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839042

INDUSTRIAL THERMOELECTRIC WATER COOLING

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ABSTRACT

A thermoelectric water cooling unit of 27 kW of cooling power is composed of 1.5 kW modular subunits ; Where the exterior heat source is a liquid, a general description is given. The performances are calculated for the following temperature ranges : 11.5 and 21.5 deg C on the cold side, and 10 to 40 deg C on the hot side, they are compared to experimental results over a range where only the hot side temperature is varied. Endurance tests consisting of start-ups, shut down and vibration tests are described. Cost estimates are given.

NOMENCLATURE

Symbol	Units	
C.O.P.	Non dim.	Coefficient of performance
g	m/s^2	Acceleration of gravity= $9.81 m/s^2$
h	$W/(m^2.K)$	Heat Transfer coefficient, between water and tube
k	W/(m.K)	Thermal conductivity
I	A	Electrical current
Q	kg/s	Fluid flow rate
r	Ω.m	Electrical resistivity
S	V/K	Seebeck coefficient
T	°C	Temperature
t(1)		Thermocouple locations numbered 1 to 6
V	m/s	Velocity of fluid
D	m	Inner diameter of tube

Indices :

c	Cooled side
h	Heated side
N	Thermoelectric material of type N
P	Thermoelectric material of type P

INTRODUCTION

A development program has led to the design of 27 kW thermoelectric water cooling units that are composed of 18 modular subunits. A subunit has been built and tested. The cooling powers measured correspond to the calculated values that used experimental values measured independantly.

1. GENERAL DESCRIPTION

A photograph of subunit without its casing is given below. The dimensions are 720 x 320 x 200mm. The technology developed consists of two independant sets of straight metallic tubes that are linked in series by 180° elbows, one set is for the heated liquid flow, the other for the cooled liquid flow. Each flow is by horizontal planes, alternatively from the bottom up there are 3 heated and 2 cooled planes of tubes. The general pattern is counter-flow.

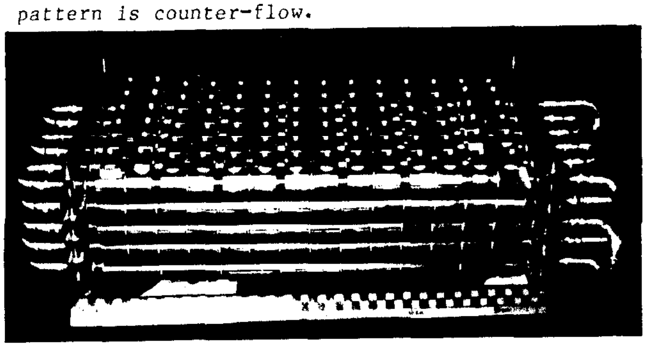

Fig.1 Subunit without casing

Along each section of straight tube are placed 14 copper pieces that transfer the thermal flux from the thermoelectric material to the metallic tubes. The tubes are grounded and are electrically insulated from the copper pieces, the electrical current goes alternatively up and down the columns as shown :

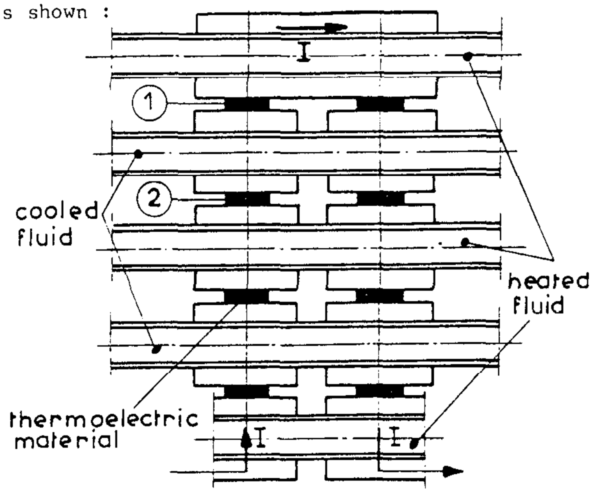

Fig. 2 Schematic of heat exchangers

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The thermoelectric material is commercialy available grade from Melcor of Trenton N.J. The subunits contain 5.04 dm^2 of material consisting of 168 couples, each pieces has an area of 1.5. cm^2 and thickness of 1.5 mm.

2. THERMAL CHARACTERISTICS

A mathematical model written for the subunit, the various thermal characteristics were measured on specific test rigs.

2.1. Thermoelectric Material

The N and P type thermoelectric materials are polycristaline and have characteristics with variations that must be taken into account. The electrical resistivity is the easiest of the 3 characteristics to measure.
The Seebeck coefficient and thermal conductivity are measured on about ten pieces of type N and of type P for a given ingot of material. The pieces were selected to obtain the maximum range of electrical resistivities. The relationships are linear in the range covered. Fig. 3 shows the relationships between the properties.

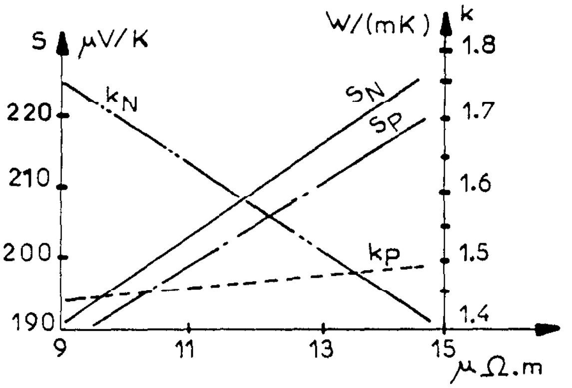

Fig. 3 Seebeck and thermal conductivity for N and P material versus electrical resistivity at 27°C.

For each type, the procedure is simple :

- electrical resistance of all the pieces are measured and the average value r(average) is calculated,
- Seebeck coefficient S and thermal conductivity are obtained from Fig 3 using r = r (average)
  This simple procedure was checked by obtaining for each piece of known r the corresponding values from Fig. 3 of thermal conductivity k and Seebeck coefficient S and calculating the average values of k and S. The results for several cases were the same as before, so the simple procedure was adopted.
  The temperature dependance factors are calculated from data given by the manufacturer.

$$r(T)=r(27)\left[1+4.72\times10^{-3}(T-27)+3.68\times10^{-6}(T-27)^2\right]$$

$$k(T)=k(27)\left[1-1.60\times10^{-3}(T-27)+4.06\times10^{-6}(T-27)^2\right]$$

$$S(T)=S(27)\left[1+1.428\times10^{-3}(T-27)\right]$$

2.2. Heat Transfer

A small test rig as shown in Fig. 4 is set up to measure heat transfer. A copper tubing with 3 bends of 180° has copper pieces on it.

The heat flux from the thermoelectric material is simulated by using copper rods that are heated by a resistance wire such as that used in soldering irons.

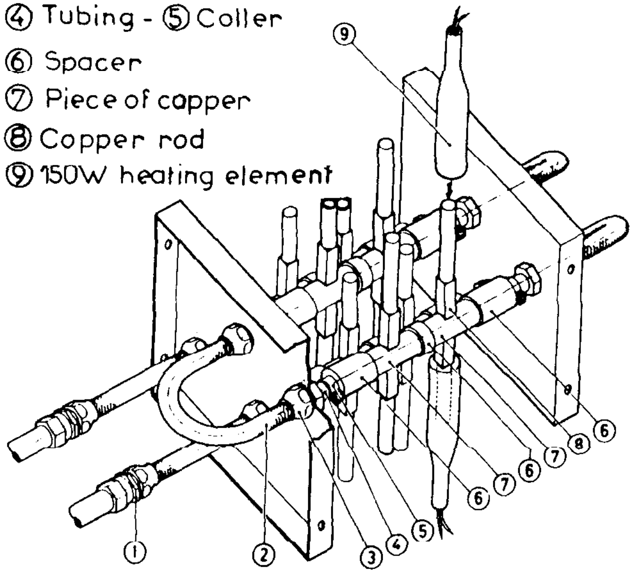

Fig. 4 Test Rig for measuring heat transfer

The heat flux from each copper rod is obtained by measuring voltage and current on each electrical resistance that is thermally insulated from the exterior.The overall heat flux is obtained by measuring the flow rate of water through the tube and its increase of temperature. Miniature thermocouples are placed as shown in Fig. 5

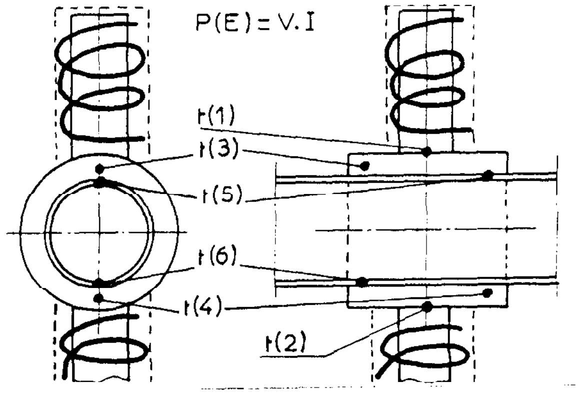

Fig.5 Detail of heat transfer rig.

- at the end of the copper rod on the axis t(1), t(2)
- in the copper blocks : several couples t(3), t(4)
- in the copper tubing t(5), t(6)

Thermocouples t(3) through t(6) are placed at a distance from the axis of the heating elements where the temperature corresponds to the average calculated temperature.
The convection coefficient was measured as a function of velocity and temperature.
function of velocity and temperature.
The coefficients are found as expected to be of the turbulence induced by the bends. (1)

$$h = 1770\,(1 + 0.015T)\,V^{0.66}D^{-0.2}$$

where h is the heat transfer coefficient in $W/(m^2.K)$, T the temperature in Celsius, V the water velocity in m/s and D the inside diameter of the tube in m.

The thermal resistances of the pieces of copper are first estimated by two dimensioned thermal conduction models and are then measured, the measured value of 0.16 K/W is coherent with the models.

The thermal resistance at the interface between the copper piece and the tubing is measured for different types of electrical insulation, values varied between

10^{-4} $(K.m^2)/W$ and 6×10^{-4} $(K.m^2)/W$

Pressure drop measurements were also made on the rig to validate well known formulae.

2.3. Thermal Model

A thermal model presented briefly in the Appendix based upon the thermoelectric equations 2, it uses the formulae and calculated values checked experimentally.

Calculations and experimentation showed that with counter flow, it is only necessary to do the calculations corresponding to 2 pieces of thermoelectric material.

- one for those between the top or bottom heated tube and a cooled tube 1
- one for those between the central heated tube and a cooled tube 2 .

An iterative calculation is used assuming that the average temperature of the thermoelectric piece has the value of the mean temperature of the hot and cold water circuits. This is to calculate the material's properties. The calculation of the heat fluxes leads to a more accurate value of the thermoelectric material's mean temperature. The calculation is repeated till two consecutive mean temperatures differ by less than 0.1 K. The last calculation gives the cooling power and other parameters with sufficient accuracy.

2.4. Experimental Check Of Model

A test bench is built with 2 water circuits that are both thermostatically controlled to maintain constant inlet temperatures into the subunit. A D.C. power supply with current control enables operation under constant current. A schematic is given of the test bench in Fig.6.

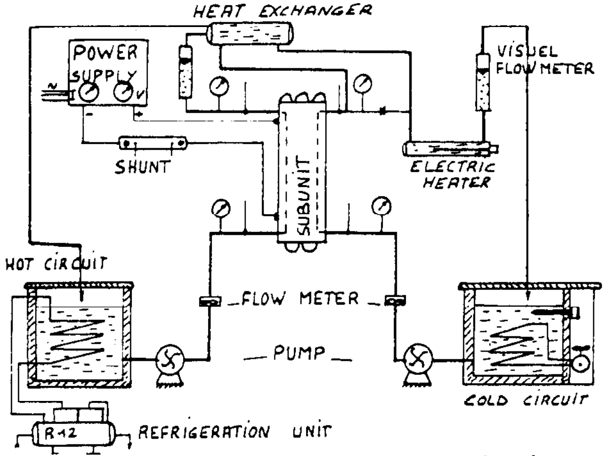

Fig.6 Schematic of thermoelectric test bench.

All measurements are collected by a Fluke Data Logger 2240 C.

A check of the model is done at a current density of 200 A amperes with constant inlet cold water temperature and small flow rates so that the temperature elevation is of about 3 deg C. The thermocouples are all calibrated and have a precision of ± 0.1 deg C. Only tests where the overall energy balances are better than 1.3 % are retained. The only parameter varied was the hot water inlet temperature which is varied between 15 deg C and 40 deg C. The experimental values of cooling power and C.O.P. are within ± 3 % of the calculated values, this is considered satisfactory. The values are shown in Fig. 7.

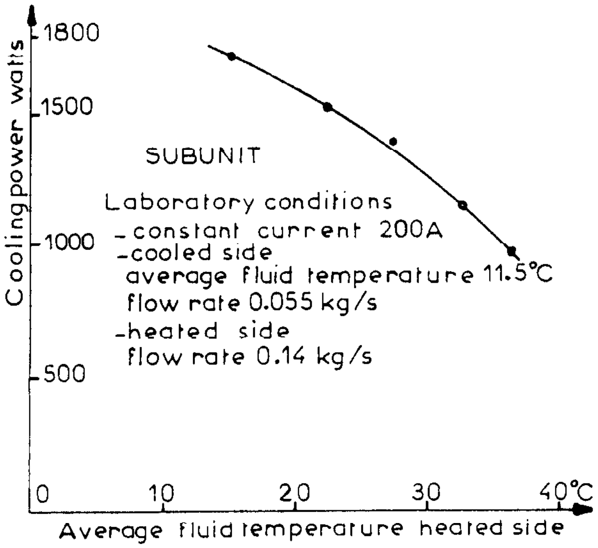

Fig. 7 Subunit, calculated and experimental

3. OVERALL PERFORMANCES

The model checked under laboratory conditions where the flow rates are respectively for the cooled side 0.055 kg/s an the hot side 0.14 kg/s, enabled the performances to be calculated for industrial flow rates of 0.30 kg/s on the cooled side and 0.80 kg/s on the heated side by using in the model the heat transfer coefficient for these industrial flow rates that had previously been measured experimentally.

The calculated values using the above procedure, are considered to be accurate to within ± 3 %. The graph of Fig. 8 gives for the subunit the cooling power as a function of C.O.P ; the curve is parametered by electrical intensity. The useful range of the curve is obviously between the extremes of 75 A and 400 A.

To show how the cooling power varies with the fluid temperatures Fig. 9 gives the cooling power versus the average fluid temperature on the heated side for 3 values of electrical current and 2 values 11.5 deg C and 21.5 deg C of the average fluid temperature on the cooled side. Values of the C.O.P. are given along the curves. For the cooled side temperature of 11.5 deg C. The C.O.P. vaies between 0.4 and 2. These curves give an overall picture of the operating conditions of the subunit tested.

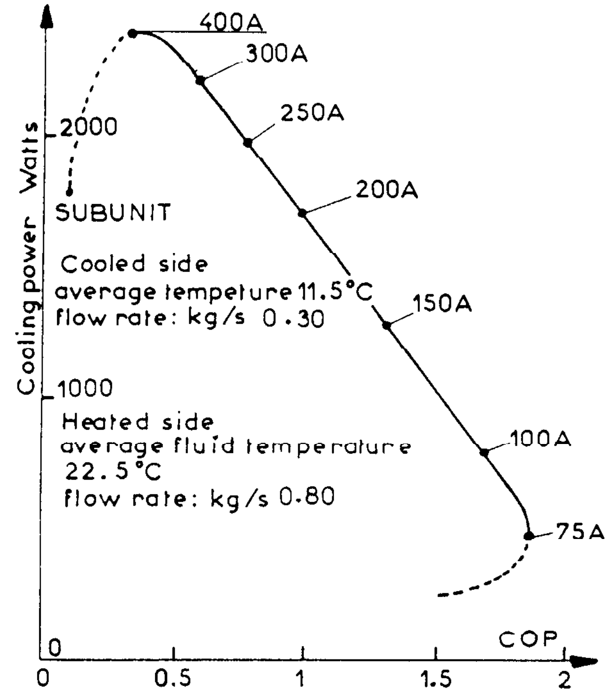

Fig.8 Subunit cooling power versus C.O.P.

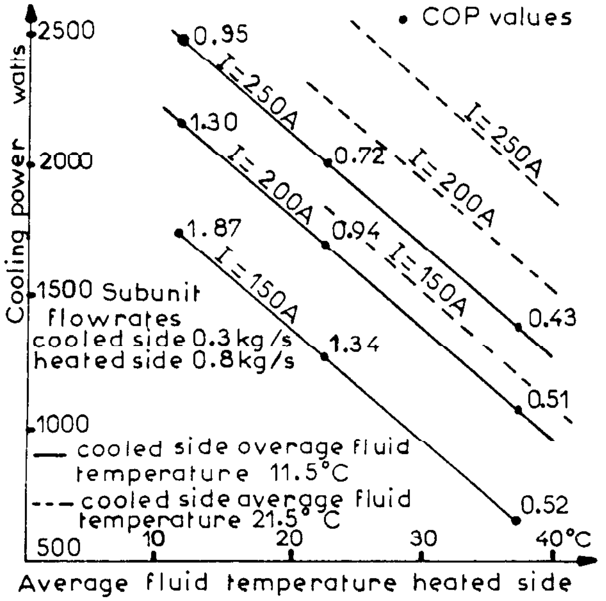

Fig. 9 Subunit cooling power versus heated side temperature for 2 cooled side temperatures.

3.2. Vibration Tests

A prototype similar to the subunit shown in Fig.1 was placed on a vibration test bench. A search for resonant frequencies was done between 1 Hz and 100 Hz for the 3 axes x, y and z of the prototype, where z is parallel to the tubes, y is vertical. The resonant frequencies found in the 3 directions were not clearly distinguishable from the overall spectrum, the maximum amplification factor found was 4. All the tests were done with a peak to peak acceleration of 10 g and lasted one hour.

Our experience has been that the best parameter to follow during vibration tests is the resistivity of the electrical circuit of the subunit. The measurement is a delicate one and requires that the temperature be as uniform as possible and stable. The electrical resistance is measured and corrected for temperature. Positive and negative variations of a fraction of a percent are found between before and after testing, the precision of the measurement being of ± 1 % the variations measured are therefore not significant. Thermal tests done before and after the vibration test do not show any significant variation.

3.3. Endurance Tests

The prototype used for the vibration tests was submitted to the following thermal cycle test.

- Cooled fluid flow rate 0.03 kg/s with inlet temperature of 16.6 deg C
- Heated fluid flow rate 0.03 kg/s with inlet temperature of 28.6 deg C
- Electrical cycle is 62 sec. with I = 200 A and 67 sec. with I = 0. Fig. 10 shows how the exit temperatures vary :

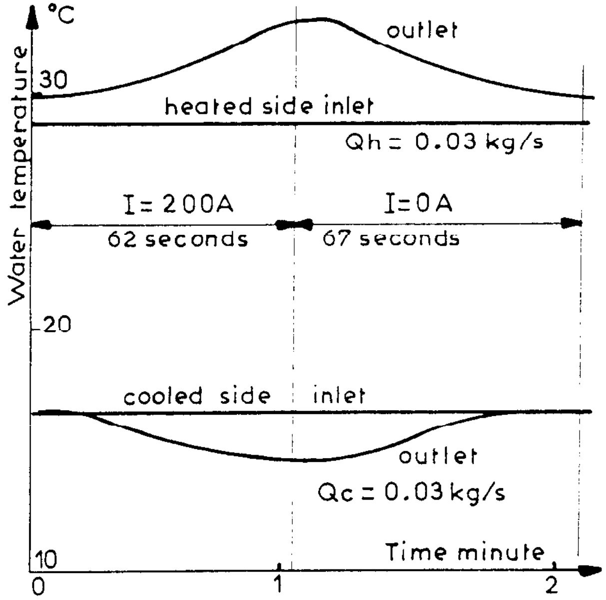

Fig. 10 Water temperatures during endurance tests.

At each cycle the heated side outlet varies by 3 deg C and the cooled side by 2 deg C. The temperature difference between the outlets of the 2 fluid circuits varies between 12 deg C and 18.7 deg C.

After several thousand cycles, the resistivity of the electrical circuit has varied less than 0.5 % which is less than the precision of the measurement. After 20 000 cycles no significant change in electrical resistivity was found nor in the results of a set of thermal tests where the measured characteristics were within ± 2 % of the predicted values by the model.

4. THERMOELECTRIC COOLING CABINET

A cooling cabinet has been designed to contain 18 subunits ; shown schematically in Fig. 11. The subunits are placed in the cabinet like drawers and are locked into position. All fluid and electrical connections are in front for easy access .

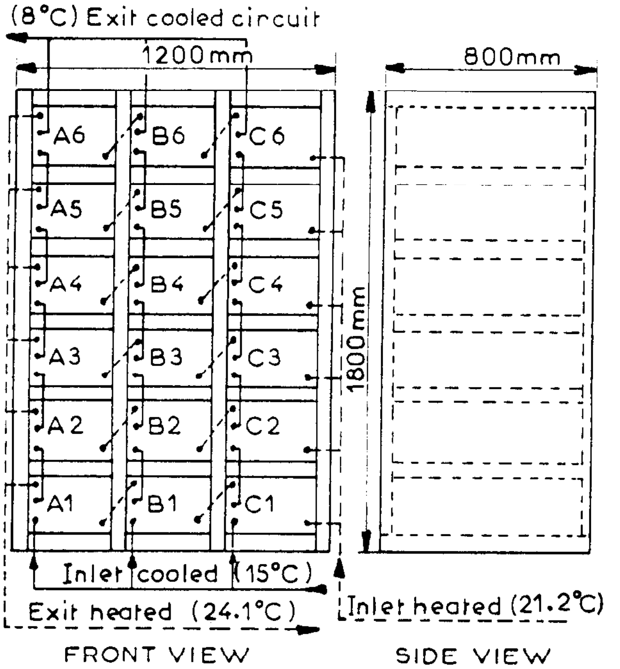

Fig. 11 Schematic of cooling cabinet with water circuits.

The 18 subunits are in series electrically . The heated circuit is composed of 6 horizontal circuits in parallel numbered 1 through 6 each has 3 subunits in series A, B and C. The cooled circuit is composed of 3 vertical circuits in parallel called A, B and C each has subunits in series (1 to 6).

The 6 nominal conditions are chosen to be :

- cooled side inlet 15 deg C outlet 8 deg C flow rate 0.83 kg/s
- heated side inlet 21.2 deg C outlet 24.1 deg C flow rate 4.7 kg/s
- C.O.P = 1

The cooling power is therefore of 30 kW, the electrical power has the same value, the voltage is 154 V with 195 A. The overall cooling power versus C.O.P. is given in Fig. 12.

The above graph gives the cooling powers for 2 thermoelectric materials. The solid line is based on the measured performances of the subunit that was built with non selected commercial grade thermoelectric material.

As the electrical resistivity of the 336 pieces of thermoelectric material was measured, a resistivity distribution curve was drawn and it was possible to study the influence of material selection on the cooling performances. The dashed curve represents the calculated performance using the best half of the N and P type material. The increase in cooling power at constant C.O.P. is found to be of 6 %.

As the selectivity increases, the performance increases. A reasonable upper bound is the dash-dot-dask line which correspond to a material with $Z = 2.84 \times 10^{-3} K^{-1}$ such a material is available but at a high premium. Even better

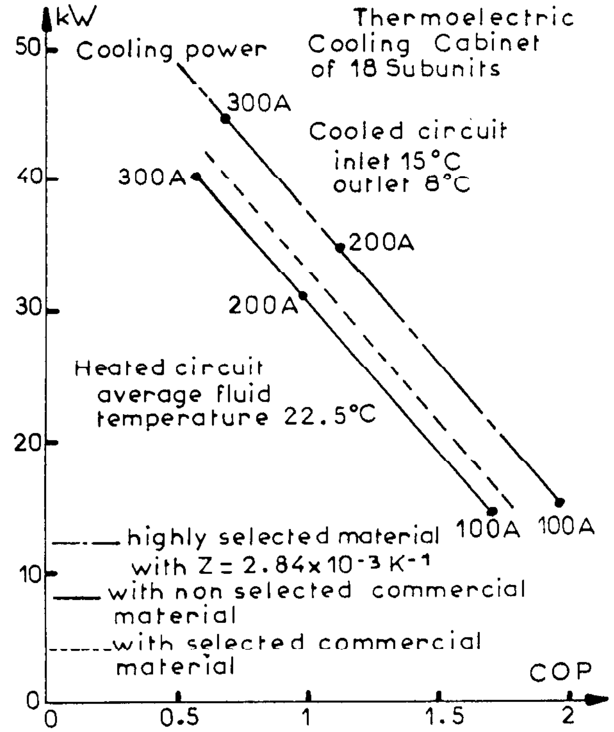

Fig.12 Thermoelectric cooling cabinet, cooling power versus C.O.P. for 2 thermoelectric materials.

materials have been made in the laboratory.

5. INDUSTRIAL DESIGN AND COST

The subunits were designed to be built industrially and the prototypes were built with parts with industrial tolerances and non selected thermoelectric materials.

A detailed cost analysis for production series using non selected commercial thermoelectric material leads to costs per thermoelectric cooling cabinet in the range of $ 100 000 to $ 150 000.

The cost of the kW of cooling varies tremendously with the operating conditions as can be seen from the performance curves given.

For a given set of operating conditions, the higher the C.O.P. : the higher the cost per kW of cooling. The practical limits correspondant to electrical intensities of about 200 A.

A low cost example is :

- Hot side : 26.5 deg C
- Cold side : 21.5 deg C

Cooling power of cabinet 38 kW

Cost per kW of cooling between $ 3 000 and $ 4 000

A high cost example is :

- Hot side 37.5 deg C
- Cold side 11.5 deg C

Cooling power of cabinet 20 kW

Cost per kW of cooling between $ 5 000 and $ 7 000.

6. CONCLUSIONS

A thermoelectric water cooling cabinet has been presented, the subunit has been thoroughly tested;

the cooling performances as known and fit a mathematical model which enables the calculation of performances in a range of operating temperatures between 10 deg C and 40 deg C. Graphs enable estimation of the performances.

The rugged design for industrial manufacturing with all water tubing grounded leads to costs per kW of cooling between $ 4 000 and $ 7 500. This shows that large scale thermoelectric cooling no longer has an astronomical cost, and becomes industrial, though considerably more costly than traditional systems with a compression expansion fluid cycle it has its place when one or more of the following advantages :

- Suppression of halogenated hydrocarbons
- Reversibility (refrigeration and heating)
- Modular Construction
- Reliability

are a prevailant factor in the choice of a system.

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2. J.G. STOCKHOLM, J.P. DESPRES - Large scale thermoelectric cooling 2nd International Conference on thermoelectric energy conversion University of Texas at Arlington. Texas 1976.

APPENDIX

The mathematical model which calculates the cooling and heating powers of the subunits takes into consideration the following 30 parameters :

- electrical intensity
- ambiant temperature
- cold circuit : flow-rate and average temperature
- hot circuit flow-rate and average temperature
- geometrical parameters :
  - . Tubing I.D and O.D
  - . Area of heat exchange by convection in tubing for cold and hot side per thermoelement
  - . Area of heat losses between hot and cold planes of tubes
  - . Area of heat losses towards the outside
- thermal coefficients :
  - . thermal conductivity as a function of temperature for all materials used such as tubing and copper blocks
  - . convection coefficients in outside air and in the inside volumes of the subunit
  - . thermal resistances of copper pieces, tubing, interface between tubing and water, and of electrical insulator
- Electrical resistances
  - . copper pieces function of temperature
  - . interfaces
- Thermoelectric material
  - . area, thickness
  - . characteristics r, S and k with temperature dependance.

The model calculates the following parameters :

- Overall cooling and heating powers
- Voltage, electrical power and C.O.P.
- For both circuits : velocity and Reynolds number, pressure drop and convection coefficient
- Temperatures at the interface of the thermoelectric material

Using experimental data, the model enables to calculate back so as to check the thermoelectric materials properties r, s and K and thermal resistances.