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INDUSTRIAL THERMOELECTRIC AIR COOLING IN THE KILOWATT RANGE WITH HEAT REJECTION TO AIR

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ABSTRACT

Thermoelectric cooling in the kilowatt range of enclosures and cabinets with heat rejection to outside air is examined for available grid voltages 110 and 220 V and vehicule voltage 28 V. A technology based on building blocks consisting of a thermoelectric module with on each side an air heat exchanger is presented. The heat exchangers serve as electrical conductors for the current to go from one module to the next. The modules are alternatively of type N and of type P. The thermoelectric characterization of the thermoelectric modules is given with the mathematical modelling of cooling units. Four types of thermoelectric cross flow cooling units are presented : air conditioner, air conditioner for breathing masks, cooling drawer for electronic cabinets and add-on cooling unit for electronic cabinets.

THERMOELECTRIC air cooling units in the several hundred watt cooling range are commercially available. The technology consists of compressing several medium or large size thermoelectric modules between flat surfaces that are part of the heat exchangers. When many modules are necessary, this manner of assembly can be advantageously replaced by a technology based on building blocks with integrated polarised modules.
This new integrated polarised module technology consists of building blocks where :
1) each individual module has its own hot side and own cold side heat exchanger,
2) the heat exchangers conduct the electricity from one module to the next module, the modules being polazised alternatively of type N and of type P.
This technology is presented with its advantages and the characterization of the modules is given. The mathematical model for cross flow units is outlined and four cooling units are described and their performances are given.

1. INTEGRATED POLARISED MODULE TECHNOLOGY

This technology uses two important factors:

- the heat exchangers conduct electricity from one thermoelectric module to another
- the thermoelectric module contains an odd number of thermoelectric elements and therefore these thermoelectric modules along the electric circuit are alternately of type N or of type P. These modules are called "polarised" (1).*

1.1. THERMOELECTRIC POLARISED MODULE BUILDING BLOCK

A thermoelectric unit based on this technology contains a number of adjacent building blocks that are defined below.
A building block consists of a polarised thermoelectric module between two heat exchangers.
A schematic of such as building block is given below in Fig. 1.

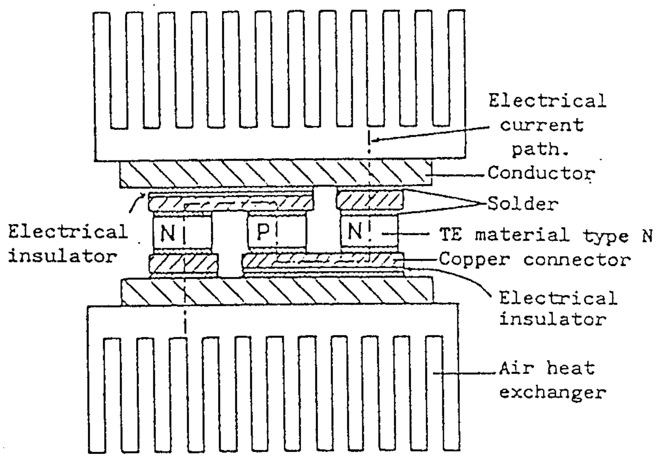

Fig. 1. - Building block with polarized module of N type (3 elements) between two air-heat exchangers

The building block is designed to include a polarised module that fits into a space of 30 x 30 x 10 mm.
The advantage of this technique is that the heat exchangers are optimised for a range of heat fluxes and for an range of operating conditions.
A photograph of a building block with pin type heat exchangers is given next page in Fig. 2.
The voltage drop across a building block depends on the size of the thermoelectric elements and their number, they are always electrically in series.

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* Numbers in parentheses designate References at the end of paper.

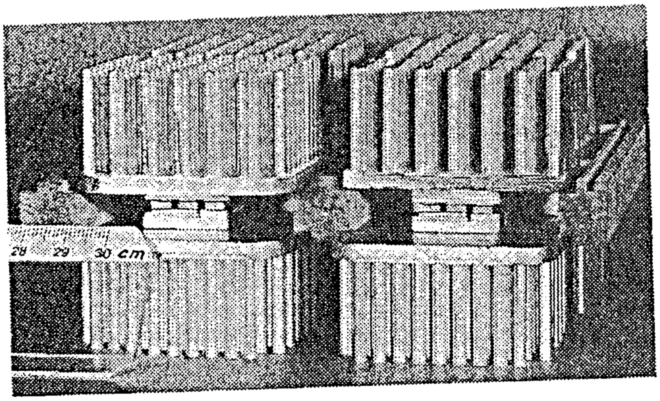

Fig. 2.- Photograph of buildings blocks with pin-type air heat exchangers

The cooling power of a building block depends in particular on the area of thermoelectric material (N*a)** in the polarized module. Most modules have a total area which is 2.5 times that of the thermoelectric material.
For typical cooling conditions, the cooling power per cm² of thermoelectric material is of the order of 2 to 3 W/cm²

1.2. COOLING UNITS

Industrial units operate generally at a constant voltage which is generally 110 or 220 V, certain military applications require for instance 28 V.
A unit for a given cooling power under a set of operating condition requires a given number of building block nb, each one requires approximately a voltage v, the overall operating voltage of the unit is therefore V = nb*v.

2.THERMOELECTRIC MODULE CHARACTERIZATION

Cooling systems consist of many building blocks.
The performance calculations require the knowledge of the module's thermoelectric characteristics. The characterization procedures of thermoelectric modules (even number of thermoelements) or polarized modules (odd number of thermoelements) are similar.

2.1. THERMOELECTRIC CHARACTERIZATION

The characterization can be approched in two ways, a detailed one or a global one.

2.1.1. Detailed methodology

The detailed methodology requires that all the components of the module :
.thermoelectric material-copper bus bars-.ceramic-interfaces,etc be characterized by:
.dimensions(m)-thermal conductivity (W(m*K)) electrical resistivity (ohm*m)-Seebeck coefficient (V/K) where relevant.
With all these characteristics a thermal model can be established that can be checked experimentally. This approach would be the one used by the designers of thermoelectric modules.

2.1.2. Global methodology

The thermoelectric mathematical model of a building block does not require all the characteristics of the detailed method. The building block model only requires the 3 overall characteristics :
- R = electrical resistance ohm
- S = Seebeck coefficient V/K
- C = thermal conductance W/K

The number N of thermoelements, their cross-section a and length ℓ .
Many characterization procedures are conceivable, two methods are presented.

2.2. PROCEDURES FOR GLOBAL CHARACTERIZATION

Two ways of measuring these characteristics are described. One is by HEYLEN (2), the other by GOUDOT et al (3).

2.2.1. Heylen method

The experimental arrangment consists of two identical modules connected in series eletrically to a power source, their cold junctions facing each other with an electrical heater sandwiched in between.
See Fig. 3 - below

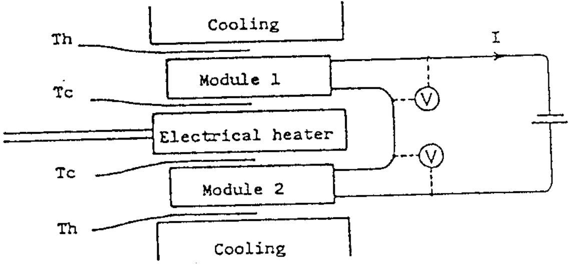

Fig. 3.- Schematic of Heylen method

-Linear equations are established which are extremelly propice for linear correlations of experimental data.
The following basic equation of the voltage drop across the module results from the Seebeck effect and ohmic effect :

$$V/I = (S*\Delta T)/I + R \qquad (1)$$

This is the equation of a straight line in the coordinate system where ΔT/I is the X axis and V/I is the Y axis.
S is the slope of the line and R the intersection of the line with the Y axis.
The cooling power equation (See Eq. (7)) gives another linear equation :

$$\frac{Pc}{I*Tc} + \frac{1}{2}\,\frac{I*R}{Tc} = \frac{-C*\Delta T}{I*Tc} + S \qquad (2)$$

that gives in a similar way C and S. The axes are :

$\frac{\Delta T}{I*Tc}$ for X axis and $\left[\frac{Pc}{I*Tc} + \frac{I*R}{2*Tc}\right]$ for Y axis
Thermoelectric characteristics depend on the material temperature, measurements are frequently done at (Th + Tc)/2 = 300 K.

2.2.2. Goudot method

This method (3) was developped to measure the thermal conductance C and the Seebeck coefficient S of large pieces of thermoelectric materials (1.5 cm²), but it is perfectly suited for the measurement of thermoelectric characteristics S and C of modules. The pieces of thermoelectric

** A Nomenclature of Symbols is at the end of paper.

material are replaced by thermoelectric modules in the set-up and the procedures are the same.
This methode measures S and C without passing any electrical current through the thermoelectric module.

2.2.3. Electrical resistance

The electrical resistance of thermoelectric material is always a delicate measurement as the electrical current generates a Seebeck voltage. Special AC ohmmeters such as : Model 1701 B, made by Electro Scientific Industries Portland Oregon, are used in the author's laboratory.
The Heylen method has led the authors to use a linear correlation method that only requires a standard DC voltameter (and ampmeter). The thermoelectric module as shown in Fig. 4 is placed between a hot and cold plate where the temperatures are measured, their temperature difference is ΔT. It is operated as a generator, the voltage and amperage through the circuit are measured.

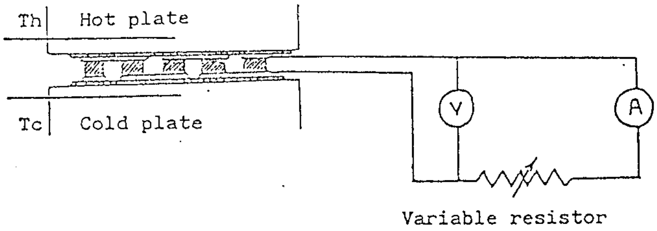

Fig. 4. - Electrical circuit for measuring S and R of module

The linear equation is :

$$V/I = (S*\Delta T)/I - R \qquad (3)$$

where $\Delta T/I$ is the X axis and V/I the Y axis. R is the ordinate at the origin and S is the slope of the line. This method has been used, to measure R but in practice the direct measurement with an AC ohmmeter is much simpler.

To conclude both methods have advantages. The Heylen method measures Joule heating (which can be accurately measured), it requires two identical modules one on each side of the heater. The Goudot method measures directly the three characteristics.

2.3. THERMOELECTRIC MATERIAL PROPERTIES

The dimensioning of thermoelectric systems that must operate at a given voltage requires modules with a number of thermoelements of a certain size. It is therefore important to know the thermoelectric material properties :

ρ : electrical resistivity ohm*m
s : Seebeck coefficient V/K
k : thermal conductivity W/(m*k)

To relate the thermoelectric material properties ρ, s and k to the global module's characteristics R, S and C, it is advantageous to use simplifying assumptions. The best assumption is to include the parasite electrical and thermal resistances of the module into the thermoelectric material properties.

- The temperature difference is measured at the outside interfaces of the module's ceramics but it is assumed to be at the ends of the thermoelements. This means that the calculated thermal conductivity for the thermoelectric material is less than the real value.
- The parasite electrical resistances between the thermoelements are included into the thermoelectric material resistivity, which is therefore increased.

With these two assumptions the following equations can be written :

$$R = \rho * (N*\ell)/a \qquad (4)$$
$$S = s * N \qquad (5)$$
$$C = k * (N*a)/\ell \qquad (6)$$

Where for the thermoelectric material ; ρ : electrical resistivity, s : Seebeck coefficient, k thermal conductivity. Each piece of thermoelectric material (also called thermoelement) has a cross section a, and a length ℓ. N is the number of thermoelements per module.
R, S and C are measured, so ρ, s and k are easily calculated.

3.MODELLING

Numerous papers have been presented on the subject of modelling cross flow thermoelectric cooling (4), (5), (6).
We shall examine the modelling of cooling units comprised of building blocks.
An important feature is that each thermoelectric module is associated with one hot side heat exchanger and one cold side heat exchanger.
It is very revealing to formulate for a building block the cooling power of the thermoelectric module in terms of ρ, s and k and N, a, ℓ and also the current density

$$J = I/a$$

$$Pc = S*I*Tc - \tfrac{1}{2} R*I^2 - C(\Delta T) \qquad (7)$$

$$Pc=(N*a)*s*J*Tc-\tfrac{1}{2}(N*a)*\ell*\rho*J^2-(N*a)*k*\Delta T$$
$$\text{with } \Delta T = Th - Tc \qquad (8)$$

Equation (8) shows that the cooling power Pc is a linear function of the product A=N*a, when the other parameters are kept constant. This means that two modules operating at the same current density J with the same total area of thermoelectric material (N*a), the other parameters being constant, give the same cooling power. The coefficient of performance COP is also the same.
A given heat exchanger base plate size is designed to transmit a cooling power that is produced by a given area of thermoelectric material. On the condition that the current density J and the product (N*a) are constant, one can modify, N and a to obtain the required voltage.

$$V = nb*v = nb*N * [s*(Th-Tc) + \rho*\ell*J] \qquad (9)$$

The number of building blocks nb depends on the flow rates and the cooling power required. Equation (8) enables one to determine the number N of elements per thermoelectric module, the area a of each thermoelement being a = A/N.

Our mathematical model calculates the performances of a thermoelectric unit (in particular cooling power Pc, COP, outlet air temperature and humidity ratio on the cold side and the operating voltage).

4.THERMOELECTRIC EQUIPMENTS

Four types of equipments are presented. One is for air-conditioning of an enclosure and one is for the air conditioning of breathing masks and two of them are for electronic cooling.

Our standard cross flow building block consists of heat exchangers with a base plate of 52 * 52 mm.
A typical assembly of 6 * 4 building blocks is shown below in the photograph Fig. 5.
The heat exchangers height can be easily adapted to suit the required operating conditions. Various heat exchanger surfaces are used such as ondulated fins and pins. The above base plate dimension is suitable for thermoelectric modules with a thermoelectric material area $A = N * a = 150\ mm^2$. This area can vary slightly depending on the operating conditions.
The following material characteristics calculated from global measurements on modules of 25 thermoelements of $4.58\ mm^2$ are used in the following equipments :
ρ = 10.76 microohm * m
s = 197.5 μ V/K
k = 1.51 W/(m*K)

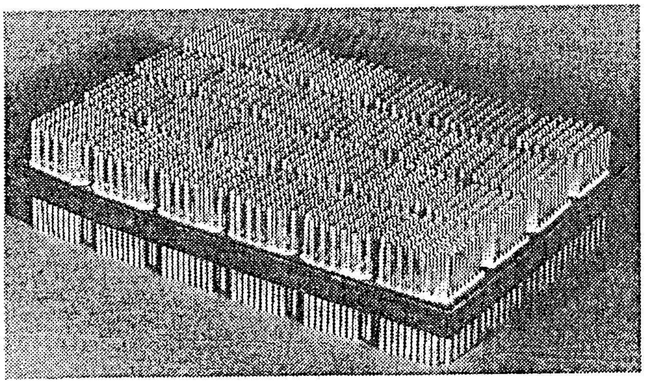

Fig. 5.- Photograph of an array of 6*4 modules

4.1. ENCLOSURE AIR-CONDITIONING UNIT

An air conditioning unit with a cooling power in the one kilowatt range is designed to operate at 220 V.
A schematic of the unit without fans is given in Fig. 6. It contains 288 buildings blocks.

The operating parameters are :
- cold side inlet conditions : 30° C 50 % RH
- cold air flow rate = 100 l/s (360 m^3/h ; 212 cfm)
- variable hot side condition are 30°C 50 % RH to 50°C, 10 % RH .The RH values are indicated below the temperatures on the X axis of Fig.7.
- hot side flow rate : 250 l/s (900 m^3/h ; 530 cfm).

The heat exchangers have a base plate of 52*52 mm, the characteristics are :
cold side heat exchanger :
7 perforated fins - fin height 30 mm

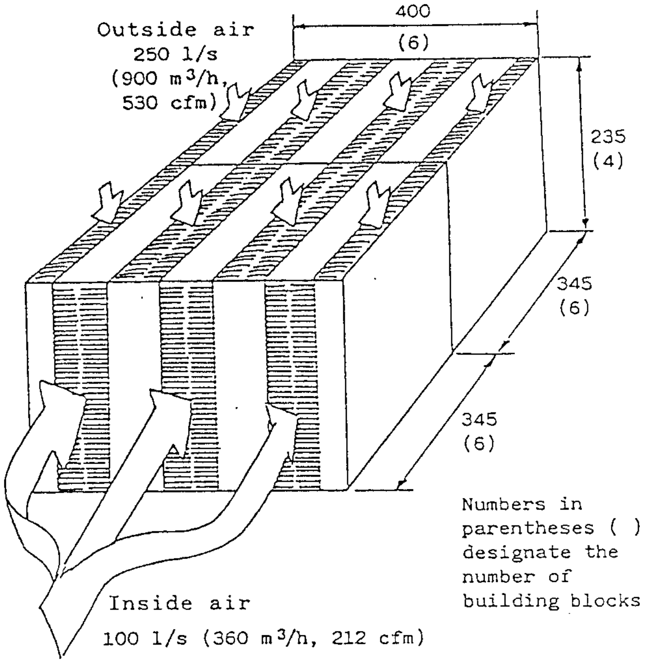

Fig. 6.- Thermoelectric air-conditioning unit

these heat exchanger are specially designed to evacuate by gravity the condensat as soon as it is formed
. air velocity (between fins) 3.9 m/s
. heat transfer coef 72 $W/(m^2 * K)$
. fin efficiency 0.71
. pressure drop 19 Pa
hot side heat exchanger :
17 fins - fin height 15 mm
. air velocity (between fins) 4.6 m/s
. heat transfer coef 60 $W/(m^2 * K)$
. fin efficiency 0.90
. pressure drop 16 Pa
The cooling power and the COP as a function of outside temperature (and relative humidity) are given in Fig. 7.

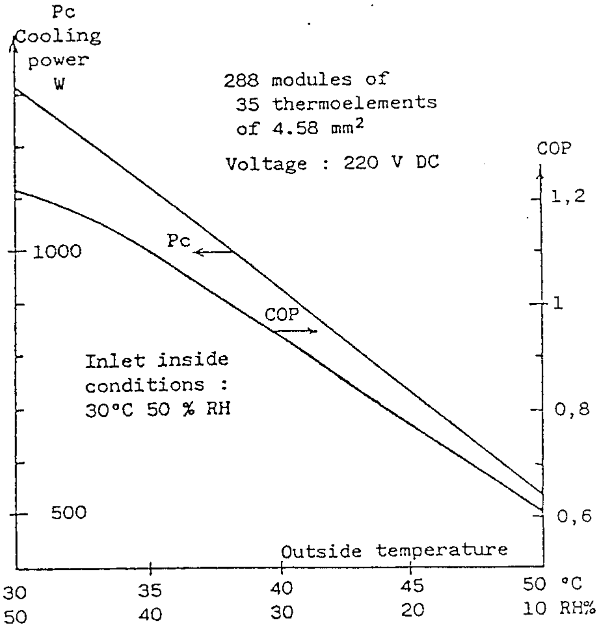

Fig. 7.- Air conditioning unit - cooling power and COP versus outside temperature

4.2. SMALL AIR CONDITIONER FOR BREATHING MASKS

A thermoelectric unit for cooling (and heating) air for breathing masks is examined. A typical cooling power range is 400 W for a cooled air flow rate of 17 l/s (60 m^3/h, 36 cfm). The cold side outlet temperature must be between confort limites such as 26° C and 32°. The unit described below has not been optimized for a given constraint such as mass, volume or power consumption.
The electrical circuit consists of two parallel circuits each containing 48 modules, the operating voltage is 28 Volts.
A schematic with the dimensions is given below in Fig. 8. It contains 96 buildings blocks.

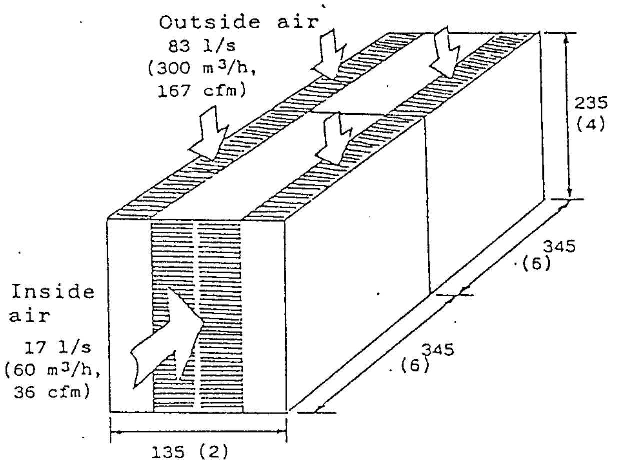

Fig. 8.- Small air conditioner for breathing masks

The chosen operating voltage is 28 V.
The heat exchangers are the same as those described in paragraph 4.1.
Cold side :
. air velocity (between fins) 1.8 m/s
. heat transfer coef 42 W/(m^3 *K)
. fin efficiency 0.80
. pressure drop 5 Pa

hot side :
. air velocity (between fins) 4.6 m/s
. heat transfer coef 60 W/(m^3 *K)
. fin efficiency 0.90
. pressure drop 16 Pa

A characteristic of the operating conditions is that the inlet cold side corresponds to the outside air conditions (no air is recycled).
The performances of the unit are given in Fig.9.

The performances are calculated for inlet air conditions (which are the same for the cold side as for the hot side) between 32° C and 55° C. Humidity influences tremendously the performances, the performance curves are obtained with a humidity ratio of 15 g of water per kg of dry air, then at 32° C the performances are calculated with 25.8 g/kg which corresponds to 85 % relative humidity. The influence of this change in humidity ratio corresponds to the shaded area for the cooling power, COP and outlet cold side temperature.

The above unit operated at 28 V is too powerful when the outside temperature is below 50° C. There are 2 ways of dropping the voltage to reduce the power, the first is to have a variable voltage supply, the other way is to construct the unit with 2 or more circuits in parallel and to have a switching device that changes parallel circuits into series circuits.
This problem is not the object of this description as it must be examined for each specific case.

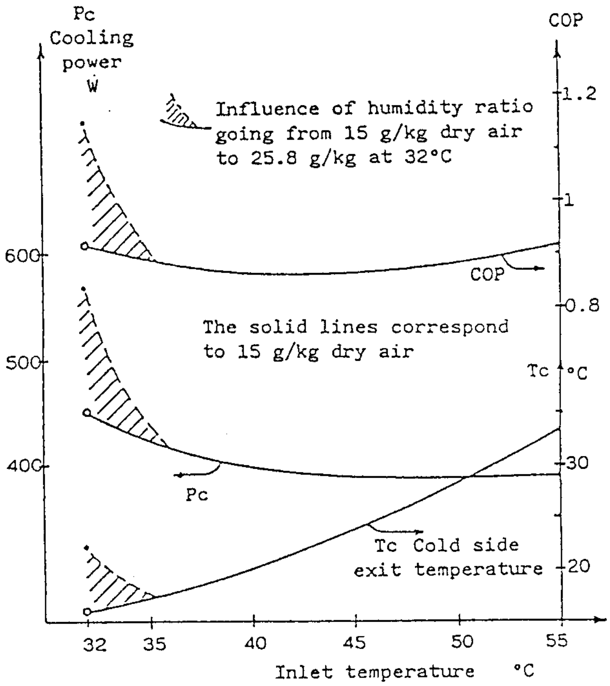

Fig. 9.- Small air conditioner for breathing masks cooling power Pc, COP and cold side exit temperature versus inlet temperature

4.3. INTEGRATED CABINET COOLING UNIT

Cooling units for electronic cabinets generally operate with a cabinet temperature higher than the outside air temperature. A unit is designed as a drawer to fit into a 19 inch rack (482 mm), the cooled air goes through the unit verticaly, the fan that moves the air through the cabinet can be placed anywhere in the cabinet. The fans for the outside air are incorporated into the front of the unit.
The operating voltage is 110 V DC, a schematic of the drawer is given in Fig.10 next page. It contains 240 buildings blocks.

The heat exchangers on each side of the thermoelectric module are dimensionnally identical
- 17 fins of height 15 mn

air inside cabinet
. velocity (between fins) 3.6 m/s
. heat transfer coefficient 54 W/(m^2 *K)
. fin efficiency 0.92
. pressure drop 11 Pa

outside air :
. velocity (between fins) 3.8 m/s
. heat transfer coefficient 52 W/(m^2 *K)
. fin efficiency 0.91
. pressure drop 12 Pa

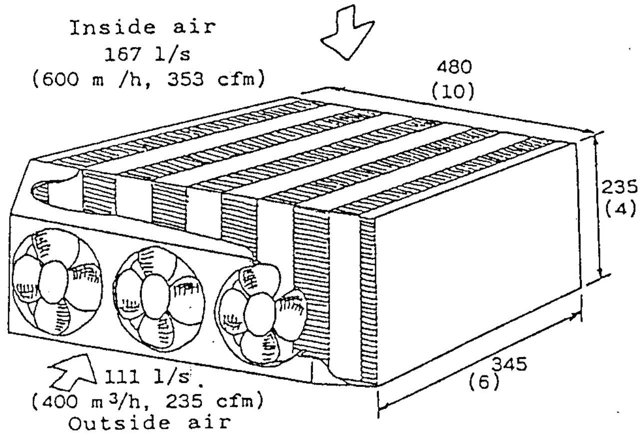

Fig. 10.- Integrated cabinet cooling unit

The performances are given below in Fig. 11.

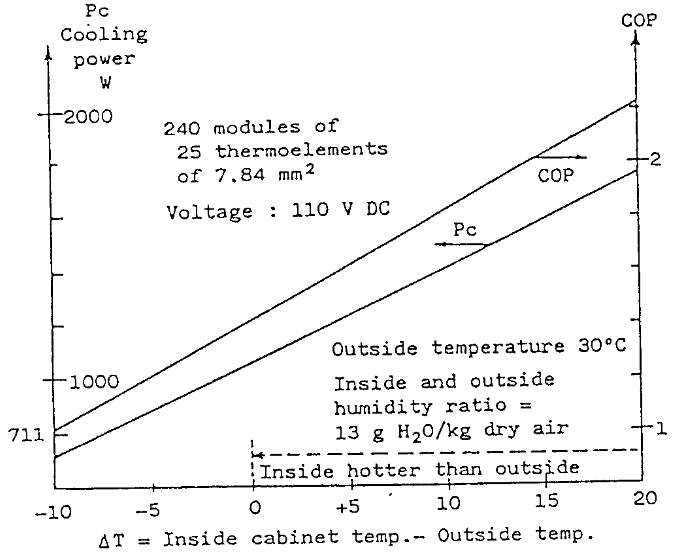

Fig. 11 Performances of thermoelectric cooling unit for integration into a cabinet

Depending on the cabinet temperature the cooling varies from 0.7 to 2 kW with a COP between 1 and 2. Positive values of ΔT (inside - outside temperature) correspond to a air in a cabinet which is hotter than the outside air In this case thermoelectrics enhances the evacuation of heat from the cabinet. These represent average performances that can be obtained from such units.

4.4. ADD-ON THERMOELECTRIC CABINET UNIT

There are many cases where a cabinet requires more cooling than initially planned. Add-on units are interesting when outside air must not go through the cabinet and when passive heat exchangers are not powerful enough.
The unit is designed to fit onto the side or the back of an electronic cabinet, it is autonomous in that it contains the fan for the inside air and for the outside air. The operating voltage is 110 V, a schematic of the unit is given in Fig. 12.
It contains 192 buildings blocks.

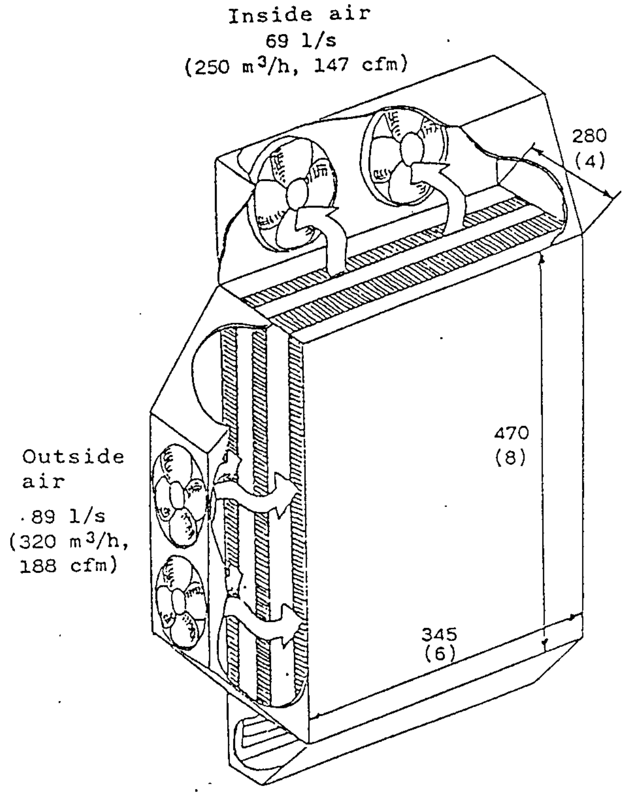

Fig. 12-Add-on thermoelectric cabinet cooling unit

The heat exchangers on each side of the thermoelectric module are the same and of the pin type, as shown in the photograph of a 6x4 array of building blocks Fig. 4. For each heat exchanger :
- 73 pins diameter 2,8 mm and height 24 mm

air inside cabinet :
. velocity (between pins) : 3.1 m/s
. heat transfer coefficient 56 $W/(m^2 *K)$
. pin efficiency : 0.93
. pressure drop : 8 Pa

outside air :
. velocity (between pins) 3.2 m/s
. heat transfer coefficient 57 $W/(m^2 *K)$
. pin efficiency : 0.93
. pressure drop 8 Pa

The performances are calculated the same way as in paragraph 4.3, they are given next page in Fig. 13.

The cooling power varies between 400 W and 1 kW, with a COP between 1 an 2.2. When space is available, units can contain more building blocks and the cooling power is increased. The COP depends essentially on the temperature difference between the cabinet air and the outside air.

5. CONCLUSION

Thermoelectric cooling units comprised of building blocks are described, this technology has proven through daily operation of several thousand building blocks over a period of 8 years, to be extremely robust to vibration and shock. This design is modular by conception.

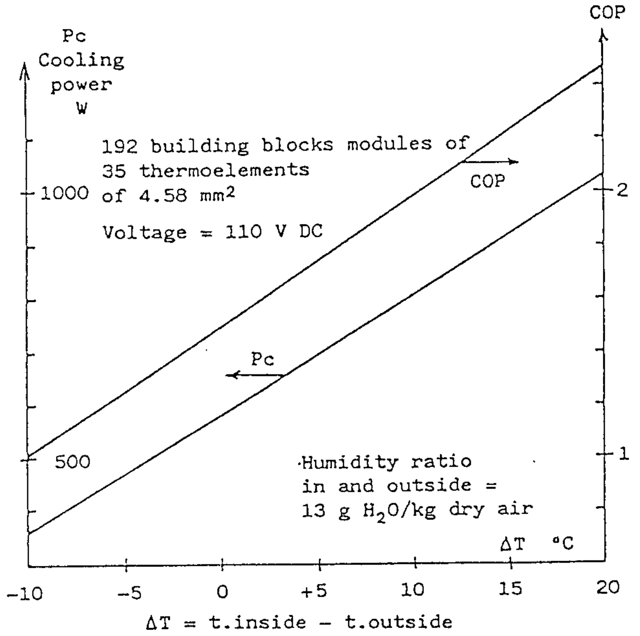

Fig. 13.- Performances of add-on thermoelectric cooling for electronic cabinet

The heat exchangers are optimized for a given cooling power range, the thermoelectric module shoud have a given area of thermoelectric material but the size and number of thermoelements can be chosen to obtain a required operating voltage.

The modularity of the design enables standard parts to be used for a wide range of cooling powers and applications, hence reducing manufacturing costs. Heat exchangers designed to evacuate condensate as it is formed, are used in all applications where there is condensation, which brings a major improvement to thermoelectric air-conditioning
This building block technology already constitutes the design for the future.

CONVERSION OF UNITS

1 l/s = 2.2 cfm
1 kw = 3413 Btu/h = 0.284 ton of refrigeration
1 Pa = 0.004 inch of H_2O
1 m/s = 196.85 ft/mn
1 W/(m^2*K) = 0.176 Btu/(h*ft^2*°F)

NOMENCLATURE

	Units	Designation
A	m^2	total thermoelectric material area per thermoelectric module = N*a
a	m^2	thermoelectric element area
C	W/K	thermal conductance of module
COP	-	Coefficient of Performance
I	A	electrical current
J	A/m^2	electrical current density
k	W/(m*K)	thermal conductivity
ℓ	m	lenght of thermoelement
N	-	number of thermoelements in series in the module
nb	-	number of building blocks = number of modules in unit
Pc	W	cooling power of a module
R	Ohm	module electrical resistance
RH	%	relative humidity in air
S	V/K	module Seebeck coefficient = N*s
s	V/K	Seebeck coefficient of TE material
Tc	°C or K	cold side temperature
Th	°C or K	hot side temperature
V	volt	voltage across a unit
v	volt	voltage across a module
ΔT	K	temperature difference across the module
ρ	ohm*m	electrical resistivity

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