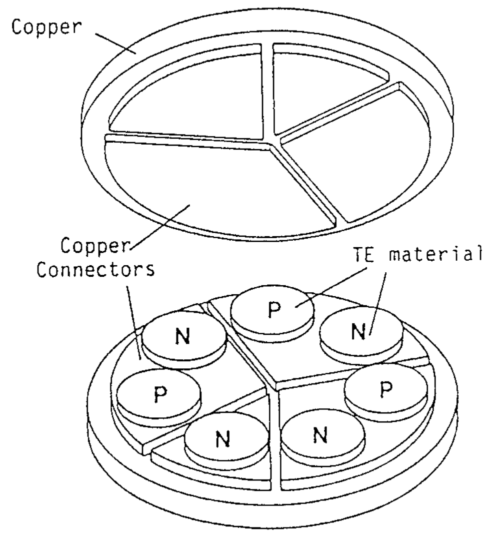


Fig.5 Schematic of a polarised module of type N containing 3 elements

3.1. Description

The idea is to replace about 1.5 cm² of thermoelectric material either N or P by an odd number of pieces of themoelectric material that are electrically in series. For a N type module the electrical current enters through a N and exits through a N. The N and P type pieces of material which are between the entrance and exit N type pieces are electrically insulated from the thermally and electrically conductive caps. A polarised thermoelectric module is a substitute for a single piece of thermoelectric material of the same type. The reasoning is analogous for a P type module. A drawing of a disc shape module is shown in Fig. 6.



Electrical insulation not shown

Fig. 6 Disc shaped polarised module

3.2. Mechanical assembly

The mechanical assembly is the same as that used in the compression module technology. The polarized module suppresses the lead wires which are a source of problem in shock and vibration tests and uses the base of the heat exchangers as electrical conductors.

3.3. Thermoelectric characteristics

Thermoelectric cooling systems that associate to each module, two heat exchangers (one on each side), require precise mathematical modelling. Models have been presented[12,14,15] that have one piece of thermoelectric material per heat exchanger. The piece is of type N or type P and has 3 overall characteristics.

- S seebeck coefficient : V/K
- R electrical resistance : ohm
- C thermal conductance : W/K

These 3 characteristics are measured directly using the technique developed by A. Goudot et al.[16]. This procedure requires a thermal conductivity standard. An experimental method not requiring a thermal conductivity standard is presented by Heylen[17]. The measured values are used in the mathematical model of the thermoelectric unit.

For exemple a module with 25 pieces of thermoelectric material of 4.58 mm² each:

S = 4.75 mV/K

R = 91.3 m Ω

C = 0.108 W/K.

4. TECHNOLOGY COMPARISONS OF MEDIUM SIZE UNITS

In medium size systems the prejudice of not segmenting was schown by Buist[18]. A typical technology using large modules is shown schematically in Fig. 7 and the technology we have developped using small modules is given in Fig. 8.

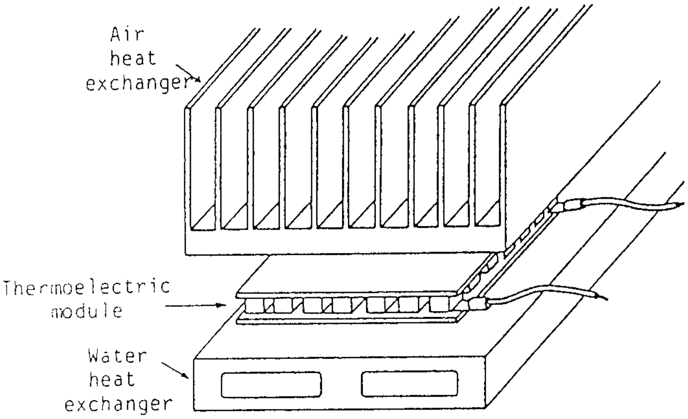


Fig. 7 Schematic exploded view of large module assembly.

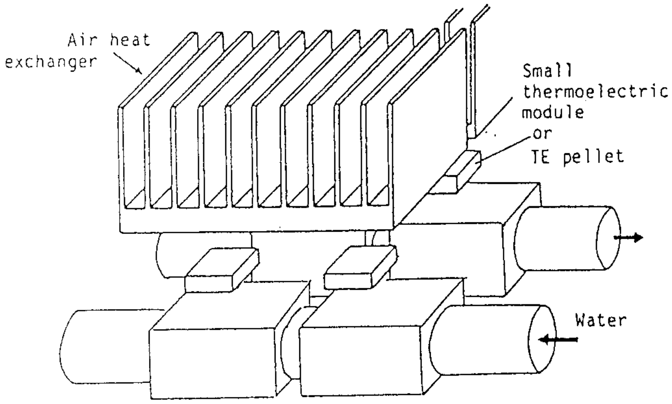


Fig. 8 Schematic exploded view of small modules or integrated pellets assembly.

The use of large modules (Fig 7) is very tempting but when one examines in details the tightening techniques when many modules are used, one encountes great difficulties to obtain a uniform pressure on the surface of the large modules, variations in pressure can crack the ceramic.
Large modules must have very flat surfaces preferably parallel.
The most important parameter which can vary between the two technologies is the thermal resistance between the interfaces of the thermoelectric module and the heat exchangers surfaces in contact with the fluids, thermal resistance calculations through the solid and overall performance calculations have shown that both technologies give very similar performances.
In the end it turns out that the technology required to obtain satisfactory robustness and reliability always prevails. Our experience confirms that both these factors are satisfied by the use of small modules.

5. PERFORMANCE COMPARISONS BETWEEN INTEGRATED T.E. MATERIAL AND POLARIZED MODULE

5.1. Air cooling experimental results

An air cooling subunit with heat rejection to water was built and equiped with 240 pieces of thermoelectric material of 1.5 cm^2 of cross section.
A photograph of a subunit showing the air inlet area is given below in Fig. 9.

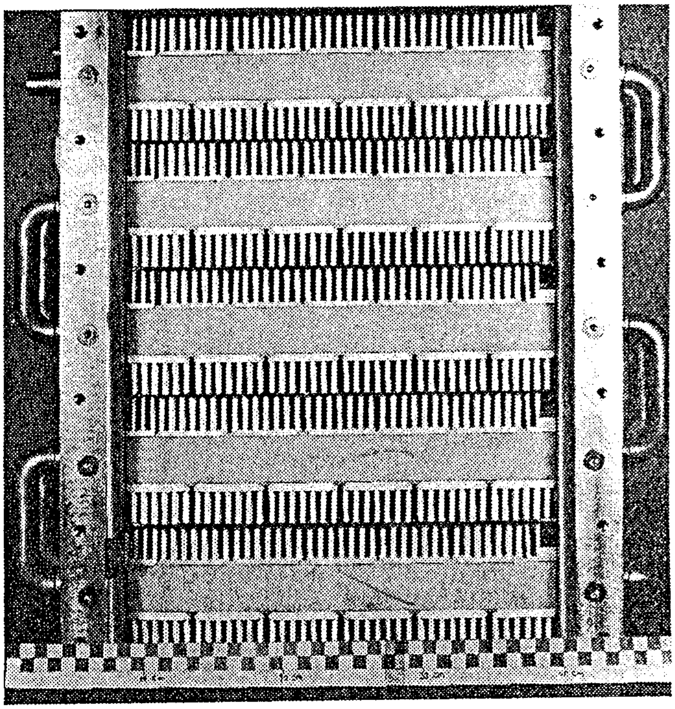


Fig. 9 Thermoelectric subunit water-to-air or air-to-water

The basic building block consists of an air heat exchanger and water heat exchanger, as shown in Fig. 8 (which shows 4 building blocks). The areas in contact with the fluids per piece of TE material are :
- air side : 178 cm^2
- water side : 6.4 cm^2

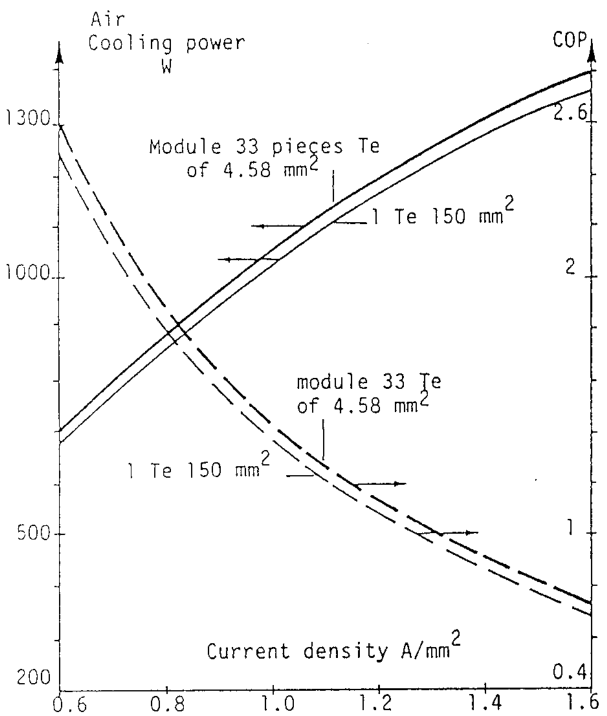
The thermoelectric material either used as single element or in polarized module has the following characteristics :
- electrical resistivity: ρ =10.14 $\mu\Omega$.m
- Seebeck coefficient :S = 189.8 μV/K
- thermal conductivity : k = 1.57 W/(m.K)

The coefficient of merit is $Z = 2.27 \times 10^{-3} K^{-1}$ which confirms that these values are very conservative.
The subunit was thouroughly tested and the results are given further along. A subunit with the same heat exchangers was equiped with 240 polarised modules. For module availability reasons the polarised modules only contain 1.145 cm^2 of thermoelectric material composed of 25 pieces of 4.58 mm^2 in area.
With the same inlet conditions (air 30° C - 50 % RH, water inlet temperature 30° C) the performances are give below :

	Units	Integrated TE materiel	Polarised modules
Current density	A/mm2	0.8	0.8
Voltage	V	4.1	96.4
Electrical power	W	487	353
Cooling power	W	877	742
COP	–	1.80	2.1

The unit with polarized module has a smaller cooling power because it has less thermoelectric material. Obviously the voltage of the polarized module is considerably higher (96.4 volts) instead of 4.1 volts with single thermoelements. Several sets of measurements similar to the ones above have enabled us to check our thermal model.

5.2. <u>Air cooling performance comparison</u>
The calculations are done on the same unit as above.
Calculations are based on the fact that we have characterized in the same way the pieces of TE material and the polarized module using the procedure indicated in 3.3. Having measured the overall values : electrical resistance R, Seebeck S and thermal conductance C and knowing the number of, and the dimensions of the pieces of thermoelectric material, one calculate the



Air inlet conditions : 30° C 50 % RH
flow rate = 0.48 kg/s
Water inlet conditions : 30° C
flow rate = 0.5 kg/s.

Fig. 10 Subunit performances as function of current density for single TE pellet and for 33 TE module.

material properties : electrical resistivity ρ , Seebeck per couple s and thermal conductivity k. In the case of modules, these calculated values integrate the thermal resistance of the ceramic and the electrical connections inside the module The results of the calculations using the same values of ρ , s and k for a unit with single elements and for one with polarized modules, each containing 33 elements are given in Fig. 10, where the cooling power Fc and the COP are plotted versus current density.
The curves show that the polarized modules give slighty better results. The only explanation comes from the reduction of Joule heating due to parasite electrical resistances because the electrical current through polarized module has been divided by a factor of 33.
At a COP = 1.5 the polarized module give 5 % more cooling power than the single thermoelements.
In practice units with polarized module can have parisite resistances which are higher than with single elements because the electrical current is much less.

6. <u>INDUSTRIAL AIR COOLING UNIT</u>

Using a mathematical model already written by J. BUFFET and experimental measurements done on : air and water exchangers, polarized modules and thermoelectric pieces of 1.5 cm² has enabled us to design a thermoelectric subunit.
The subunit corresponds to the unit previously described. It contains 240 polarized module with 33 elements of 4.58 mm². The air goes through two rows of heat exchangers (each one associated to a polarized module).
This subunit can be assembled either in serie or in parallel on the air circuit. For the following applications the water circuits are in series.

Calculations for very different applications using the same subunits give certain results which show that the units are not optimized for the applications. Nevertheless, the results are used as basis for comparison.

6.1. <u>Electronic air cooling with heat rejection to water</u>
The overall unit dimensions are :
480 x 510 x 170 mm
This unit consists of a single subunit.
The operating voltage is 110 V.DC obtained directly from AC grid without a transformer.
The performances are given in Figure 11 (next page) as a function of inlet water temperature.

The cooling power can be increased in two ways :
One method is to increase the number of rows of air heat exchangers along the air circuit. This method is limited if one excludes any condensation because the dew point can be reached by the base of the fins. The other method is to put several units in parallel on the air circuit, the water circuit can be either is serie or in parallel.
This technology leads to a range of equipments from 500 W to several kilowatts of cooling.

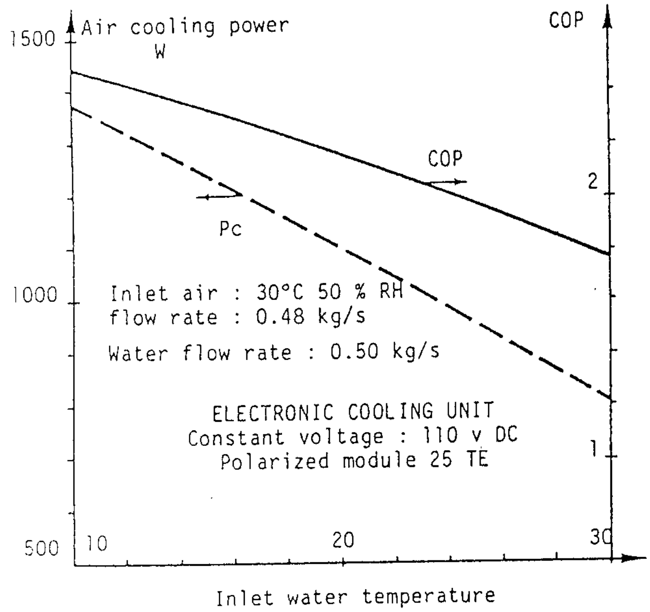


Fig. 11 Performances of electronic air cooling subunit.

6.2. Water cooling for electronics with heat rejection to air

Electronic cabinets generally have a water to air heat exchanger which cools the air with a chilled water circuit. In some cases it is interesting to replace a centralized chilled water loop with a thermoelectric water chiller (with heat rejection to air) per cabinet or per group of cabinets.
We have calculated the performances of a unit consisting of 3 subunits in series on the air circuit.

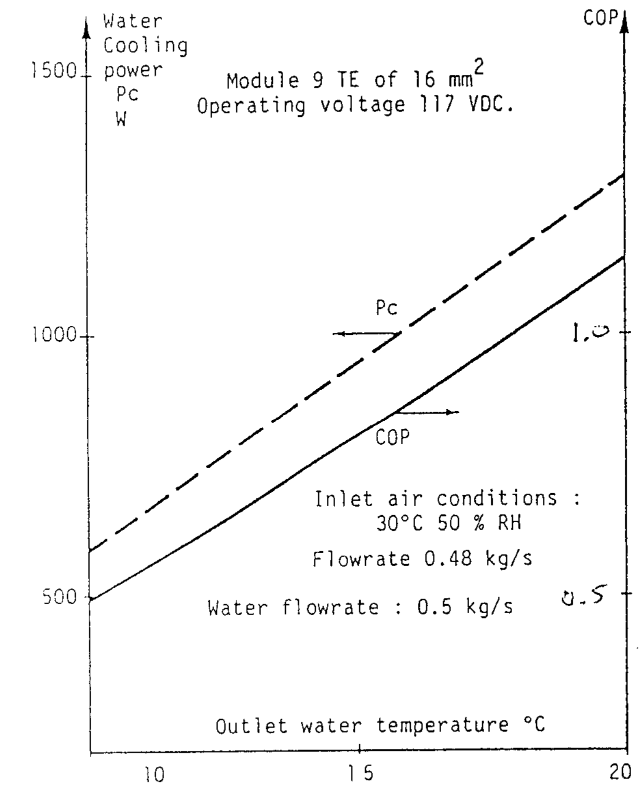


Fig.12 Electronic water cooling unit. (with 3 subunits)

The overall dimensions are :
- length along the air circuit : 340 mm comprising 6 heat exchangers instead of 2 for the previous unit used for cooling air
- the two other dimensions are unchanged 480 x 510 mm.

This unit has not been optimized for water cooling with heat rejection to air, nevertheless it gives a general indication of the performances which are obviously below those of the optimized unit. The cooling power Pc and COP are given as a function of outlet water temperature in Fig. 12.
The plot shows how the cooling power and COP vary tremendously with the outlet water temperature.

6.3. Air conditioning with heat rejection to water

Four of the subunits presented in paragraph 5.1 are assembled in series on the air circuit and in series on the water circuit.
The overall dimensions are :
air inlet section : 480 x 510 mm
depth along the air circuit : 460 mm
The unit is equipped with 960 polarized modules, each one containing 15 elements of 10 mm².
The unit has been calculated for the following operating conditions :
air inlet conditions : 26°C 50 % RH
air flow rate : 0.48 kg/s
water flow rate : 0.50 kg/s
constant voltage : 220 V.

Should one wish to operate at 110 V, then two of the subunits should be connected in series electrically and likewise for the other two, this constitues a series-parallel electrical assembly that will operate at 110 V. The cooling power and COP as a function of the inlet water temperature are given below.

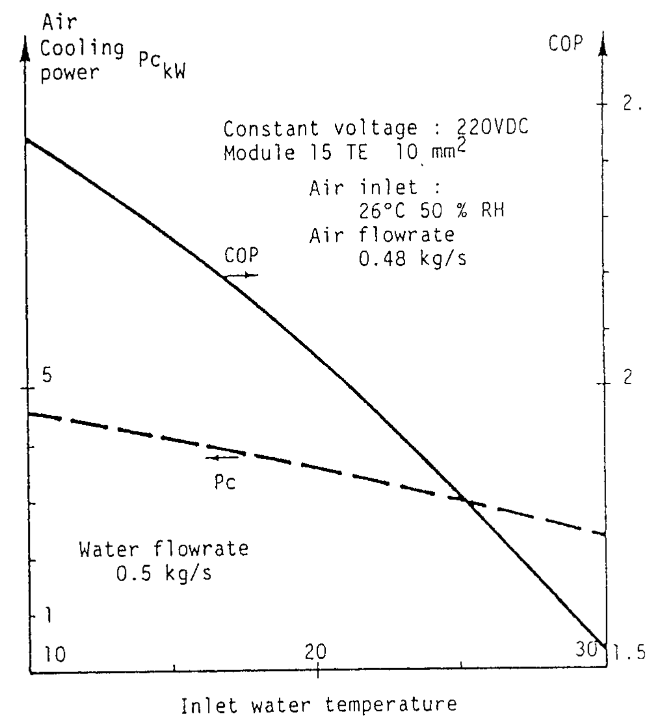


Fig.13 Performances of air conditioning unit with heat rejection to water (4 subunits)

For an inlet water temperature range between 10 an 30° C, the cooling power varies from 4.6 to 2.3 kW, while the COP drops from 2.45 to 1.55. It is interesting to note that the electrical current density is in the order of 0.8 A/mm².

Like all thermoelectric heat pumps, the cooling power can be increased by increasing the electrical current density, but to the detriment of the COP which will drop considerably.

There are several ways to increase the current density to values of 1 to 1.4. A/mm², the first is to increase the voltage on the system , the second is to decrease the number of the pieces of thermoelectric material in the module, but on the condition that the amount (area) of thermoelectric material per module remains constant.

7. CONCLUSIONS

A new technology has been developed for thermoelectric cooling systems in the kilowatt range, that operates at 110 V or 220 V. Experimental results on an air-water subunit have been used to adjust a mathematical model. Units that are made of one or more subunits have been calculated for air or water electronic cooling and for air conditioning of small enclosures.

This design uses proven technologies derived from the integration of thermoelectric materials into the heat exchangers. The robustness is outstanding.

This is the first time that industrial thermoelectric cooling powers in the kilowatt range can operate directly from the electrical grid with a rectifier.

CONVERSION OF UNITS

Cooling power :
- 1 kW = 3413 Btu/h
- 1 kW = 0.284 ton of refrigeration

Flow rates :
- for water : 1 kg/s = 15.852 gpm
- for air at 30° C 50 % RH :
  1 kg/s = 1832 cfm.

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