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Large-Scale Cooling: Integrated Thermoelectric Element Technology

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53.1 Introduction

Large-scale cooling is defined here as corresponding to cooling powers greater than several kilowatts. In this chapter integrated thermoelectric element technology is discussed because it is a logical design for large systems. The heat exchangers conduct electricity between consecutive n- and p-type pieces of thermoelectric material, referred to as elements. The size of the elements depends on the application.

In large systems, because of the cost of power, the electrical power consumption is important. The overall efficiency, which is characterized by the coefficient of performance (COP = cooling power/electrical power), becomes an important parameter when the cooling exceeds several kilowatts.

The thermal resistances characterize the thermal barriers that exist between the thermoelectric material and the fluid and correspond to temperature "drops" which decrease the performance. Evidently these temperature drops must be small when attempting to achieve high efficiencies.

Thermoelectric systems constitute an assembly of thermoelectric building blocks. A thermoelectric building block consists of thermoelectric material with a heat exchanger on the cooled side and on the heated side.

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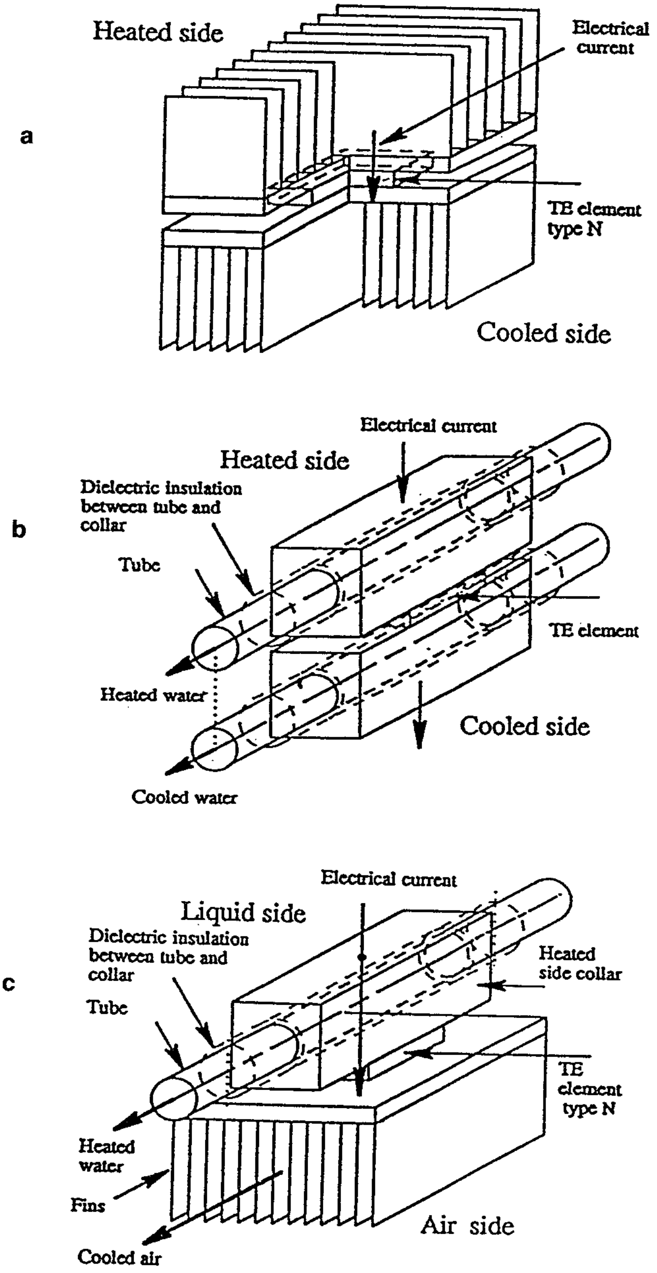

FIGURE 1 (a) Air-air thermoelectric building block; (b) water-air thermoelectric building block; (c) water-water thermoelectric building block. (With permission of the Institute of Electrical Engineers of Japan, Tokyo, Japan.)

53.2 Building Block Design

The design of the building block depends on the type of fluid employed, gas or liquid, and the three combinations, gas-gas, gas-liquid, and liquid-liquid, are considered. Generally the gas is air and the liquid is water. Typical building blocks for air-air, air-water, and water-water are shown in Figure 1.

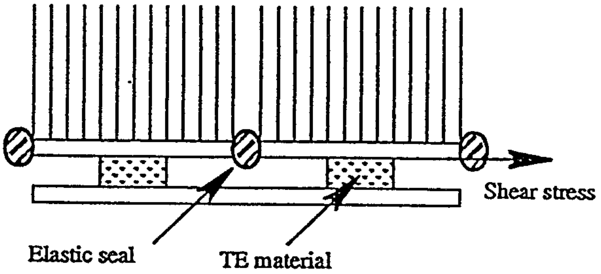

FIGURE 2 Air heat exchangers.

Constraints

There are a number of constraints when designing building blocks for large systems:

1. Electrical constraints—two aspects; the dielectric insulation where electrical codes specify tests between the electrical circuit and ground, which depend on the voltage of the system and the safety of people where electrical codes specify rules concerning the access to parts with an electrical potential, the codes depending on the maximum voltage on the system.
2. The continuity of the fluid circuit; this requires that the circuit be sealed and that adjacent heat exchangers along the fluid circuit are electrically insulated.
3. The mechanical means of absorbing shear stress, which is detrimental to thermoelectric material.

It is necessary to examine separately the constraints for gas and for liquid heat exchangers.

Air Heat Exchangers

All the air heat exchangers are in the electrical circuit which contains the thermoelectric material. Adjacent air heat exchangers along the air circuit are electrically connected through thermoelectric material and therefore they are at a different electrical potential; consequently there must not be a direct electrical connection which bypasses the thermoelectric material. This is relatively easy to achieve because, even with moist air, the metallic surfaces in contact with the air can be at an electrical potential without forming parasite electrical circuits through the air. The difficulty arises when there is a film of condensed water which joins adjacent heat exchangers.

So that condensation does not accumulate it must be eliminated, for example by gravity; one needs only to have sufficient space between adjacent heat exchangers. In practice several millimeters are sufficient because the voltage potential between the heat exchangers of adjacent building blocks is well below a volt.

In Figure 2 two adjacent air heat exchangers with a flexible elastic material between them which constitute a gas seal, an electrical insulator, and a means of absorbing the shear stress on the thermoelectric material are shown. The material can be silicone or rubber and can be applied with a gun or made in a mold.

Liquid-Heat Exchangers

For a non-electrically conducting fluid, such as an organic liquid, the liquid serves as its own electrical insulator. Nevertheless, the tube containing the liquid must be isolated electrically between adjacent pieces of thermoelectric material. In the case of an electrically conducting liquid such as water electrical insulation in theory is not necessary provided that the voltages are insufficient to create electrolysis. Nevertheless, a grounded water circuit constitutes safer and more reliable equipment.

At higher voltages a dielectric insulation is absolutely necessary to avoid electrolysis and the water circuit is consequently grounded. Figure 3 shows two methods of electrically separating

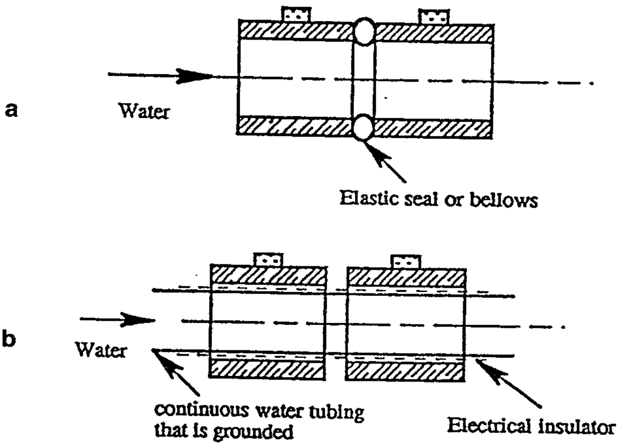

FIGURE 3 (a) Water heat exchanger, low-voltage operation; (b) high-voltage operation.

adjacent heat exchangers along the liquid flow which are not adjacent electrically. In Figure 3a two adjacent water heat exchangers with no dielectric insulation between the electrical circuit and the water are shown. The component between the heat exchangers can be a rubber-type seal, an "O ring", or bellows, etc. This technology is limited to an operating voltage of several volts. The component absorbs the shear stress and ensures that electrical insulation is maintained between two adjacent heat exchangers. A small electrical current will flow through the water from one heat exchanger to another, due to their small electric potential difference.

Figure 3b shows two adjacent heat exchangers with a tube which is grounded. There is a dielectric insulation between the tube and the electrically conducting collars. This technology satisfies the continuity and the dielectric aspect, but precautions must be taken relating to the transmission of shear stress to the thermoelectric material.

53.3 Assembly Structures

Types of Assemblies

Three types of structures will be defined which are characterized by the relative position of the pieces of thermoelectric material which are alternately of n-type and of p-type semiconductor.

They are located with air heat exchangers on the cooled and on the heated sides.

1. Column structure (Figure 4a)—The heat exchangers have two bases which are perpendicular to the line formed by the electrical circuit.
2. Linear structure (Figure 4b)—The heat exchangers have only one base and are located on the side of the line formed by the electrical circuit
3. Planar structure (Figure 4c)—The thermoelectric material is situated in a plane and the electrical current passes alternatively up and down through the thermoelectric material.

Mechanical

The structure must be such that:

1. The thermoelectric material must always be under compression; this is achieved by using tie rods and bolts
2. The thermoelectric material should only be subjected to a small shear stress; this requires that the structure includes all necessary means for absorbing thermal expansion

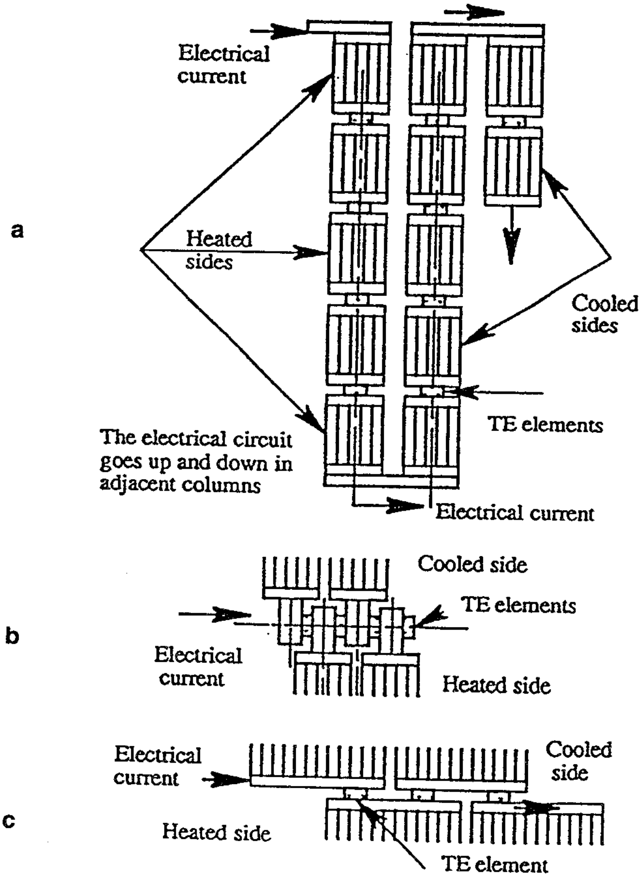

FIGURE 4 Types of assemblies; (a) column structure; (b) linear structure; (c) planar structure. (With permission of the Institute of Electrical Engineers of Japan, Tokyo, Japan.)

Air heat exchangers are shown because, should there be any shear stress due to the differential thermal expansion, it can be absorbed by an elastic seal which is located between the heat exchangers.

Liquid heat exchangers can be used instead of air gas heat exchangers in all three types of structure, provided that the shear stress is absorbed by the structure and not transmitted to the thermoelectric material.

Electrical

The electrical current must pass from one thermoelectric element to the next and there must be no short circuits between adjacent heat exchangers. This is achieved by having a gap between air heat exchangers and using an electrically insulating seal.

53.4 Fundamentals

The design of large systems requires the thorough study[1,2] of thermoelectric material interfacing and shear stress, sealing techniques, and fluid circuitry.

Thermal Aspects

This topic is covered in detail in books on thermoelectricity[3,4] and in heat transfer books.[5]

Structural Aspects

The mechanical properties of thermoelectric material require that the structure allows levels of compression in excess of 5 MPa on the thermoelectric material, while keeping the shear stress on the thermoelectric material to levels well below 5 MPa.

The shear stress essentially arises from the difference in the thermal expansion of the hot-side and the cold-side heat exchangers. For air heat exchangers an elastic seal is an efficient way of absorbing any thermal expansion parallel to the interface of the thermoelectric material.

Several techniques can be used for liquid heat exchangers: (1) compressible material, bellows, and "O" rings, which create segmentation on the liquid circuit and decrease the circuit's water tightness reliability, and (2) insulated continuous tubing, which requires capped thermoelectric material with a thermal grease interface.

The compression on the thermoelectric material ensures that the soldered interfaces between the thermoelectric material and intermediate parts (caps), or the interface with the heat exchangers, do not separate. Separation would result in high electrical resistance and possible arcing.

Thermoelectric Material Interfacing

There are several alternatives:

1. Direct soldering to the heat exchanger. This results in the lowest thermal and electrical interface resistances. However, it must be physically possible to solder the thermoelectric material to one or both heat exchangers *in situ* and the shear stress at the interface must be below 5 MPa.
2. Greased pressure contact at interface. Thermoelectric material is soldered to copper or aluminum caps with the outer surface of the caps flat (plane) or spherical.

The interface resistance varies considerably with pressure. When the pressure is below 0.5 MPa the resistance values can vary severalfold, so in practice it is necessary to have interface pressures in excess of 1 MPa. It is easy to maintain the quality control of thermoelectric elements with metallic caps.

53.5 Past Designs and Applications

Many companies were involved in thermoelectrics in the early 1960s and this period is covered in an excellent review by Lynch.[6] Although there were many designs, few large-scale applications were built. A convenient way to present the various designs is through the patents that were filed relating to large systems. Many of the designs did not mature into actual systems due to lack of development work, but nevertheless some of them are relevant and warrant attention.

Inventors

The most prolific of inventors in thermoelectric refrigeration was Elfving, who filed over 15 different patents. His most frequent air technology used tubes with fins but none of his ideas were ever used in large systems.

There are many people who have filed a few patents, some of which are of great importance because they influenced the trend of integrating the thermoelectric material to the heat exchangers. They are Lindenblad of RCA, A. B. Newton of Borg-Warner Corp., and C. J. Mole and H. D. Coe of Westinghouse Corp.

Patents were filed in 1964 on the column structure for air-air exchangers by C. J. Mole[7] of Westinghouse and by A. B. Newton[8] of the York Division of Borg-Warner. The Mole patent was published in 1965. However, the Newton patent was only published in 1970, which indicates that there was opposition to the publication of the patent, although the reasons are not publicly known.

A major concept, due to Coe[9] of Westinghouse, was a column assembly of alternating hot and cold heat exchangers which are compressed together by wires to form a cubic-type structure.

The patents of Newton, Mole, and Coe form the base of air-air subunits for large systems where elements of thermoelectric material are used and the electrical current goes through the air heat exchangers.

There were many patents in the 1960s on linear structures,[10–13] although none led to any known prototypes.

Mole[14] patented the concept of not electrically insulating the water heat exchangers in water-air units and having bellows between each heat exchanger in a planar structure. Benicourt et al.[15] and Buffet[16] patented a column structure for water-water systems with grounded tubing which uses capped thermoelectric material with a flat surface on one side and either a spherical or cylindrical surface on the other.

Borg-Warner

The York Division of Borg-Warner was only interested in air-air systems. The approach taken by Newton was to "solder" the entire "cubic" structure simultaneously in an oven. Borg-Warner had a policy of not publishing, so very little is known apart from the information in the patents. It appears that major difficulties were encountered when soldering all the junctions simultaneously.

Westinghouse

The same approach was employed for air-air[17] with the columns being tightened with a central tie rod. Small units were manufactured with cooling powers of several hundred watts for use in military prototypes, but none were commercialized.

In 1972 two highly documented papers[17,18] which covered the design of a water-water 7-kW unit, model 20GS, were published.

Westinghouse was very active in water-air systems for naval applications.[17–19] The design was based on the Mole patent.[14] The U.S. Navy had a thermoelectric unit made by Westinghouse for the air-conditioning on the USS Dolphin. It is a water-air unit with a planar structure and the water in direct contact with the electrical circuit. In order to avoid electro-corrosion the operating voltage is in the range of 5 V and the unit operated over a 10-year period.

ASEA

A prototype unit to air-condition and heat a passenger railway coach was built by ASEA for the Swedish railways. Two Swedish publications are available: one by Ridal[20] of the Swedish railways and one by Lundqvist[21] of ASEA. The design was based on two patents by Widakowich.[22,23] The first describes a planar structure that uses thermoelectric material, the second relates to capping the thermoelectric material with copper and using a pressure contact. The units operated for several years before being dismantled.

Air Industrie—Railway Application

Air Industrie was a manufacturer of compression cycle air-conditioning for passenger railway coaches. In 1973 J. P. Buffet initiated a development program for thermoelectric air-conditioning of passenger railway coaches for the French railways. The design was the column structure based on a patent by Gaudel.[24] This type of structure was retained after studying the planar and the linear structures and was considered to be the most sturdy of the three structures. Capped thermoelectric material was used because soldering a complete unit was found to be unreliable. The heat exchangers are based on patents by Buffet.[26] The program led to a coach being equipped in late 1977 with a 20-kW air-conditioning unit.[25] The coach was operated for over 10 years without a single thermoelectric failure.

Air Industrie—Naval Application

In 1980 the French Navy started a research and development program with Air Industrie to develop a water-water unit for producing cold water for air-conditioning. The column structure was chosen[15,16] with the water tubing electrically insulated from the heat exchangers which are in the electrical circuit.

The patent[15] describes capped thermoelectric material with, on one side a flat surface and on the other either a spherical or a cylindrical interface. During the tightening process this interface allows some movement of the cylinder or sphere to compensate for the nonparallelism of consecutive layers of water heat exchangers.

A patent[16] covers the mechanical linking of the hot and cold tubes so as to reduce the differential thermal expansion. Because of the differential thermal expansion of the hot and cold tubes capped thermoelectric material with one flat surface is used so as to absorb the mechanical shear stresses transmitted by the tubes.

The units have been described in the literature[27,28] and have undergone extensive endurance testing for more than 5 years.

Conclusions on Technologies for Large Systems

Interfaces

The soldering of thermoelectric material directly to both the heat exchangers presents the same difficulties as those in the manufacture of thermoelectric modules. The largest modules contain about 127 couples. Nobody has yet successfully soldered more than a few thermoelectric elements to heat exchangers in one operation. When thermoelectric elements are soldered on both sides to heat exchangers, and as most structures transmit shear stress to the thermoelectric element, that shear stress can be incompatible with the mechanical properties of the thermoelectric material.

If only one face is soldered and the other is a capped flat surface with a pressure contact, this surface can accommodate the shear stress.

A thermoelectric element when capped on both sides and with two pressure contacts facilitates the quality control of each piece. A safe and reliable design is a thermoelectric element with one flat cap and one spherical cap: the flat surface allows positioning and displacement without creating shear stress, while the spherical cap allows correct interfacing between nonparallel planes.

In large systems the area of the pieces of thermoelectric material is generally greater (0.5 to 3 cm^2) than in modules (0.2 cm^2).

Air-Air Systems

A column structure with a tightening mechanism per four columns is considered the most reliable of today's design. It is considered that direct soldering of the thermoelectric element to the heat exchangers can only be used for small individual columns. Capped thermoelectric material is more suitable for large subunits.

Water-Water Systems

There is published data on only two large water-water systems: a Westinghouse 7-kW model, 20GS, designed for low-voltage operation with the electrical circuit in contact with the water, and an Air Industrie 15-kW unit 10T925, designed for operating voltages in excess of 100 V with a grounded water circuit.

Water-Air Systems

In the case of water-air systems the only documented system built, and which has been in operation for a prolonged time, is from Westinghouse.[19] It was installed on the USS Dolphin for a period of 15 years. The design is a planar structure having a central tube with an air heat exchanger above and below. The central tube consists of hollow blocks, as shown in Figure 3a, with bellows between each block. The thermoelectric elements (3 cm^2) are soldered to the hollow block and to the "double " air heat exchangers.

53.6 Future Applications

Currently a number of applications where large powers are involved are being examined, developed, and in some cases commercialized.

Parked aircraft — The air-conditioning of an aircraft parked at a terminal gate requires cooling powers of several tens of kilowatts. The systems that are being studied are air-air.[29]

Trains — The air-conditioning of passenger railway coaches[25] is on hold at the moment but applications to drivers' cabs are being studied. The cooling powers are of several kilowatts, but this application will no doubt come out sooner than the air-conditioning of a whole railway coach because the cooling powers are less and the electrical power consumption is less critical.

Automobiles — There is considerable interest in the thermoelectric cooling of automobiles, especially electric cars. At the present time people are more concerned with comfort cooling (blowing cool air onto the passengers) rather than reducing the overall temperature of the air in the car. Because of the large potential market some companies are examining the integrated technology.

Naval — Navies are pursuing the use of thermoelectrics for several reasons. In naval applications seawater is always available, where the heat can be rejected either directly or indirectly. Heat rejection to water leads to thermoelectric systems that are more efficient than those rejecting heat to air. When dealing with confined volumes (submarines) the elimination of a source of a CFC is always an asset. Large-scale water-water cooling is already a reality.[27] A water-water thermoelectric system has the advantage of replacing traditional compression systems, which produce chilled water. Another application is decentralized thermoelectric air-conditioning which produces directly cooled air. Another potential area for development is the cooling of naval containers. The commercialization of large two-stage modules has opened up areas where greater temperature differences are required, such as cold rooms and deep-freeze rooms.

Containers — There has been considerable interest in thermoelectric cooling by companies either manufacturing or using containers. The economics are such that a thermoelectric system is much more expensive than a compression cycle system, especially when one requires deep freeze temperatures. Specialized thermoelectrically cooled containers which are limited to maintaining +4°C may have a future.

53.7 Conclusions

Over the past 30 years the performance of thermoelectric material has increased by about 20% and the potential improvement of bismuth telluride is also about 20%. However, today we must work and design with existing materials.

The integrated thermoelectric technology which emerged in the 1960s is slowly progressing. This technology is necessary for large-scale cooling because it can be adapted to large electrical currents. It will really increase with mass production which will reduce costs considerably. Today there is no mass production; the only ongoing production using this technology is for naval systems, but the numbers are small so the costs are still high.

This technology can also be applied to medium powers using smaller thermoelectric elements but systems with thermoelectric modules are cheaper than systems with thermoelectric elements provided the production numbers are well below those of thermoelectric module production.

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