

Thermoelectricity Applied to Heating of a Fuel Filter of a Car in a Cold Starting

Jorge Vázquez, Miguel A. Sanz-Bobi, Rafael Palacios, *Antonio Arenas
Universidad Pontificia Comillas
Escuela Técnica Superior de Ingeniería-ICAI
Instituto de Investigación Tecnológica, *Departamento de Fluidos y Calor
Alberto Aguilera, 23
28015 Madrid (Spain)
E_mail: masanz@iit.upco.es
Phone: 34 – 91 542 28 00
Fax : 34 – 91 542 31 76

Abstract

This paper presents the results of an investigation about the use of thermoelectricity in a car fuel filter in order to prevent the problems associated to its obstruction due to the creation of paraffins when the car is stopped for a long time in an environment where the temperature is very low. Also, it describes the main features of a redesign of a conventional car filter in order to include thermoelements able to transfer heat, precisely at the moment of the car starting, from an eutectic fluid to the cold fuel contained in the filter. Several numerical simulations and performance tests of the new designed car filter will be presented.

Problem statement

If a car is stopped for a long time outside and the temperature in the environment is very low, paraffins can appear in the fuel contained in the motor filter of the car. This process is more likely if diesel is used as fuel for the car. If paraffins are present in a filter, they block up the holes in the paper of the filter, and therefore its flow capability is reduced or eliminated and the filter can not perform its original function. This is a problem that appears when the vehicle is not used for some hours, and is parked outside where temperatures are low. It is also very important to take into account that a fuel filter of a car is a critical component that permits the passage of the fuel to the motor.

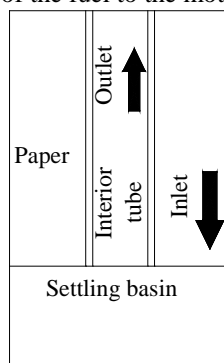


Figure 1. Schematic diagram of a conventional car filter.

Fig. 1 represents a scheme of a conventional car fuel filter. It consists of three main parts: the paper chamber, in which the fuel is introduced into the filter and actually filtered; the settling basin for the separation of water from the fuel; and the interior tube, which is the outlet of the filtered fuel.

Currently, the problem of obstruction of the filter by paraffins is solved using an electrical heater located on top of

the car filter and supplied by the car battery when the car is started.

This paper presents an investigation based on the use of thermoelectricity as an alternative to the use of an electrical heater.

Problem solution

A new method has been proposed for the elimination of paraffins in the filter when a car is started after several hours in a cold environment. The solution proposed has taken as starting point a conventional fuel filter like the one represented in figure 1, manufactured by a company of such filters. The main idea of this new design is to store the heat produced by the fuel passing through the filter when the car is running and to use this reserve of heat when the car is started in order to eliminate the paraffins along the way from the fuel input to the fuel output of the filter. For this purpose, the filter is isolated and its bottom put in contact with an eutectic fluid. This eutectic fluid acts like a heat reservoir and is selected for changing its phase around the temperature of the paraffin generation. A set of thermoelectric modules are located between the filter and the eutectic reservoir and they are in charge of the control of the heat to and from the reservoir to the filter. When the temperature decreases, the thermoelectric modules will operate to prevent the eutectic from changing its phase. When the car has to be started after several hours in a cold environment, the thermoelectric modules will force the change of phase of the eutectic fluid in order to produce heat.

The solution described is represented in figure 2. In this figure the insulation put over a conventional filter can be observed, along with the addition of a reservoir for the eutectic fluid and the set of thermoelements able to control the transfer of heat. Also, in this figure dimensions can be observed in millimetres. The eutectic fluid selected for use has its phase change at -3°C . The design has taken as reference an ambient temperature of -20°C .

Performance tests

The performance of the new car fuel filter presented in figure 2 was analysed by numerical simulation before testing it under real conditions. However in order to know some parameters of the real performance required for a better simulation, several tests were performed.

First, the filter with the insulation around it was analysed in order to estimate the real thermal conductivity of the heat insulation, to know if the temperature was uniform inside the

filter, and how long the temperature was up to the phase change point of the eutectic fluid.

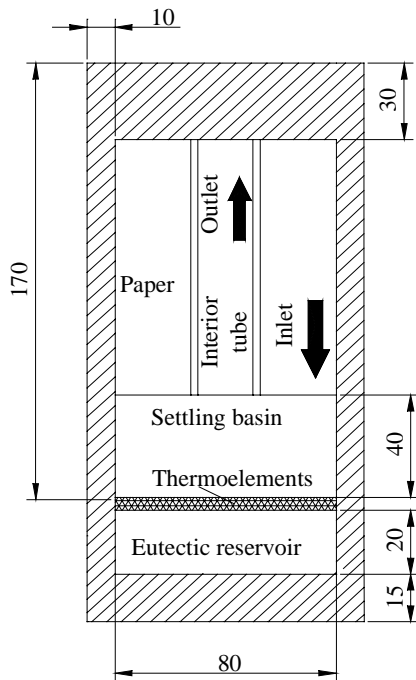


Figure 2. New fuel filter using thermoelements

Second, an investigation was carried out concerning the transfer of the eutectic latent heat when it changes its phase to the fuel using thermoelectric modules.

After all these tests, a study of the performance based on finite elements methodology was done and the more suitable thermoelements were selected.

The main results of all these steps will be presented in the following sections of the paper.

Performance tests of a conventional car fuel filter with insulation

The first new idea introduced in the design in figure 2 is the isolation of a conventional filter. Different tests were developed in order to obtain experience concerning the filter working with the insulation such as shown in figure 3.

The filter was covered with the insulation, the thickness in the lateral surface was 10 mm., 15 mm. at the bottom and 30 mm on top.

To avoid the danger of a possible deflagration due to gaseous emanations of fuel at high temperatures (around 80°C) the fluid used to fill the filter was not fuel, but rather all tests were done using water. The principal inconvenience was that the water specific heat was more or less twice that of fuel. The higher the specific heat, the better the results because there is more heat accumulated. However, the capacity of the filter was 0.8 l and the amount of water introduced in it was 0.4 l.

A set of thermocouples was introduced in the filter as is represented in Figure 3. A thermocouple (K-type) was located in each of the parts (T1, T2, T3) and one more between the external surface and the insulation (T4).

The idea of this test is to know how the heat inside the filter is lost during the time the car is stopped and the filter is isolated. The temperature conditions inside the filter were similar to the real ones because water was introduced at the

same temperature as that of the fuel circulating through the filter when the car is running. This temperature was close to 60°C. The objective of this study was to know the evolution of the temperature inside the filter, when the temperature of the ambient outside is -20°C at the moment that the engine stops, but it was impossible to reach this low temperature in the laboratory. All the tests were done with a temperature in the surroundings of the filter of 22 °C.

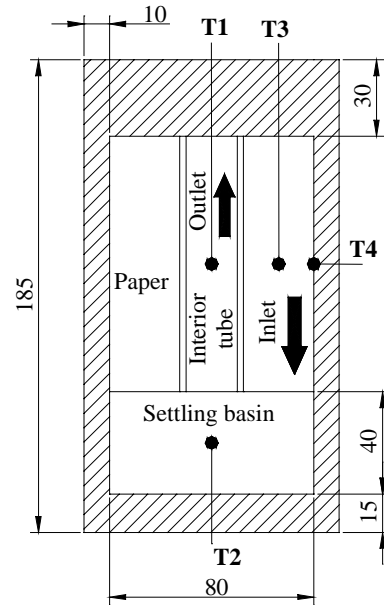


Figure 3. Scheme of the car fuel filter with insulation.

Temperatures in the filter were registered under the previous conditions and a graph of temperature vs time was plotted. This is shown in figure 4.

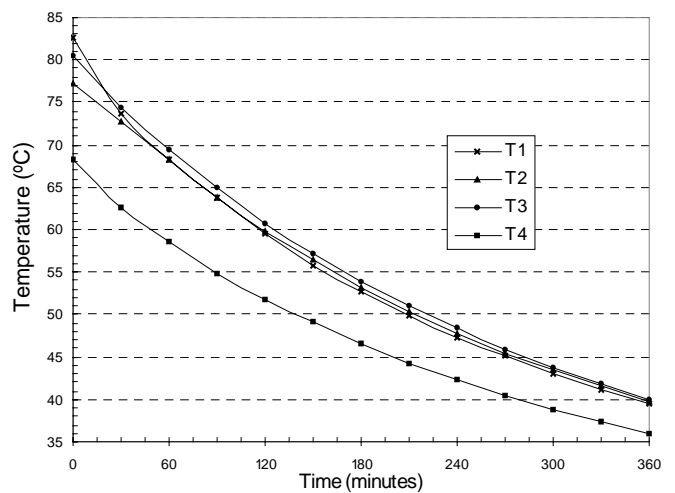


Figure 4. Variation of the temperature inside the filter. Insulation thickness=10 mm, Tamb=22°C.

Using the global thermal capacity model, it is possible to estimate the equivalent thermal conductivity of the insulation and from this value the operation conditions of the filter can be interpolated.

Assuming that the temperature inside the filter can be considered uniform, it is possible to use equation (1) in order to calculate the equivalent thermal conductivity of the insulation.

$$T = T_{amb} + (T_o - T_{amb}) \cdot e^{-\frac{K_i \cdot A}{B \cdot e_i} t} \quad (1)$$

where:

$$B = m_w \cdot c_{p_w}$$

$$\frac{A}{e_i} = \frac{A_1}{e_1} + \frac{A_2}{e_2} + \frac{A_3}{e_3}$$

The result obtained was $K_i = 0.023 \text{ W/mK}$ which is different from the theoretical value of 0.045 W/mK . A possible explanation for this difference could be the paper inside the filter, which is a good thermal insulation and it had not been considered. The theoretical results obtained from interpolation agree with the results derived from the tests. This is presented in figure 5.

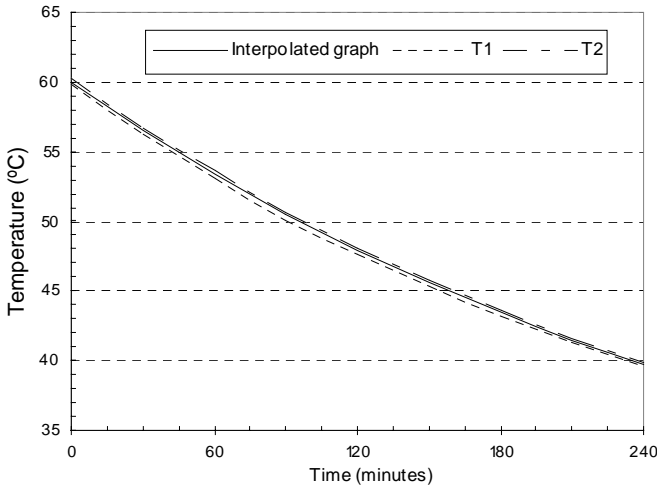


Figure 5. Comparison between the experimental and the interpolated performance.

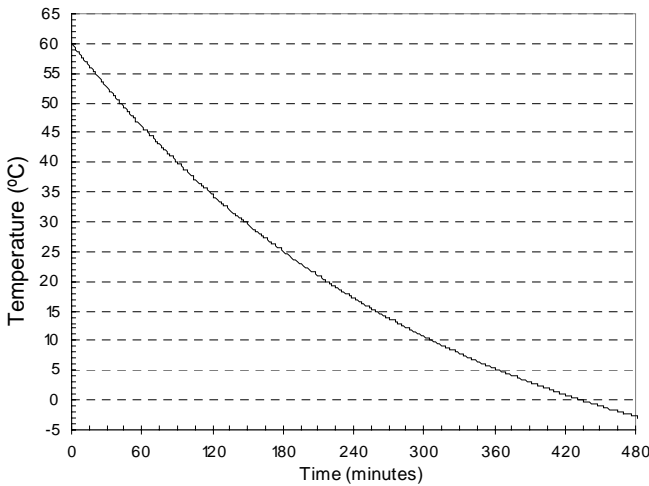


Figure 6. Estimated temperature variation inside the filter. Insulation thickness=10 mm, $T_{amb} = -20^\circ\text{C}$

Once the equivalent thermal conductivity had been derived from the tests performed at 22°C as ambient temperature, it was possible to predict the time required by the filter to reach the temperature of phase change for the eutectic which is at -5°C as was mentioned in a previous section. According to this, in the case that the ambient temperature is -20°C , at least

seven hours have to pass to reach the temperature for changing the eutectic phase. This is due to the insulation put in the car fuel filter without any other mechanism. Figure 6 confirms the previous assertion.

Performance tests of the eutectic fluid changing its phase by thermoelements

Several tests were done in order to gain experience about the transfer of heat due to the change of phase in the eutectic fluid. This change had been forced by thermoelements. Figure 7 shows a scheme about a test bench constructed to perform these tests.

As shown in figure 7, the test bench consists of a heat exchanger, a thermoelectric module and a small eutectic tank covered with a copper plate to make the temperature uniform on the cold surface of the thermoelectric module. The eutectic tank was surrounded with heat insulation of which the properties were tested as was mentioned in the previous section. The temperature was measured in the copper plate (T3) and at two different levels in the eutectic tank (T4 y T5). The thermocouples T1 and T2 measured the temperature on the hot side of the thermoelectric module. The ambient temperature was 22°C .

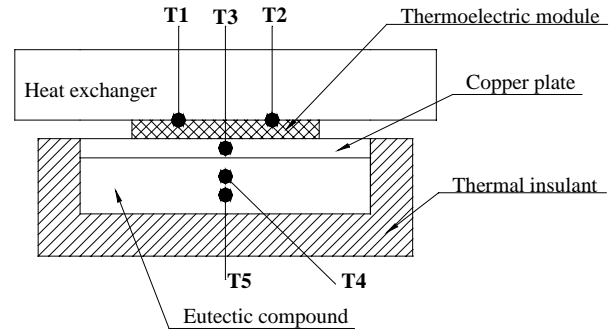


Figure 7. Scheme of the test bench.

The electric current supplied to the thermoelectric module was approximately constant at 2 A during the tests. This permitted to reach a temperature in the copper plate lower than the phase change temperature of the eutectic fluid (-3°C). Figure 8 and table 1 show the results obtained in one of tests performed.

Time	T1	V (V)	I (A)	Time	T1	V (V)	I (A)
0	22.6	6.7	2.0	75	27.3	7.6	2.1
15	24.4	7.3	2.0	90	27.8	8.0	2.2
30	25.5	7.2	2.0	105	28.2	8.0	2.3
45	26.1	7.3	2.0	120	28.7	8.8	2.4
60	27.0	7.4	2.0	135	29.0	9.1	2.5

Table 1. Voltage and current in the thermoelectric module

As can be observed in figure 8, the temperature in the eutectic fluid decreased and then remained constant at 0°C or -2.5°C . This difference of temperature depends on the depth in the eutectic tank. This test demonstrates that the thermoelectric modules can extract the heat accumulated in the eutectic fluid, but when the ambient temperature was 22°C . In this case the phase change of the eutectic fluid could not be shown clearly because the temperature on the cold side of the module was close to this point.

In figure 9 the previous test was repeated introducing the test bench inside an accurate refrigerator. In this case the ambient temperature was set at -10°C . As shown in Fig. 9, the

temperature remained more or less constant between -1.5°C and -2°C for fifteen minutes corresponding to the phase change of the eutectic fluid.

When all the latent heat was consumed, the temperature in all the eutectic fluid converged to be the same.

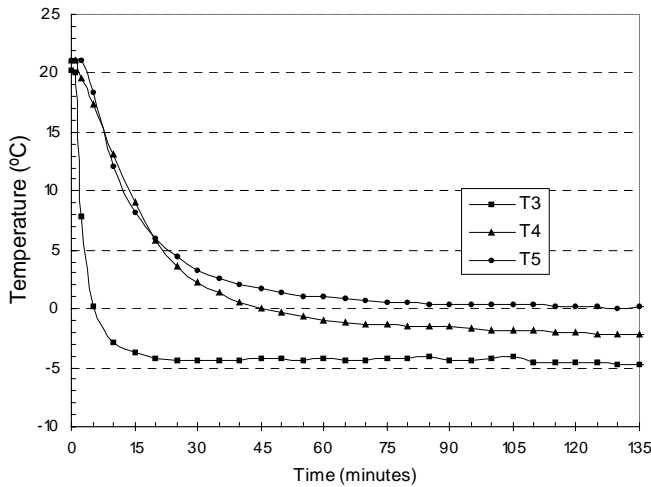


Figure 8. Temperature evolution of the eutectic fluid when the thermoelectric module is working, $T_{amb}=22^{\circ}\text{C}$.

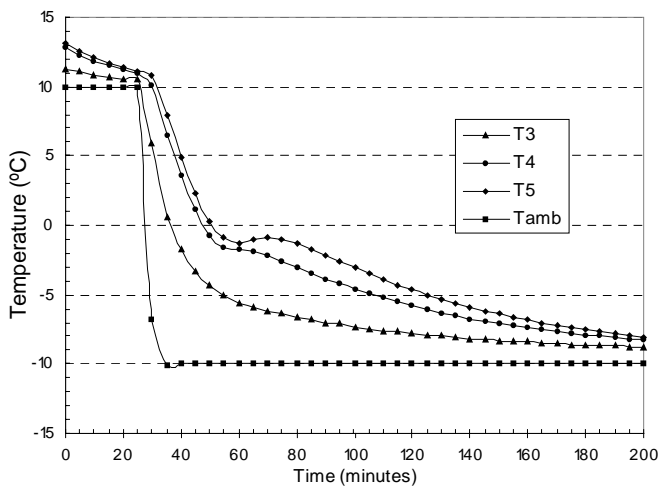


Figure 9. Temperature evolution of the eutectic fluid when the thermoelectric module is working, $T_{amb}=-10^{\circ}\text{C}$.

Performance analysis of the new fuel car filter using numerical simulation by finite element techniques

After the collection of knowledge obtained from the previously mentioned tests, a detailed analysis of heat transmission using numerical simulation by finite element method was done in the new car fuel filter represented in figure 2. The main objective of this simulation was to guarantee a path for the circulation of fuel inside the filter where the paraffins would be removed in the case that they existed in a cold starting of the car. The path would be created by the heat generated during the change of the eutectic phase using thermoelectric modules and the transmission of this heat through a pipe in contact with the input and output of fuel.

This study aided in the decision of whether or not it was possible to reach the objective of a free way of paraffins for the fuel before proceeding to the construction of the new filter.

The numerical simulations were done under the following assumptions:

- Initially, the temperature in all parts of the filter was the cold ambient temperature at -20°C , except in the eutectic tank which would be kept up to its phase change temperature and would remain constant due to the latent heat.
- The medium convection coefficient around the filter was $5\text{W}/\text{m}^2\text{K}$
- The entire filter was considered full of solidified fuel in the form of paraffins. This assumption makes the heat transmission difficult due to the low heat conductivity of the fuel.

The main results of the numerical simulations are presented in figures 10 and 11. In these figures only one half of the filter has been represented because the filter can be considered as a revolution figure (axial symmetry), in fact, the model was solved in two dimensions. Both graphics shows the temperature distribution inside the filter. A scale of temperature from the maximum to the minimum value was used on the left graphic, while on the right one was used another scale to show clearly the areas of the filter where the temperature was higher or close to the temperature of paraffin formation.

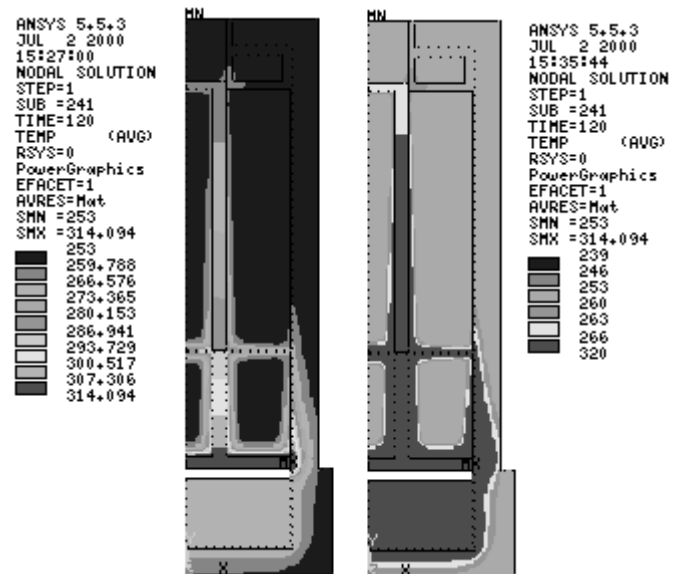


Figure 10. Distribution of temperatures inside the filter (K) after two minutes of thermoelements working. Interior pipe made of copper.

Both figures 10 and 11 contain the same information and they are obtained under the same conditions of simulation except for the material of the pipe that separates the fuel unfiltered (outer part) from the fuel filtered (inner part). The material of the pipe in figure 10 is copper and in figure 11 it is aluminium. This pipe is used to create a path free of paraffins along the pipe using the heat of phase change of the eutectic and a set of thermoelements. The main advantage of the use of this pipe is the generation of a free path of paraffins at the same time for the unfiltered fuel incoming to the filter and for the filtered fuel leaving the filter.

In order to build this new car fuel filter some redesign of a conventional filter had to be done. First, it was necessary to extend the original pipe till the bottom of the settling basin and to put it in contact the thermoelectric modules. Moreover, the thickness of the interior pipe had to be increased 5 mm in order to improve the heat transmission of a good thermal conductor such as copper or aluminium.

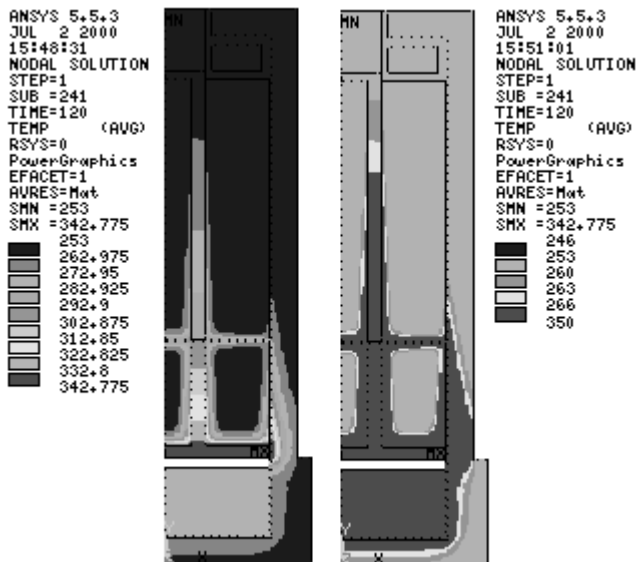


Figure 11. Distribution of temperatures inside the filter (K) after two minutes of thermoelements working. Interior pipe made of aluminium.

After several analysis the optimum heat power applied to the bottom of the filter was 150 W. As shown in Fig. 10, if this power is applied, after two minutes the temperature along a path in the interior pipe was higher than the temperature of formation of paraffins (-10°C).

Another important point analysed was the temperature reached at the point of contact between the thermoelectric modules and the pipe of the filter. If this temperature is too high, it could have a problem of capability to transfer heat and the process to create a path free of paraffins is less efficient. In figure 12 the evolution along the time of that temperature is presented using a copper pipe and an aluminium pipe. When using copper the difference of temperature between the cold and the hot side of the thermoelectric modules would be down to 45°C during all the transient. The results are worse in the case of using aluminium instead of copper, but it can be an alternative to the possible problems of corrosion in the joints of the different parts of the filter.

Selection of the thermoelectric modules

The thermoelectric modules to be used in this new design of car fuel filter have to work in two different modes. First, they have to work as an active insulation preventing the phase change of the eutectic fluid when the car is parked in a cold environment. They have to pump heat from the fuel to the eutectic fluid. Next, they have to force the phase change of the eutectic fluid and to transfer heat to the fuel inside a cold car filter. They have to transfer heat from the eutectic fluid to the fuel to eliminate the paraffins, if they exist.

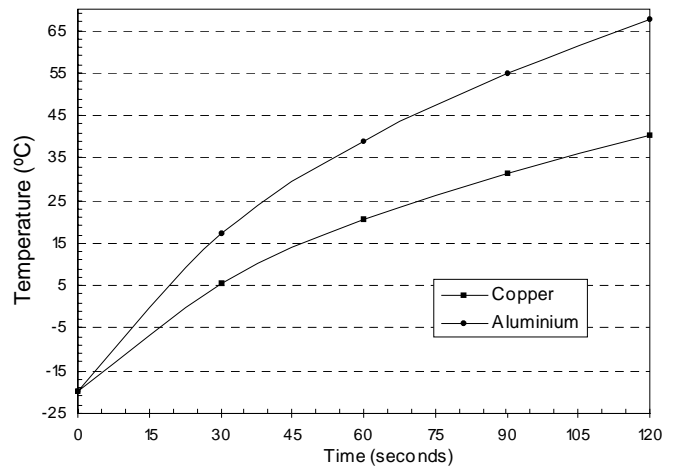


Figure 12. Evolution of the temperature at the bottom of the filter using copper or aluminium.

These two modes of operation of the thermoelectric modules would require different types of thermoelectric modules in order to operate in their best possible conditions because the difference of temperatures between the module sides is variable in the two modes of operation and also the heat power and its direction.

All the numerical simulations were done in order to get the maximum efficiency. The following properties of the Bismuth Telluride were considered constant:

$$\sigma = 2 \cdot 10^{-4} \text{ V/K} \quad k = 1.6 \text{ W/mK} \quad \rho = 9 \cdot 10^{-6} \text{ } \Omega \cdot \text{m}$$

According to the area available at the bottom of the car filter, it was decided to set four thermoelectric modules of 40x40 mm including 254 thermoelements. This allowed for the reduction of the electrical connections and there were a great variety of commercial modules with these geometric dimensions.

As was demonstrated in [1], a study was performed to select the best thermoelectric modules based on the ratio between the length and the cross section of the thermoelements. This ratio is the inverse of the geometric factor:

$$E = 1/GF = L_p / A_p$$

The following design criteria were taken into account in the selection of the thermoelectric modules:

- In both modes of operation the temperature of the side in contact with the eutectic fluid was considered constant and equal to the phase change temperature (-5°C).
- The heat power pumped to and from the eutectic fluid. In the first mode of operation, the heat power required to keep the eutectic without a change of phase was 2 W. This is required to equilibrate the heat losses around the eutectic tank isolated during the time that the car is parked. While in the second mode of operation, the heat power required to be transferred to the cold fuel was 200W in order to remove the paraffins. This power has to be pumped only for few minutes during the cold starting of the car.

Second mode of working of the thermoelectric modules.

As was mentioned, the temperature on the cold side was considered constant (-5°C) while increased on the hot side. An analysis was done in order to make a decision concerning the best thermoelectric modules to select.

Table 2 shows the estimation of optimum E for each of the differences of temperature between both sides of the thermoelectric modules. As example, eg, the particular value $E=445.8\text{ m}^{-1}$ insures the best efficiency at 30°C as difference of temperature between hot and cold sides and transferring a heat power $\dot{Q}_h = 50\text{ W}$ to the hot side, but if the temperature difference or \dot{Q}_h change, the thermoelectric module does not work in the best point.

ΔT	\dot{Q}_h	\dot{Q}_c	\dot{W}_e	COP	I	V	E
5	50	43.78	6.22	803.8	5.99	1.04	57.4
10	50	38.45	11.55	433.1	5.59	2.07	121.9
15	50	33.84	16.16	309.5	5.25	3.08	193.2
20	50	29.81	20.19	247.7	4.95	4.08	271.2
25	50	26.26	23.74	210.6	4.68	5.07	355.4
30	50	23.11	26.89	185.9	4.44	6.05	445.8
35	50	20.30	29.70	168.3	4.23	7.02	541.9
40	50	17.77	32.23	155.1	4.04	7.98	643.7
45	50	15.49	34.51	144.9	3.87	8.92	750.8
50	50	13.42	36.58	136.7	3.71	9.86	863.2

Table 2. "E" value which optimizes the efficiency, mode 2.

As shown in Fig. 13, the efficiency of the modules decreases when the difference of temperature between the hot and cold sides of the thermoelectric modules rises. The higher the E value is, the better the results are working with high temperature differences, but the worse they are with low temperature differences.

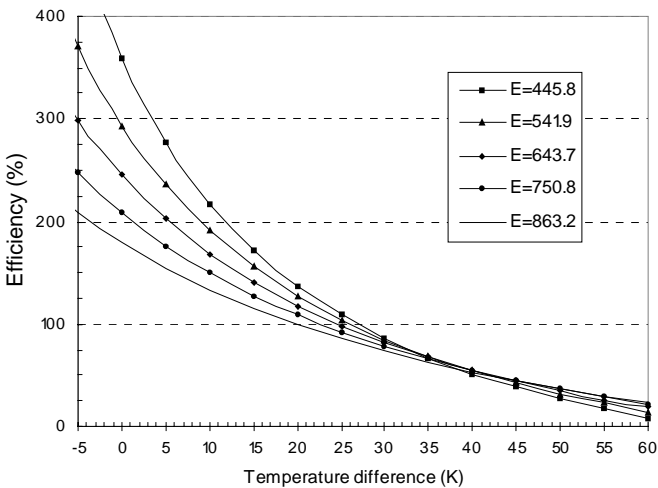


Figure 13. Efficiency of the thermoelectric modules in all the transients, $T_c = -5^{\circ}\text{C}$, $Q_h = 50\text{ W}$.

First mode of working of the thermoelectric modules.

As was mentioned, the temperature on the hot side is constant (-5°C) while decreased on the cold side. In this case, only one thermoelectric module is required pumping 2 W to the eutectic fluid.

T_h	T_c	\dot{Q}_h	\dot{Q}_c	COP	I	V	E
-5	-10	2	1.74	779.5	0.24	1.05	1431.2
-5	-15	2	1.51	408.7	0.23	2.12	3046.1
-5	-20	2	1.30	285.2	0.22	3.20	4853.0

Table 3. "E" value which optimizes the efficiency, mode 1.

As shown in Table 3, the minimum value of E would be 1431.2 m^{-1} . If this E value is used in the second mode of operation, the thermoelectric modules would be optimized for a difference of temperatures between sides of 75°C . In this case, if the interior pipe is made of aluminium, a temperature difference that is so high, is achieved.

Using equations presented in [2], the behaviour of two commercial thermoelectric modules were analysed in both two modes of operation. The theoretical characteristics of both modules are shown in Table 4.

	N	E	I_{max}	\dot{Q}_{max}	V_{max}	ΔT_{max}
1	254	1295.9	3.9	33.4	15.4	70
2	254	583.2	8.5	68.8	15.4	67

Table 4. Main characteristics of two commercial thermoelectric modules used (1) CP-1.4-127-10L, (2) CP-1.4-127-045L.

Figures 14 and 15 show the performance of both commercial thermoelectric modules for the two modes of operation in the new car fuel filter. As an example, the module CP-1.4-127-045L is not efficient in the first mode of operation (figure 15) when the difference of temperatures on both sides of the module is 15°C , but this condition is very far away from the real conditions in the new filter. However, the behaviour of the same module in the second mode of operation (figure 14) is better than the behaviour of the module CP-1.4-127-10L, at least until the difference between the side temperatures is up to 45°C .

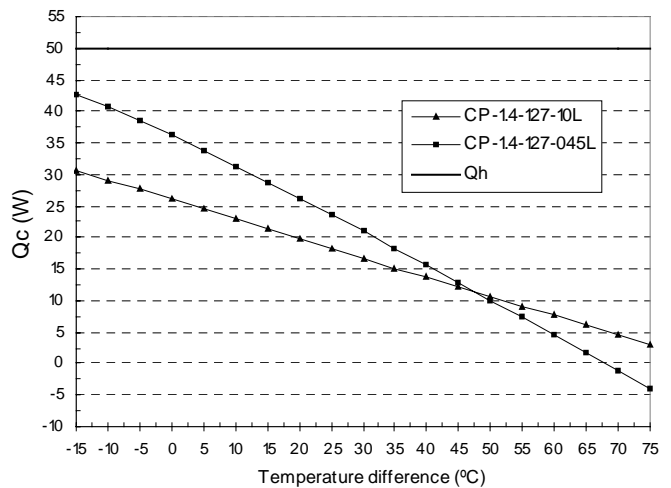


Figure 14. Heat power extracted from the cool side. $T_c = -5^{\circ}\text{C}$, $Q_h = 50\text{ W}$. Second mode of operation of TE modules.

In order to select the best thermoelectric module for this application, the capability to transfer heat through the interior pipe in the filter has to be taken into account, because it will fix the difference of temperatures on the sides of the thermoelectric modules. In this application copper is

recommended, however it is also possible to use aluminium, but with less efficiency.

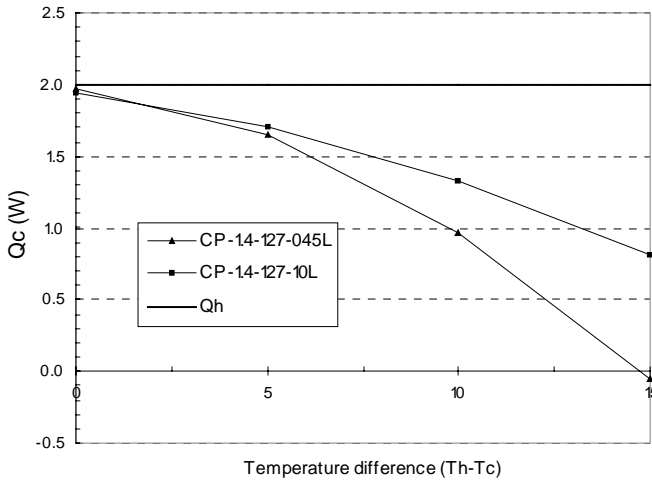


Figure 15. Heat power extracted from the cool side. $T_h = -5^\circ\text{C}$, $Q_h = 2\text{W}$. First mode of operation of TE modules.

Nomenclature

All magnitudes are expressed in SI units, except time.

A : total surface of the filter.

A_1 : lateral surface of the filter.

A_2 : surface of the bottom of the filter.

A_3 : surface of the top of the filter.

A_p : cross section of a thermoelement.

COP : Coefficient Of Performance

c_{p_w} : water specific heat

E : inverse of the geometric factor.

e_1 : thickness of the insulation in the lateral surface.

e_2 : thickness of the insulation at the bottom.

e_3 : thickness of the insulation at the top.

m_w : mass of water inside the filter.

I_{max} : input current resulting in greatest ΔT .

K_i : thermal conductivity of the insulation.

L_p : length of a thermoelement.

n : number of thermoelements in a module.

\dot{Q}_c : amount of heat absorbed on the cold side.

\dot{Q}_h : amount of heat given away on the hot side.

\dot{Q}_{max} : maximum amount of heat that can be absorbed on the cold side (occurs at $I = I_{max}$, $\Delta T = 0$).

T_{amb} : ambient temperature.

T_c : temperature of the cold side during operation.

T_h : temperature of the hot side during operation.

T_0 : initial temperature.

V_{max} : voltage at ΔT_{max} .

ΔT_{max} : maximum difference of temperature that a TE module can achieve (occurs at $I = I_{max}$, $\dot{Q}_c = 0$).

Conclusions

This paper presents the results of an investigation about the use of thermoelectricity in a new design for a car fuel filter in order to prevent the problems associated to its obstruction due to the creation of paraffins when the car is stopped for a long time in an environment where the temperature is very low. The new filter uses the conventional filter adding an external insulation, a small tank at the bottom of the filter including an eutectic fluid and a set of thermoelectric modules added in between the bottom of the conventional filter and the top of the tank. All parts are covered by insulation. This new fuel filter allows for the storage of heat coming from the circulation of the fuel in the filter when the car is running using insulation and an eutectic fluid. The thermoelectric modules will operate in two modes when the car is stopped for a long time in a cold environment. In the first mode, the TE modules will operate as an active insulation in preventing the phase change of the eutectic fluid. In the second mode, the TE modules will force to change the eutectic phase, when the car is required to start, transferring heat from the eutectic phase change to the fuel and eliminating the paraffins along a path from the input to the output of the fuel in the filter.

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