Thermal modelling of a thick film based soot sensor for automotive applications

Andreas Larsson, Frøydis Oldervoll

SINTEF ICT
Forskningsveien 1
0314 OSLO

andreas.larsson@sintef.no

Abstract

Legislations necessitate new and more sophisticated control of diesel engines with sensors for On Board Diagnostics (OBD). In the mnt-era.net project, 'Soot sensors for a healthy environment'; a soot sensor based on an innovative technology was developed. Thermophoresis is employed, in terms of a cold sensor surface for increased sensitivity to soot, where the concentration is very low. The sensor device is, e.g. a common finger electrode structure; a chrome/gold finger electrode, employed on an alumina substrate, monitoring the resistivity change for soot deposition. To achieve a cold spot at the sensor surface, the thermo-mechanical design of the sensor must be considered very carefully. This paper presents results from the thermal modelling used to find an optimal cooling solution for the sensor.

A simple 2D finite element analysis (FEA) was done to study the temperature distribution as an effect of interconnection choice. A 3D model was then analyzed, for a more realistic heat transfer between the hot exhaust gases and the substrate. This model was as well used to check the effect of the insulation lengths. As a result from the initial FEA results, a new concept for the sensor packaging was developed; an air filled, 'thermos concept'. The thermos concept was modelled as a realistic 3D model including compressible, turbulent flow with both conduction and convection. The simulation results from the thermos concept show a dramatic improvement in temperature reduction at the sensor location. It seems achievable to get temperatures well within the range for the thermophoresis to work.

Key words: Thermal modelling, concept development, FEA

Introduction

The ever increasing demands for cleaner vehicle exhaust gases due to legislations and customer demands necessitate efficient and reliable, post cleaning equipment and sophisticated control tools. To monitor and control the levels of pollutant particles and the health of e.g. a particular filter, a sensor is needed.

The SootSens project was started to investigate and try to design a sensor for soot density detection inside an exhaust pipe for diesel engines [**1**]. The sensor concept is based on the physical phenomena thermophoresis. Thermophoretic deposition of particles in a gas is driven by the temperature gradient [**2**]. Small soot particles are drawn towards colder regions in the gas and may finally deposit onto cold surfaces, if present. When soot deposits on top of a common finger electrode structure it is possible to monitor the resistance change, i.e. detecting soot. This could then tell if the particular filter is full and needs be regenerated or replaced.

The aim for the SootSens project was to see if thermophoresis could be used for soot sensing, by efficient cooling of a sensor surface. The particle velocity for thermophoresis is directly proportional to the temperature gradient. Thus, a high gradient in the sensor vicinity increases the sensitivity of the sensor, since more soot is deposited. The aim of the current study was to develop a thermal design that would lower the temperature on the sensor surface as much as possible, relative to the hot exhaust gases and thus give efficient soot deposition. Preliminary results within the project have suggested that a temperature difference, between the sensor surface and the hot gases, in the magnitude order of 50-70°C, is enough for thermophoresis to work.

The finite element analysis (FEA) program COMSOL Multiphysics was used to study the different design parameters.

Method

The thermal design was studied and improved with the aid of FEA. FEA is a fast and cost effective method to do extensive experimental work without time consuming and costly real life experiments. However, results from FEA shall, a far as possible, be validated by theoretical estimations and/or real life experiments. The reason for this is that the results of the FEA can be misleading. The results can be sensitive to the input and usage of the FE program. E.g. the use of non realistic physical conditions can generate results, but results that are not representative for the problem at hand. This paper will not get into further details about technicalities around FEA. Instead it will focus on the thermal design and how FEA was used for design improvements and train of thought. Experimental work for validation of the theoretical models presented here, are work in progress. Preliminary results seem promising and coherent with simulations.

Physical conditions

The normal operation temperature of the exhaust gas is around 300°C and the mass flow rate can be up to 0.6kg/s (corresponding to 7.9m/s for the pipe used in the simulations) [**3**]. The exhaust pipe was estimated to hold a wall temperature of around 120°C. Near sea level operation was considered, hence ambient pressure, 1atm, was applied at the outlet of the pipe.

The flow rate give Reynolds numbers (Re) in the magnitude order of 100-500 for 17% of max flow rate and up to 47000 for max flow rate, see Table 1. A pipe flow with Re in the magnitude order of a few 10^3 or more may be considered to be in the turbulent region [**4**]. This means that the flow may be estimated to be laminar for lower flow rates and is probably fully developed turbulent flow for higher flow rates. Re is calculated according to Equation 1.

Table 1: Reynolds number for the different parts in the flow.

Part	Mean fluid velocity u [m/s]	Typical dimension D [m]	Kinematic viscosity ν [m^2/s]	Reynolds number Re
Pipe	7.9	0.305	$50 \cdot 10^5$	$\sim 4.7 \cdot 10^4$
Pipe	1.3	0.305	$50 \cdot 10^5$	~520
Sensor	7.9	0.005	$50 \cdot 10^5$	~790
Sensor	1.3	0.005	$50 \cdot 10^5$	~130

Equation 1: Reynolds number

$$Re = \frac{uD}{\nu}$$

where u is the mean fluid velocity, D is the typical dimension and ν is the kinematic viscosity of the gas.

Boundary conditions (BC) for fluid to solid surface were set to 'No slip'.

Materials

The material properties used for the FE models are presented in Table 2.

Table 2: Material properties used in FE models

Part	Density ρ [kg/m^3]	Dynamic viscosity η [Pa*s]	Thermal Conductivity k [W/(m*K)]	Heat capacity C_p [J/(kg*K)]
Sensor	3900	-	25	900
Heat sink	8700	-	400	385
Insulation*	1000	-	0.1	1000
Pipe	7850	-	44.5	475
Exhaust	1.15	$1 \cdot 10^4$	0.025	900

* Typical values for insulating materials

Sensor placement

The sensor is placed at the top of a long thin alumina substrate and the senor is integrated in the thick film. Further details of the sensor will not be covered here. A picture of the sensor can be seen in Figure 1.

Figure 1: Soot sensor prototype.

Finite element analysis

Mesh and sensitivity

The mesh was checked for all models and was found to be adequate. The models sensitivity to the choice of material properties was checked and found to be satisfactory for this study.

Pipe wall insulation

The first idea was to have the sensor substrate penetrating the exhaust pipe wall and cool it on the outside by a water cooled heat sink maintained at

22°C. The aim was to see if the heat conduction within the substrate was sufficient to conduct heat from the sensor surface to the exterior, to keep it cool enough. The temperature distribution within the sensor was believed to be highly dependent of how well the sensor was thermally insulated from the pipe. To study this, two 2D FE models were analysed; one sensor without insulation and one with insulation. Figure 2 shows the BC setup used for both 2D models. It also shows the global temperature distribution for the insulated case. The 2D FEA demonstrate that insulating the sensor from the pipe will drastically improve the cooling performance, see Figure 3.

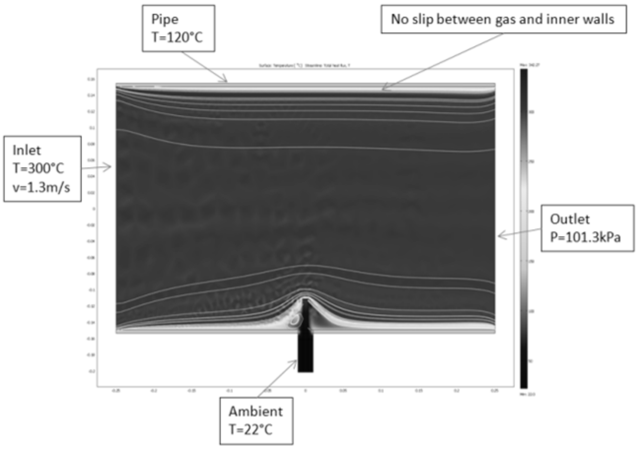
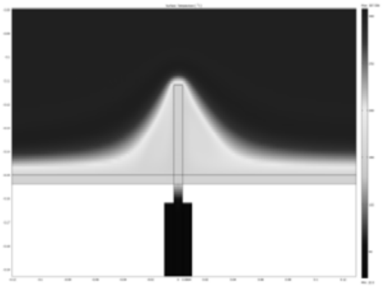
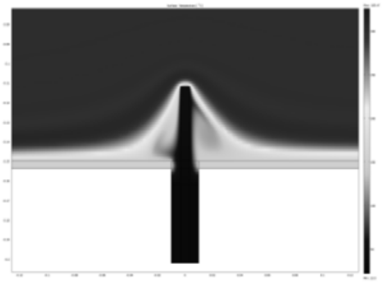


Figure 2: Temperature distribution for insulated sensor. Streamlines shows velocity field.



(a) without insulation, T_{sensor}≈146°C.



(b) with insulation, T_{sensor}≈45°C.

Figure 3 Temperature distribution for sensor.

There is a low temperature zone at the bottom of the sensor in Figure 2 and Figure 3. This temperature wake is an effect from the 2D assumption with incompressible laminar flow. It makes the sensor seem like an 'infinite wall' object, rather than a rod. I.e. no hot gas can flow around the rod where the sensor intersects the pipe, instead it force most of the hot gases to pass over the sensor instead. This produce regions where gas can circulate and loose heat energy. Still, the effect of the insulation is evident.

Insulation length

From the 2D analysis it was clear that a 3D model was needed. A study of the effect of the insulation length was also proposed.

Since the COMSOL modules, at hand when the 3D analysis was started, did not support compressible turbulent flow, two simplified 3D FE models were established; one with short and one with long insulation. They were both based on incompressible, laminar flow. But, as mentioned earlier, the flow is probably turbulent, at least for higher flow rates, see Table 1.

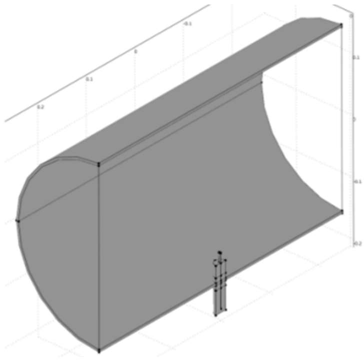
The model with the long insulation is shown in Figure 4. The BC was applied as described earlier, cf. Figure 2. To reduce the mathematical size of the model, symmetry conditions were used.

Due to the turbulent nature of the flow, at higher flow rates, no stationary solution could be found. For a flow velocity of 1.3m/s, a solutions was found for each model.

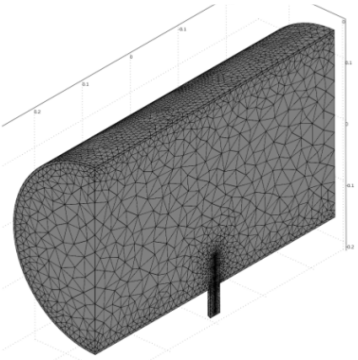
The temperature distribution plots for the two models are shown in Figure 5. It can be seen, as anticipated, that the sharp temperature gradient is smeared out and pushed further towards the upper part of the sensor substrate, the longer the insulation gets. This will reduce the temperature at the top of the substrate where the sensor is placed.

It is also clear that the heat from the hot exhaust gases, quite easily penetrates the insulation. To achieve acceptable temperatures at the sensor, too much insulation is required to be practical for the SootSens project.

For the short insulation model, a case with lower pipe temperature (60°C) was also simulated. The results indicated a small decrease in overall temperature, ΔT≈-3°C, at the sensor centre.

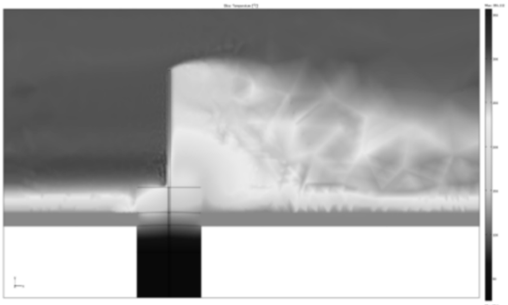


(a) Geometric model (exhaust gas is hidden)

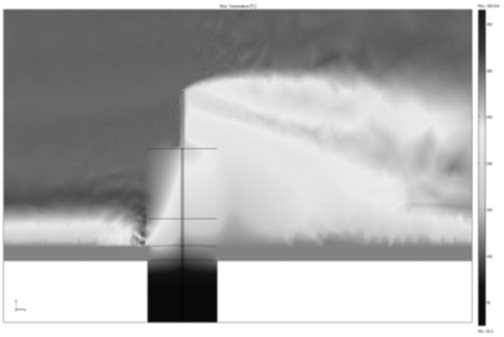


(b) Symmetric FE model (b)

Figure 4: 3D model.



(a) with short insulation, T_{sensor}≈285°C.



(b) with long insulation, T_{sensor}≈275°C.

Figure 5: Temperature distribution for model.

Improved thermos design

A more realistic and complete 3D model was set up to capture the compressibility of the gas and turbulence at higher flow velocities.

The heat penetration, from earlier results, gave inspiration to adding a heat shield. A heat shield could conduct the heat directly to a distant location, away from the sensor at the top, e.g. the pipe wall. Thus, the design of the insulation for the sensor was improved in the model, as well, to test the heat shield idea. The improved design works basically as a thermos which the sensor sticks trough, see Figure 6. The 'thermos design' provides a heat shield that conduct the heat from the hot gases (~300°C) directly to the much colder (~120°C) exhaust pipe walls.

Air is encapsulated by the heat shield and acts as a good insulator. The air will probably reduce the efficiency of the cooling of the top part of the substrate, to some extent, by natural convection (NC). This effect has not yet been included in the full model, since it greatly complicates an already advanced and computer power expensive model. A smaller local model has been checked to confirm the presence of NC. Preliminary results indicate that NC does not reduce the efficiency much for the thermos design. From a thermal management point of view, vacuum instead of air would be a better choice, but that makes the production process of the cooling device more complicated. Thus, the primary interest here, was to see if air would be sufficient.

To fasten the sensor piece at the bottom interconnection (sensor to thermos walls) an insulating adhesive was added and at the top connection a small piece of insulating ceramic paper was added. As for the previous models, the sensor was still cooled at the outside of the pipe, keeping it at 22°C. This FE model was modelled with non-linear materials for the sensor substrate and the insulation, for more realistic thermal material behaviour, see Table 3 and Figure 7. Table 4 shows the remaining materials properties used for the improved model.

To reduce the model size, i.e. decrease computational power required to solve the model, symmetry was used and the pipe and heat sink were excluded from the model. The temperature BC, seen in Figure 2, was instead applied directly to the gas mantel surface and the sensor/heat sink interface surface. This approximation should not affect the solution much, since the temperature distribution is very uniform within the pipe and heat sink, cf. Figure 2, Figure 3 and Figure 5.

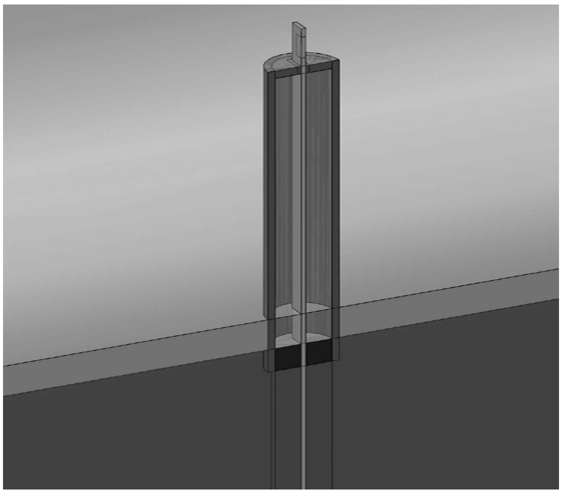
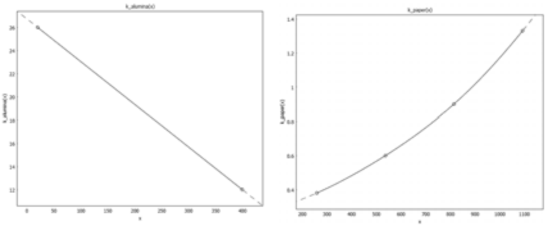


Figure 6: Cross-section of the thermos design.

Table 3: Thermal conductivity as a function of temperature, given input.

Part	Temperature T [°C]	Thermal conductivity k [W/(mK)]
Sensor substrate	20	26
	400	12
Insulation at top interface	260	0.38
	537.8	0.60
	815.6	0.90
	1093.3	1.33



Sensor substrate **Insulation at top interface (thermos/sensor)**

Figure 7: Thermal conductivity as a function of temperature. X-axis is temperature and y-axis is thermal conductivity.

Table 4: Material properties used for improved FE model.

Part	Density ρ [kg/m^3]	Thermal Conductivity k [W/(m*K)]	Heat capacity C_p [J/(kg*K)]
Adhesive	1161	3.33	1046.7
Sensor substrate	3900	see Table 3 and Figure 7	900
Insulation at top interface	192.1	see Table 3 and Figure 7	1046.7
Thermos walls	8700	400	385

Since the flow velocity is much lower than 0.3M the exhaust gas was modelled as weakly compressible [**5**]. The turbulence was modelled using the k-ω turbulence model. Heat transfer between the gas and the sensor surface was coupled and both heat conduction and convection was included.

From Figure 8 it is clear that the heat shield or heat guide works as expected. The heat is removed efficiently, and the temperature at the substrate top is reduced significantly compared to the previous models.

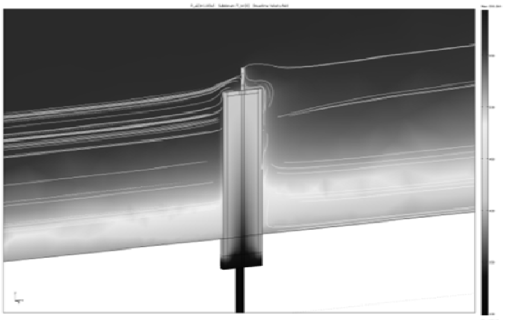


Figure 8: The grey scale shows the temperature distribution and the streamlines shows the velocity field for the thermos concept. T_{sensor}≈176°C.

Comparison of results and discussion

Since the aim for the study was to achieve a relatively low temperature at the sensor surface, for the thermophoresis to work, a comparison of the temperature at the sensor centre for the 3D cases was performed. The input data and results from the FEA are shown in Table 5 and Figure 9. It can be seen that the temperature of the pipe walls affects the sensor temperature little, when only insulation is used (setup 1 and 2). For the thermos design (setup 4) this will instead significantly affect the performance, since that design is somewhat limited by the pipe temperature. The results also show that a longer insulation (setup 2 and 3) reduces the temperature some, but that it is not efficient enough. The temperature reduction at the sensor was found to be significant for the thermos design.

Higher flow rates increase the heat transfer between the gas and the solid while a more turbulent flow reduces it [**6**]. It is believed that the exhaust gases are more or less always in the turbulent flow region for a real exhaust gas flow. Thus, more efficient cooling is probably required to maintain low temperatures at higher flow rates than for low flow rates. Note that the flow rate is at max (7.9m/s) for the thermos concept and only at 17% of max (1.3m/s) for the others in Table 5 and Figure 9.

Table 5: Inputs and corresponding results for temperature estimation at sensor centre

Setup [#]	1	2	3	4
Insulation type	Short	Short	Long	Thermos
Flow velocity [m/s]	1.3	1.3	1.3	7.9
Exhaust gas temperature [°C]	300	300	300	300
Pipe wall temperature [°C]	60	120	120	120
Resulting temperature at sensor surface [°C]	282	285	275	176

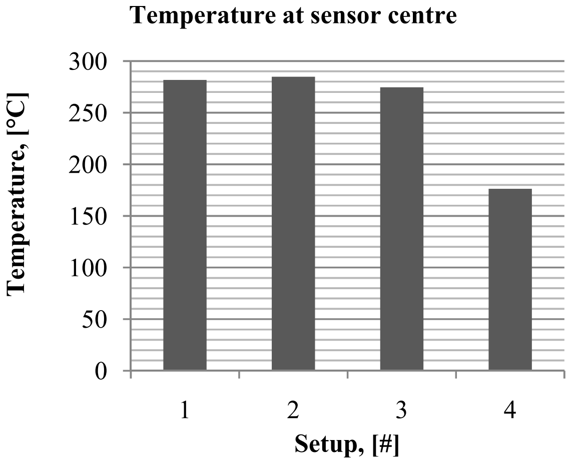


Figure 9: Comparison of temperature at sensor centre for the cases presented in Table 5

These case studies shows how FEA can be used to develop an understanding of the problem at hand, during the concept development, and how new ideas emerge from the new insight. It also illustrates that FEA can be used to easily test the effect of an improvement or design change, without extensive real experiments and testing. FEA provides a cost effective tool when designing a package, whether the design is e.g. thermal, electromagnetic or structural. Note that, FEA does not replace tests and experiments, it rather provides a quick, easy and cost effective tool during the design process, if used with care.

Conclusions

This study shows that it is possible to cool a ceramic substrate, mounted in a hot gas flow, enough for thermophoretic deposition to occur. It also shows the value of using FEA when designing a package for thermal management of a device.

Acknowledgments

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