Prototype of heat pump based on Peltier effect. Results of performance tests

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Abstract

Air conditioning based on the Peltier effect has many theoretical advantages over other air conditioning techniques, such us reliability, control... This idea encouraged the development of a research project oriented to study the feasibility of this technique to industrial and domestic applications. In this project an experimental heat pump has been designed and built to study the behavior of Peltier cells in a real application. In this paper experimental results are shown. A brief description of the heat pump, external equipment and sensors used during the tests is included. The methods used to measure physical magnitudes like flows, heats and temperatures are also described. Several working conditions have been tested to study the performance of the heat pump. We mainly regulated the current supplied to the Peltier cells to different levels. Successful experiments, reaching steady temperatures and power exchange, have been carried out for heating and cooling modes. Results of the most relevant experiments, including the values of steady temperatures, flows and heat power, are shown in this paper.

1 Introduction

Peltier cells are electronic devices that pump heat from one of its sides, the cold sink, to the other one, the hot sink, when a continuous current is supplied. By changing the sign of the current the cell behavior is reversed, exchanging the cold and hot sides and thus changing the sign of the heat flow. By adjusting the current and its sign it is possible to control in a very simple way the cell behavior, and thus the heat flow.

The main advantages of this technology are:

- no moving parts are required, preventing from noise and vibration, and possibly increasing the reliability.
- no CFC´s or other gases, preventing from leakages and environmental damage.
- easy electric control by continuous supply regulation, without bypass and regulation valves.

However some disadvantages should be pointed out:

- high cost of the cells
- limitation of the gradient temperature between both sides of de cell.
- low performance

A heat pump was designed and built using Peltier cells to study the viability of this technology to industrial and domestic applications. A detailed description of the pump can be found in [1]. The purpose of this paper is to communicate the results of the experimental testing of the heat pump.

2 Brief description of the heat pump

The heat pump consists of three main parts: a heat exchanger by air, a heat exchanger by water and the Peltier cells, as shown in figure 1.

The pump was designed to transfer 1450 watts of heat on each exchanger, therefore when one exchanger is working as the cold sink it is over-dimensioned. The heat pump has an external radius of 720 millimeters and is mainly made of aluminum. Although cooper was also taken into account during the design phase, allowing a reduced dimension pump, the resulting cost was much higher and aluminum was finally chosen.

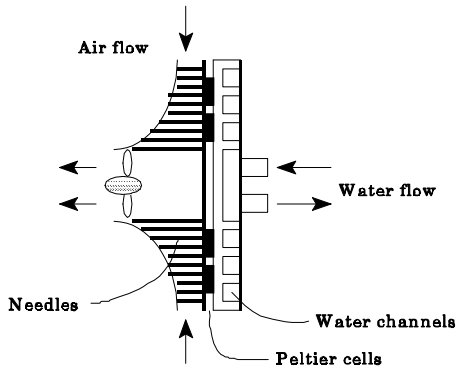

Figure 1: Prototype of Peltier heat pump

The first and more complex heat exchanger is a circular and needle exchanger whose cooling or heating fluid is a forced air flow. The needles are mounted perpendicularly to the plate where the cells are glued, forming concentric rings of different heights, the inner one being the higher (this configuration keeps the Reynold's number constant). At the geometrical center of the plate, next to the inner needle ring, a fan was mounted to produce the forced air flow, its rotation axis being perpendicular to the plate.

The second exchanger is a heat exchanger by water with five concentric channels distributed from an internal to an external radius. At the external side of this exchanger there

is an aluminum sheet which serves as a cover for the channels and supports the water inlet and outlet.

Finally between both exchangers 24 Peltier cells were located seeking the most uniform temperature distribution along each side (being this a design hypothesis)

3 Sensors and measurements

Many sensors, most of them thermocouples, were first installed in order to verify the behavior of the prototype. The electrical signals of the sensors were conditioned and converted to digital format in a data acquisition system and they were then transferred to a personal computer for later analysis. Different types of sensors and instruments have been used to measure temperature, air pressure, water flow, voltage, current... The proper operation of the heat pump was achieved mounting thermocouples at the following strategic points:

- directly over both sides of one Peltier cell
- at different needles and at different heights of the same needle.
- at different points in the needle exchanger to measure air temperature.
- at different channels of the heat exchanger by water.

Once the proper operation had been proved, we began working on the instrumentation for performance measurements. Performance parameters are based on the electric power and on the heat power of both exchangers.

The electric power is calculated as the product of voltage and current. Since three DC power supplies were used, the total electric power is calculated as:

$$Q_e = \sum_{i=1}^{3} V_i \cdot I_i \qquad (1)$$

where
Q_e is the electric power (W)
V_i is the voltage of the power supply i (V)
I_i is the current of the power supply i (A)

The power of the heat exchanger by air is calculated with the next formula:

$$Q_a = C_a \cdot \rho_a \cdot (h_s - h_e) \qquad (2)$$

where
Q_a is the heat power (W)
C_a is the air flow (m^3/s)
ρ_a is the air density (kg/m^3)
h_s is the outgoing enthalpy (J/kg)
h_e is the incoming enthalpy (J/kg)

ρ_a is calculated as $\dfrac{P(\text{Pa})}{R\left(\dfrac{J}{kg\ ^\circ K}\right) T(^\circ K)}$

If the dry-bulb temperature and the wet-bulb temperature are measured, the variation of the enthalpy can be calculated precisely. If not, it can be approximated as the product of the specific heat (J/kg°K) and the variation of the temperature (°K).

Most of the effort was made in the construction and instrumentation of the systems used to obtain reliable air flow measures. The air flow was measured according to ACMA standard 210-67 norm, following the *nozzle on outlet duct* scheme (figure 2) and the *nozzle on outlet chamber* scheme (figure 3). In the first case the flow rate is calculated as:

$$C_a = \frac{\pi d_4^2}{4} \frac{C \cdot Y}{\sqrt{1-\beta^4}} \sqrt{\frac{2}{\rho_a}(P_3 - P_4)} \qquad (3)$$

and in the second case as:

$$C_a = \frac{\pi d_4^2}{4} C \cdot Y \sqrt{\frac{2}{\rho_a}(P_3 - P_4)} \qquad (4)$$

where
C_a is the air flow (kg/s)
d_4 is the small diameter of the nozzle (m)
C is the nozzle discharge coefficient (dimensionless)
Y is the nozzle compressibility correction factor (dimensionless)
ρ_a is the air density (kg/m^3)
P_3-P_4 is the pressure differential across the nozzle (Pa)
β_4 is the dimensionless characteristic of the nozzle d_4/d_3

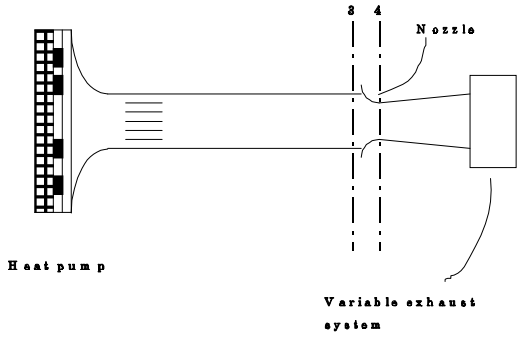

Figure 2: Nozzle on outlet duct

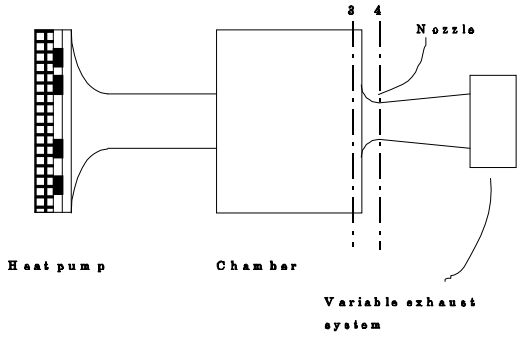

Figure 3: Nozzle on outlet chamber

The power of the heat exchanger by water is calculated from the increment of temperature and the flow with the following formula:

$$Q_A = C_A \cdot \rho_A \cdot ce_A (T_{SA} - T_{EA}) \quad (5)$$

where
Q_A is the heat power (W)
C_A is the water flow (m^3/s)
ρ_A is the water density (kg/m^3)
ce_A is the specific heat (J/kg°K)
T_{SA} is the outgoing water temperature (°K)
T_{EA} is the incoming water temperature (°K)

4 Performance tests

The main purpose of the tests has been to obtain the performance parameters of the heat pump, therefore steady state had to be reached. Steady condition is difficult to reach because of the thermal inertia of the system and because the environmental conditions may change during the test. Usually more than 30 minutes were necessary in order to get steady temperatures.

As an example, figure 4 shows the evolution of the air temperature in v9 test. Incoming-air temperature was maintained approximately constant while outgoing-air temperature needed about 45 minutes to became steady.

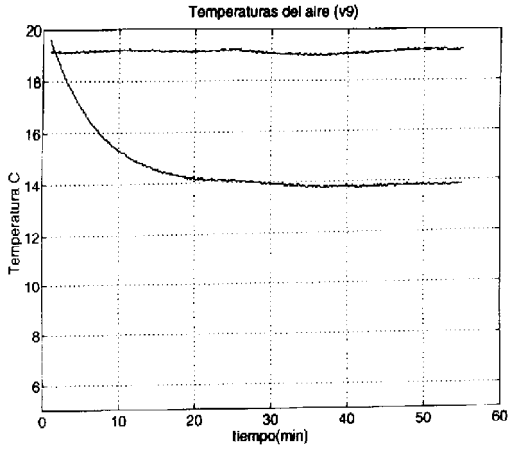

Figure 4: Evolution of the air temperature in v9 test cooling air

The heat pump was designed to work in two different configurations, cooling air (and therefore heating water) or heating air (and therefore cooling water). To change the configuration no pipes or valves had to be moved, since taking advantage of the Peltier technology it is only necessary to swap the polarity of the cells. Successful experiments, reaching steady temperatures and power exchange, had been carried out for both configuration. The results are shown on section 5.

All the tests can be grouped in two sets. The first set of tests (coded v*) was carried out at the Laboratory of Fluids and Heat of the University "Pontificia Comillas". In this laboratory, environmental conditions such as water temperature or air temperature and moisture were not controllable, although they remained fairly constant during the tests. The air flow was measured using the *nozzle on outlet duct* scheme described in section 3 without variable exhaust system and therefore making the heat pump work at lower air flow rates than desired. Even so, most of the tests where run in this laboratory and most of the results and conclusions come from these tests.

The second set of tests (coded ASI*) was carried out at the Heat Pump Laboratory of ASINEL. This laboratory is in charge of the official approvement of conventional heat pumps. The main purpose of these tests was the evaluation of the heat pump working at adverse environmental conditions according to the ISO norm. At this laboratory the cooling tests were run with air at 27°C and 50% relative humidity and water at 30°C while heating tests were run with air at 21°C and 40% relative humidity and water at 22°C. The air flow was measured using the *nozzle on outlet chamber* scheme described in section 3. In general, the air flow rates used in the second set of tests where higher than in the first one.

It is important to notice that the power of the heat exchanger by water has been calculated as the difference between electrical power and power transferred in the heat exchanger by air. This is $*Q_A = Q_a + Q_e$ when cooling air and $*Q_A = Q_a - Q_e$ when heating air.

This decision was taken after some measurement problems were found in the water circuit. The main problems were caused by the high thermal capacity of water with respect to the low power of the experimental heat pump built. Running the heat pump at high flow rates produced unmeasurable temperature variations while trying to obtain higher temperature variations lead to problems in the controlling and measuring the water flow, as well as a big delay in the measurements before the steady state was reached.

All other powers where calculated using the equations of section 3. Special care was taken in the measurements involved in the computation of the power of the heat exchanger by air. Up to four thermocouples where installed in the air outlet in order to get an accurate temperature and the differential pressure sensor installed in the nozzle was carefully calibrated.

In order to evaluate the performance of the heat pump, two dimensionless parameters have been calculated, the *cooling coefficient* CF (performance of the heat pump considered a cooling system) and COP (performance of the heat pump considered a heat system). CF and COP are defined as follows:

$$CF = \frac{Q_{cool\ sink}}{Q_{electric}} \quad \text{and} \quad COP = \frac{Q_{hot\ sink}}{Q_{electric}} \quad (6)$$

CF is usually less than 1 and COP is usually greater than 1.

5 Experimental results

Many tests have been carried out with different environmental conditions and different working settings. The incoming air temperature have ranged from 17°C to 27°C and the incoming water temperature from 7°C to 30°C. Electric current per cell has been adjusted from 3 A to 6.7 A, giving electric power from 0.4 kW to 2.6 kW. As results from the tests, the following values were obtained:

- The heat power in the exchanger by air has ranged from 110 W in one of the cooling test to 2.4 kW in one of the heating test.
- For the heat exchanger by water, power ranged from 38 W to 2.6 kW.
- Outgoing air temperature ranged from 7.5°C to 56°C
- Outgoing water temperature ranged from 7.7°C to 36°C

In this paper we are presenting only the results of the tests that we consider more significant and reliable. The following tables show the main measurements and calculated parameters of the steady condition of these tests. Except T_{ea} and T_{sa} all the names and units of the parameters shown in the tables have been explained before.

The numbers shown are signals from on-line sensors, values read from instruments or values calculated using the formulas explained before.

Table I: Results of the tests cooling air

	Q_e	Q_a	$*Q_A$	CF	COP	A/cell	V	C_a	T_{ea}	T_{sa}	C_A	T_{EA}
v1	390	135	525	0.35	1.35	3	5.5	0.030	17.0	12.5	0.64	7.0
v9	430	115	545	0.27	1.27	3	5.8	0.021	19.0	14.0	0.34	13.8
v12	453	120	573	0.26	1.26	3	6.1	0.022	19.0	13.0	0.13	13.5
v12repe	455	110	565	0.24	1.24	3	6.1	0.022	18.0	13.0	0.12	14.0
v13	629	125	754	0.20	1.20	3.5	7.1	0.022	15.5	12.8	0.13	14.0
v11	775	135	910	0.17	1.17	4	7.8	0.021	19.5	13.0	0.34	13.5
v14	811	140	951	0.17	1.17	4	8.2	0.022	18.8	12.5	0.13	14.5
v2	2100	220	2320	0.10	1.10	6.7	13.1	0.019	19.0	7.5	0.24	10.0
asi8e5	616	207	823	0.34	1.34	3.5	7.4	0.048	26.9	21.9	0.24	29.3
asi8e4	1263	263	1526	0.21	1.21	5	10.5	0.054	27.0	21.5	0.31	29.6
asi8e3	2324	256	2580	0.11	1.11	6.67	14.5	0.069	27.0	22.3	0.27	29.5

Table II: Results of the tests heating air

	Q_e	Q_a	$*Q_A$	CF	COP	A/cell	V	C_a	T_{ea}	T_{sa}	C_A	T_{EA}
v16masb	740	1100	360	0.49	1.49	3.5	8.5	0.038	19.0	47.0	0.13	13.9
v17	953	1200	247	0.26	1.26	4	9.5	0.040	20.0	50.0	0.13	14.3
asi9e6	464	878	414	0.89	1.89	3	6.4	0.066	21.1	28.9	0.50	21.1
asi9e5	1405	1712	307	0.22	1.22	5	11.7	0.072	20.9	36.0	0.50	20.7

The first conclusion from these values is that the heat pump performed better in the ASI* test than in the v* tests. We think this is mainly because the air flow used in ASI* tests was high and therefore made the needle heat exchanger work better.

Better performance was obtained with lower currents per cell in heating and cooling tests suggesting that it is possible to improve the prototype just by adding more Peltier cells in the same surface and making each of them work at lower power.

6 Conclusions

The broad environmental conditions and the ranges of heat power and temperature obtained have shown the usefulness of thermoelectricity for domestic applications. The commercial Peltier cells currently available have reached enough technical development to be applied in many fields where heat transfer is needed. Nevertheless, future work will be necessary to increase the temperature difference between the cold and the hot sides for other applications.

The reliability of the Peltier cells has been confirmed. No aging or loss of performance have been detected and no cell has fail, in spite of having moved the heat pump several times among different laboratories. Most of the problems we had during this research came from sensors and measurement accessories or from leakage and control of the water circuit, but never from the Peltier cells.

Heat power calculations are very sensitive to measurement errors in temperatures and flows, very accurate and calibrated measurement equipments must be used for this kind of testing, specially for testing low power prototypes.

From our experience in industrial and domestic applications of thermoelectricity, we consider the following systems specially suitable for this technology:

- Systems where fine temperature control is important.
- Environments where toxic gases of cooling fluids can be dangerous, such as food industry.
- Environments where noise or vibrations from motors and compressors may be harmful.
- Portable systems or applications where reliability is important and DC electric power is available.

7 References

[1] Sanz-Bobi M.A., Palacios R.,Villar J.,Arenas A. "Prototype of heat pump based on Peltier effect for applications in ambient temperature condition." Proceedings of the XI International Conference on Thermoelectrics. The University of Texas 1992

[2] Ioffe A.F. "Semiconductor thermoelements and thermoelectric cooling." Infosearch Limited, 1957

[3] Goldsmid H.J. "Thermoelectric refrigetation." Tempel Press Book Limited, 1964

[4] Heikes R.R., Ure R.W. "Thermoelectricity: Science and engineering." Interscience Publisher, 1961

[5] Cadoff I.B., Miller E. "Thermoelectric matherials and devices." Reinhold Publishing corp., 1960