Simulation of time response of thermal sensors with fins

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Abstract

This paper shows by numerical simulation that addition of fins to a thermal sensor may be a convenient way to improve its time response. Fins are of usefulness when the heat exchange sensor-ambient is a rather poor one. In the present work the fin performances of configurations of interest are evaluated with the aid of an standard finite element package. Typical responses of sensor to a step function are given. The numerical results helps to establish criteria of engineer utility.

1 Introduction

Time response of a thermal sensor depends on its inner structure and the characteristic of the heat exchange between the sensor itself and the ambient.

By means of a simplified analysis, considering the sensor as a lumped system, it can be found the first order response of the sensor [1]. So the typical time constant $\tau$ can be written:

$$\tau = \frac{\rho c V}{h A}$$  \hspace{1cm} (1)

being:

$\rho$ : density
$c$ : specific heat
This classical formula states the physical fact that the more sensor thermal capacitance ($\rho c V$) the less sensor ability to follow thermal ambient evolution. On other hand, a high $h A$ value means a great heat exchange, and consequently, a short time lag.

Nothing is said about the time influence of the external shape of the sensor. Common experience seems to probe that shape is of little relevance. However, certain experiment in which the addition of fins to a sensor produces an important reduction of the lag time [2] and the numerical simulations presented here, show that an adequate design of the external shape could be a way to improve the sensor in many cases.

The optimal design of fins for lag time reduction is not a simple task. The known fins theory refers basically to stationary situations and is not applicable here. The use of a package software (ALGOR) based on finite elements appears as a convenient tool to deal with the intrinsic geometric complexity of the fins design problem. The governing partial differential equation solved in the analysis is

$$\rho c \frac{dT}{dt} = \nabla \cdot (k \nabla T) \quad \text{in} \quad \Omega \quad (2)$$

subjected to the following boundary conditions:

$$(k \nabla T) \cdot \vec{n} = 0 \quad \text{in} \quad \Gamma_o$$

$$(k \nabla T) \cdot \vec{n} = h (T - T_a) \quad \text{in} \quad \Gamma_h$$

with:

- $c$: specific heat
- $\rho$: density
- $k$: thermal conductivity
- $h$: heat transfer coefficient
- $\vec{n}$: outward unit vector normal to the surface
- $T_a$: ambient temperature

Figure 1 shows the configuration of the sensor with fins and the symmetry condition applied to perform the finite element analysis.
Figure 1: Thermal sensor with fins

a) Geometric configuration
b) Finite element representation of the model
2 Considerations about symmetry of thermal sensors and simulation technique

Currently available sensors exhibit a great diversity of shapes, sizes, and inner structures. Thermal modelization of all of them is possible but an enormous task which are out of the scope of the present paper. Nonetheless, it is possible to simulate the effect of fins using cylindrical symmetry in such a way that a wide number of situations can be represented. It must be taken into account that sensors are frequently encapsulated in cylindrical tips (platinum sensors, e.g.) or protected with tubular wells (thermocouples). After symmetry choosing, the problem is to find fins configurations which work properly. To do it, the time evolution of a thermal sensor with a given fins configuration must be compared with the evolution of the corresponding bare sensor. Time evolution are produced in each case by the same step change of the environment temperature. As a reference, it is considered that the bare sensor has a thermal capacity of 0.1 (S.I. units). As the calculations are focused on lumped systems, the Biot Number [3] is selected to be lower than 0.01.

Some experimental knowledge about sensor with fins [2] and classical thermometry theory aid to identify basic subjects to be studied in order to reduce lag time. Firstly, it is important to determine for what external conditions (heat transfer coefficient value) the fins can produce a reasonable profit. On the other hand, to increase the heat exchange area (2 x fin area x number of fins), to vary the fin material and the cross section of fin, are other possibilities to be explored.

The following simulations examples were performed to illustrate about these sorts of subjects.

EXAMPLE 1: Time performance of a sensor with four fins for different heat transfer coefficient values.

A sensor with four fins of conductivity $k_f$ equal to the bare sensor conductivity $k_s$ was considered for simulating the sensor response to a 30 degree step change in the ambient condition.

First simulation was made using a $h = 1 \text{ W/ m}^2 \text{ C}$ value, it is said that $h$ is a little below the limit of natural convection (2-25 W/m$^2$ C, according to [4]). In figure 2(a) the time evolutions for the bare sensor and the sensor with fins are shown. The improvement due to the fins addition can be clearly appreciated. A reduction in the time constant of 51% is obtained by using the fins.

Simulation corresponding to $h = 5\text{ W/ m}^2 \text{ C}$ (figure 2(b)) shows an important "fins effect", even not so "strong" as in the $h = 1 \text{ W/ m}^2 \text{ C}$ case.

For values of the heat transfer coefficient larger than 10 W/ m$^2$ C the use of fins only originates a little advantage, as can be deduced from figure. 2(c). A comparison between the time lags of the sensor with and without fins can be seen in the figure. 3(a), for the range $h = 1$ to $10 \text{ W/ m}^2 \text{ C}$. The curve in figure. 3(b) gives the percental reduction of $\tau$ using fins.
It must be noted that the case $k_s = k_f$ can be associated to a particular fin shaped design of a thermal sensor. Such a sensor could be of interest in practice. Anyway, the use of more conductive fins material, up to $k_f = 10$ W/m°C, can produce certain time response acceleration. For $k_f$ from 10 to 50 W/m°C $\tau$ remains near constant (see figure 4).
Figure 3: Time lag of sensor with and without fins vs heat transfer coefficient

Figure 4: Time lag of sensor with and without fins vs fin thermal conductivity
EXAMPLE II: Effect of fin thickness on time constant

To improve time response of thermal sensors the total thermal capacitance of the attached fins must be negligible. Optimum performance of the sensor with fins are achieved using a fin thickness << sensor radius. Such thin fins do not increase the total thermal capacitance but if their cross section are reduced in excess, heat flux sensor-fin will be very poor and the fins contribution will be null.

The numerical simulation for a typical case (figure 5) shows the existence of an optimum thickness which can be associated to a minimum time lag.

Figure 5: Effect of fin thickness on lag time reduction
EXAMPLE III: Reduction of the time lag by multiplying the fins number

Multiplication of thin fins produces sorpressive reduction of the time constant when the sensor is operating in a poor heat exchange condition. In figure 6 the number of fins (thickness = 0.01 cm) is modified between 0 and 16. For the last value results a reduction of .79% is obtained.

![Graph showing the effect of fin number on lag time reduction](image)

Figure 6: Fin number effect on lag time reduction
3 Conclusion and perspectives

A little studied strategy of time lag reduction of thermal sensors has been evaluated by finite elements analysis. The numerical results illustrate about the main features of such reduction strategy. An initial simplification of the involved modelization seems to be the better way to point out the fundamental design requirements. In present work, numerical simulations indicate that the technique is only reliable with some conditions e.g., rather low $h$ value, thin fins, and a great $hA$ value, (but with negligible total thermal mass). Authors think that the information here displayed is of relevance to deal with an ample range of measure-control temperature problems. Research in the field of this paper appears as a very promising one.

References