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The Use of a Phase Change Material within a Cylinder Wall in order to Detect Knock in a Gas SI Engine

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Abstract

The present paper studies the possibility to develop a new method of knock detection in a gas SI engine. This method is based on the increase in the wall heat flux when knock occurs. It also must be simple enough to be used by industry. In order to achieve this goal, a metallic Phase Change Material is put within the wall cylinder. The melting of the PCM means that knock has occurred and is persistent. The melting of such a phase change material would be easy to detect using industrial measurement tools.

In this paper, numerical simulations of unsteady heat transfer across the cylinder wall are presented. Unsteady heat transfer from the hot gas to the wall chamber is simulated by a self-developed program. This program allows fixing instantaneous local heat flux values deduced from the literature in case of both normal and knocking combustion. Heat transfer across the cylinder wall is solved by the finite volume technique. Grid is validated by comparison with analytical results. Melting is treated by the Voller and Prakash model and Sodium is chosen as PCM. Among all the results, we can notice that an increase in the knock intensity changes the shape of the isothermal curves around and inside the PCM. This leads to an increase in the melting velocity with a higher rate than the increase in the heat flux.

Introduction

Knock is due to an unexpected combustion in Spark Ignition (SI) engines. It is a result of spontaneous ignition of a portion of end gas in the engine chamber, ahead of the propagating flame. The very rapid heat release implied by this abnormal combustion generates shock waves that can lead to the decrease in output, the increase in some pollutants and the destruction of the engine. Although knock has been more or less overcome in gasoline engines by controlling the fuel quality, gas engines are not safe from knock. Natural gas contains different gases (CH_4, C_2H_6, etc.) with variable knock-resistance. Its composition varies widely with time and place. Consequently, an engine can start to knock if the gas reaches too low anti-knocking properties. A reliable method for the detection of knock in gas SI engine is then of high interest.

The knock detection is currently based on data generated by accelerometers or cylinder pressure sensors [1, 2]. Due to its simplicity, accelerometry (vibration measurement) is largely employed in industry. Nevertheless, parasitic noises relative to engine operation often affect the quality of knock detection in this method. On the other hand, cylinder pressure data provide a direct and reliable way to analyze knock. The major disadvantage is that a suitable probe has to be provided in the engine cylinder that may reduce the engine lifetime [3].

Knock occurrence is accompanied by an important increase (up to 4 times higher) in the wall heat transfer inside the combustion chamber [4-6]. Thus, an alternative to the current methods could be the detection from analysis of the thermal signal measured near the outer side of the cylinder. However, the deadening effect of the cylinder wall makes such detection difficult [7-9]. Moreover even low knock intensity (with low increase in heat transfer) should be detected in order to protect reliably the engine. The use of a Phase Change Material (PCM), placed within the wall cylinder, can make this target reachable because the phase change is easy to detect with industrial tools.

The present paper treats numerically the melting of a metallic PCM. It is divided into three main parts. Firstly, the background in the field of knock detection deduced from heat transfer analysis is presented. Secondly, the

Nomenclature

c_p	specific heat capacity, J/kg.K
d	depth of the slot, m
e	wall thickness, m
h	enthalpy, J/kg
k	thermal conductivity, W/m.K
l	connecting rod length, m
r	crankshaft radius length, m
T	temperature, K
t	time, s
w	width of the slot, m
w/d	width to depth ratio, -
x	horizontal coordinate, m
y	vertical coordinate, m

Greek letters

α	thermal diffusivity, m^2/s
Δh	latent heat of melting, J/kg
θ	crank angle, rad
ω	angular frequency, rad/s
ρ	density, kg/m^3

Subscript

e	on the outer side of the wall
i,	i direction
m	time averaged
ext	external
w	on the inner side of the wall

modeling assumption and the validation of the model are detailed. Finally, model is exploited and main results are then exposed and discussed.

Background

In previous studies [7-9], we studied numerically the thermal signal in the coolant flow close to the outer side of the cylinder wall. A rib or a slot was made on the external surface in order to enhance the temperature variations. An example of sketch of those studies is presented in Fig. 1. We treated the case of a water-cooled engine running at 1500 rpm and full load. Its stroke is 170 mm and bore is 152 mm.

The computational domain (Fig. 1) includes the cylinder liner, (made of cast iron), the water jacket (10 mm wide) and the cylinder head (made of aluminum). The representation of the latter is very simplified because only its contribution to the vertical heat flux in the cylinder liner has to be taken into account. A cavity [8] or a rib [9] was machined at the top dead center on the outer surface of the cylinder liner. The coolant flow is vertical and extents from the bottom to the top of the cylinder liner along the external side of the cylinder. Calculations have shown that a two-dimensional plane representation was equivalent to a 2D asymmetric one so the coolant is assumed to flow in a 10 mm wide rectangular duct.

The heat transfer from the hot burnt gas to the chamber walls is simulated by a self-developed program that allows fixing instantaneous heat flux values deduced from the literature in case of both normal and knocking combustion. An example of heat flux is plotted in Fig. 2. In all the studied case, knock occurs one time every two cycles. The combustion starts when the piston reaches top dead center and its duration is 0.033s (corresponding to 30° Crank Angle at 1500 rpm). The equation of the piston movement (Eq. 1) is given by:

$$y = \left[r \times \cos\theta + l \times \sqrt{1-(r/l)^2 \times (\sin\theta)^2} \right] \quad (1)$$

where y is the vertical position of the piston, θ the crankshaft angle and r and l the lengths of the crankshaft radius and of the connecting rod.

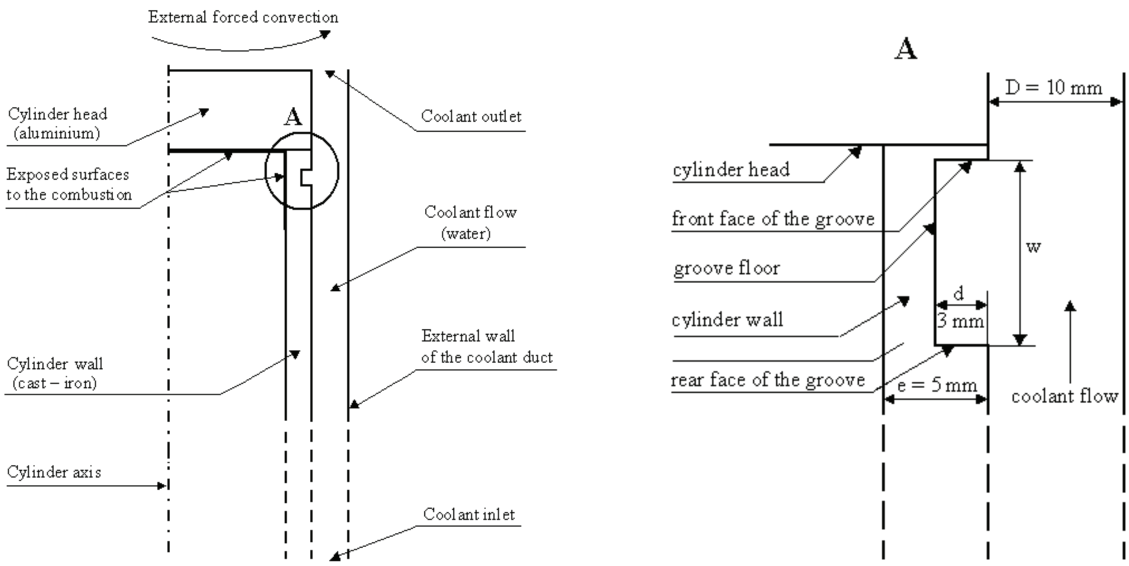


Fig. 1 Sketch of a previously studied configuration [8]

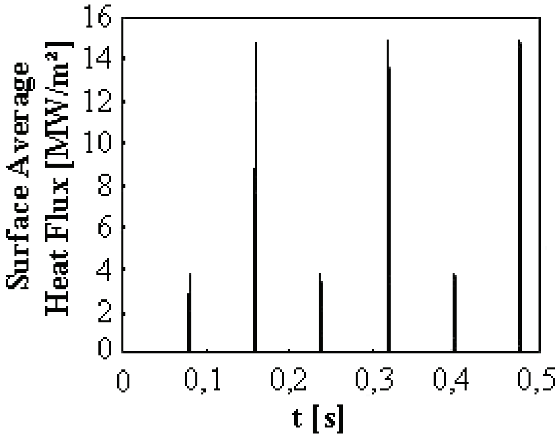


Fig 2. Unsteady heat flux imposed for a semi knocking combustion (50%) [8]

According to Eq. (1), only 31.64 mm of the wall height can face the combustion, during the combustion period. This distance is divided into five parts. The heat flux received by each one is a function of the time they are exposed to the combustion. The associated heat flux is assumed to have sinusoidal variation with time during the combustion period.

The two previously obtained main results are summarized here. More details can be found in reference [7-9]. Firstly, in the case of a square slot machined on the outer wall surface, Fig. 3 shows the resulting temporal variations of temperature in the coolant, 0.5 mm above the floor. Only variations due to knocking combustion can be seen. Those variations are the highest in point 1 (see Fig. 3a) which is situated in the upstream corner of the groove. At this location, they are 3 times higher than for a 2 mm thick smooth plane wall (Fig. 3b). This is due to the low velocity of the flow that makes the fluid stagnant. The passage of the fluid in this location of the groove occurs after a larger residence time along the cavity floor compared to other points. Moreover, the location of point 1 coincides with streamlines that skim the cavity floor.

Loubar et al. [9] studied the effect of a rib placed in the outer side of the wall. They found a similar result. A surface roughened gives good results in terms of amplitude amplification. The temperature variations are approximately 20 times those obtained with smooth surface at the same location (Fig. 4). The presence of recirculation in downstream of the rib (Fig. 4) makes the residence time of the fluid in contact of the wall more important. Consequently, the fluid has got more time to collect the thermal signal. As in Ollivier et al. [8], they found that the best location regarding amplification is located in the upstream left corner of the recirculation.

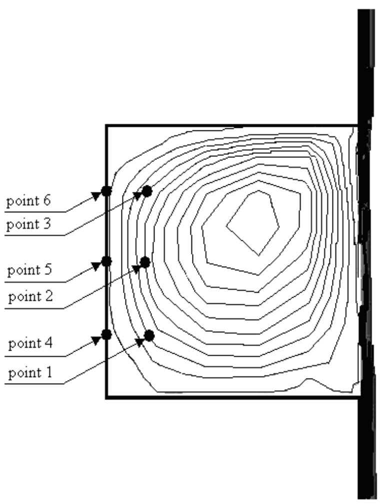
Even if thermal signal amplitude inside the coolant may be significantly increased compared to a smooth wall case, we must notice that temperature variations are always weak within the water (around 0.2 K in the best case). This is due to the important deadening effect of the metallic wall. Consequently, it would be difficult to detect knock by measuring such variations using industrial measurement tools.

The use of the phase change phenomena in order to detect knock occurrence can lead to the development of method that requires less accuracy regarding the thermal sensors. Thus, the melting of PCM placed within the wall cylinder is now going to be numerically treated.

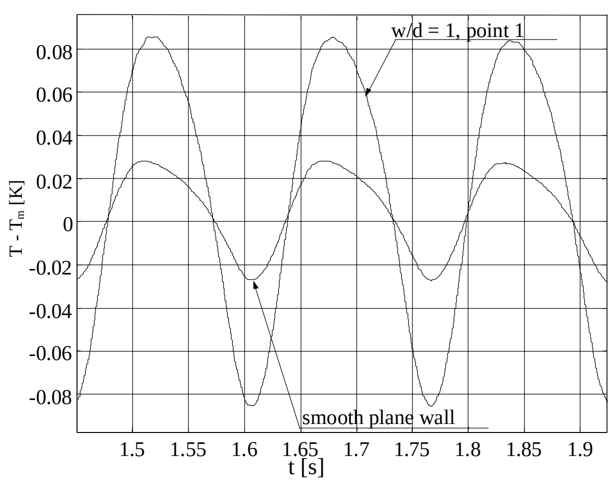
Modeling assumption

The principle of the proposed technique is illustrated in Fig. 5. A cavity filled with a Phase Change Material (PCM) is placed within the cylinder wall. The melting temperature of the PCM should be chosen in order to be solid in the case of normal combustion.

In the chosen configuration, there is no need to simulate the heat transfer within the coolant flow. The computational domain is then reduced to the cylinder wall (made in cast iron) and the cylinder head (made in aluminum, cf. Fig. 5).

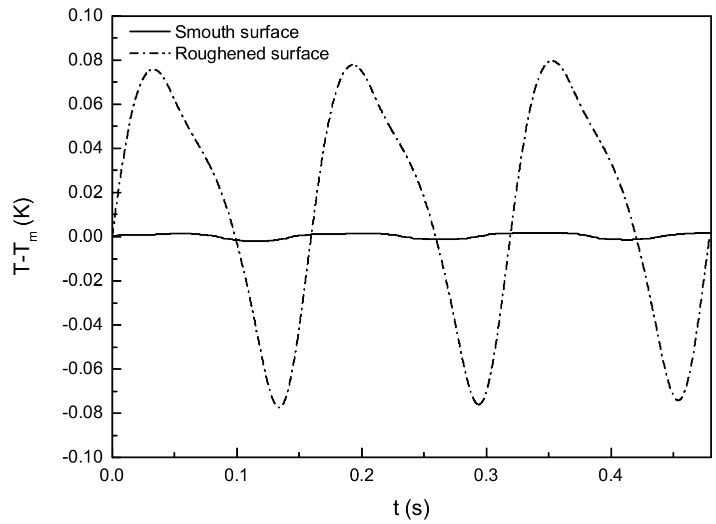


a)



b)

Fig. 3 a) Recording points in the square slot (*w*/*d* = 1)[8] b) Temporal temperature variations for a 2 mm thick smooth plane wall and in point 1 of the square slot [8]



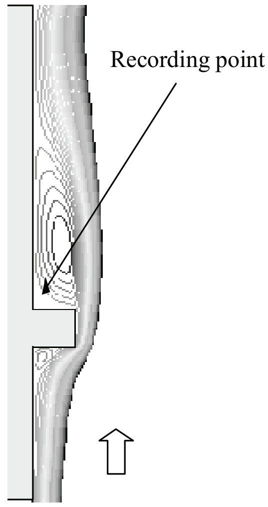


Fig. 4 Temporal variation of temperature in the fluid (0.5 mm from the wall) and recirculation zone downstream the rib [9]

Eq. (2) governs the heat transfer in the whole computational domain:

$$\frac{\partial \rho h}{\partial t} = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i} \right) - S_h \qquad (2)$$

where h and T are respectively the enthalpy and the temperature of the material; c_p its specific heat, ρ the density and k the thermal conductivity. S_h is a source term.

The thermal properties ρ, c_p, and λ depend only on the material nature because of the low temperature gradients observed outside the combustion chamber [4-10].

Moreover, the mesh is structured and has got 20 cells in the thickness of the cylinder wall.

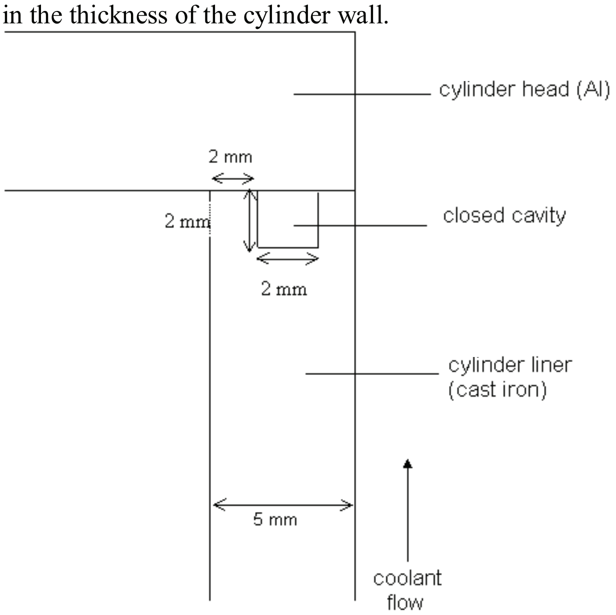


Fig 5. Studied configuration

The melting of the PCM is treated by the Voller and Prakash [10] model. Its allows to calculate the source term of Eq. (2), S_h. It uses an enthalpy formulation methodology and a fixed grid to solve mushy region phase change problems.

Boundary conditions

The cylinder head and the cylinder wall cooling is taken into account by “external convection” boundary conditions. The external heat transfer coefficient and temperature are respectively: h_{ext} = 2500 W/m²K (corresponding to forced convection with liquid) and T_{ext} = 353 K (corresponding to the temperature regulation of coolant in an actual engine).

Unsteady heat transfer from the hot burnt gases to the chamber wall is simulated by the previously presented self-developed program. Four types of combustion are simulated: a normal combustion and knocking combustion with three levels of knock intensity. In case of knocking combustion, cyclic variations (generally met in engine operation) are taken into account by imposing successively a high and a low peak heat flux value. Table 1 summarizes all the peak heat flux values that are used in this study. Their are deduced from literature [6].

Table 1. Peak heat fluxes for the four different types of combustion [6]

Type of combustion	**Peak Heat Flux (MW/m²)**	
	Low Value	**High Value**
Normal	2.5	2.5
Knocking (low intensity)	2.5	3.5
Knocking (moderate intensity)	3.5	5
Knocking (high intensity)	5	8

Numerical technique

The energy equation (Eq. (2)) is solved by the finite volume technique. The time dependent term is integrated using a 1st order implicit scheme. The time step is fixed at 10^{-4} s (corresponding to 30 steps during one combustion period with engine cycle period of 0.08 s).

Four iterations per time step were adopted because more iterations do not improve the convergence of computations. This choice gives good results while preserving a reasonable calculation time.

Mesh validation

The accuracy of the model has to be checked before being used for the simulation of the PCM melting. Thus, the numerical results are confronted to an analytical solution in a simplified 1D case without cavity.

The combustion chamber wall constitutes a frontier between hot gases and water coolant flow. Its thickness is *e*. It is assumed to be isotropic and can be considered, in this step, as a semi-infinite plan in order to make the problem mono-dimensional. On one side, the temperature varies periodically (combustion chamber), on the other it remains constant (coolant flow).

The mesh validation for the conduction problem consists in the confrontation of the calculated temperature field within the wall thickness with analytical solutions deduced from the resolution of the unsteady heat conduction equation in an one dimensional case (Eq. (3)):

$$\frac{\partial T(x,t)}{\partial t} = \alpha \cdot \frac{\partial^2 T(x,t)}{\partial x^2} \qquad (3)$$

where α is the thermal diffusivity of wall material (cast-iron in the present case) and x the position from the internal side of the wall.

The boundary conditions can then be written as:

- $T(0,t) = T_w(t)$, at x=0
- $T(e,t) = T_e$ = const, at $x = e$

The periodic variations of temperature on the inner side of the wall can be expressed as a Fourier Series in the following form (Eq. (4)):

$$T_w(t) = T_0 + \sum_{n=1}^{n=\infty} A_n \cdot \cos(n \cdot \omega \cdot t) + B_n \cdot \sin(n \cdot \omega \cdot t) \qquad (4)$$

where ω is the angular frequency of temperature variation (in the case of a four-stroke engine, ω is half the engine angular speed).

The temperature at any point of the wall can take the form of Eq. (5).

Fig. 6 represents the instantaneous temperature in different points of the cylinder wall thickness. Good agreement is found between numerical and analytical results. The difference between the numerically and analytically calculated temperatures is less than 0.1 K. The phase shift between the thermal signals is also well predicted. Moreover the numerical results appeared to be independent of the mesh within the range 20-40 cells in the wall width.

$$T(x,t) = T_0 - (T_0 - T_e) \cdot \frac{x}{e} + \sum_{n=1}^{n=\infty} e^{-x \cdot \sqrt{\frac{n \cdot \omega}{2 \cdot \alpha}}} \left(A_n \cdot \cos\left(n \cdot \omega \cdot t - x\sqrt{\frac{n \cdot \omega}{2 \cdot \alpha}}\right) + B_n \cdot \sin\left(n \cdot \omega \cdot t - x\sqrt{\frac{n \cdot \omega}{2 \cdot \alpha}}\right)\right) \qquad (5)$$

Choice of the PCM

As previously explained, the PCM placed within the wall should melt if knock occurs. Thus, the melting temperature of the PCM must be slightly higher than the coolant one (363 K) in order to melt only if the thermal load increases. Among the different possibilities, the sodium was chosen because of its thermal diffusivity (5.6 10^{-5} m^2/s at 371 K) which is much more close to cast iron than the thermal diffusivity of non metallic PCM. Thus, isothermal curves around the top of the cylinder are not much changed in comparison with the situation without the PCM. Otherwise, the use of the Voller and Prakash [10] model requires that the thermal properties of the material must be assumed constant with temperature and phase. Finally, Table 2 summarizes the thermal properties used to simulate the Sodium melting.

Results

A reference test is initially performed. In this test, heat flux corresponding to a normal combustion is imposed. In these conditions, once the thermal regime is established, the melting temperature in the cavity is slightly under the melting temperature of the PCM. The gap between cavity and melting temperature is comprised between 0.5 and 1.5 K depending on the location within the cavity. Starting from this reference situation, each knocking combustion is simulated.

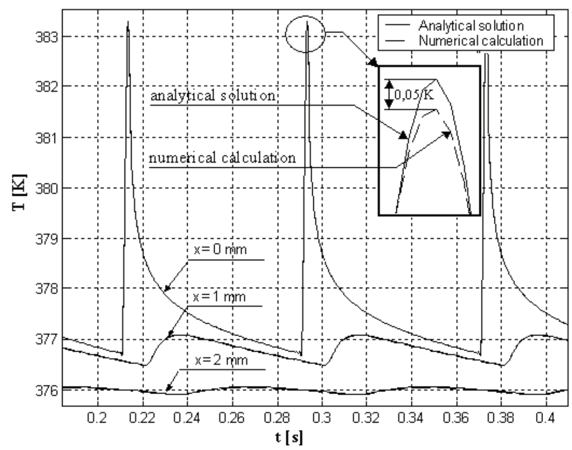


Fig. 6 Validation of the mesh (cast iron wall, normal combustion: Peak Heat Flux = 2.5 MW/m²)

Table 2. Thermal properties of the sodium

$T_{melting}$ (K)	ρ (kg/m^3)	k (W/m.K)	Δh (J/kg)	c_p (J/kg.K)
371	930	85	113000	1380

The average liquid fraction in the cavity is plotted as a function of the time in Fig. 7. In each case, the PCM totally melts. Of course, the melting process is much slower with the low knock intensity.

In Fig. 8, we compare the number of engine cycles that separate the knock occurrence from the end of the melting for the three studied knock intensity. If we assume that melting would be detected as soon as it has ended (using a probe located on the outer side of the cavity, for example), we can notice that the detection of knock occurrence would be done after 17 to 120 engine cycles depending on the knock intensity. So the knock must appear and be persistent to be detected. On the other hand, wall heat flux can also change because cyclic variation always present in engines (see ref. [4] for examples that show changes in peak heat flux generated by cyclic variations). Thus, one of the advantages of the proposed technique is that a non persistent heat flux increase due to cyclic variations would not totally melt the PCM. This can be seen as a protection against wrong detection of knock occurrence.

The results plotted in Fig. 8 show that the melting speed is not proportional to the increase in wall heat transfer due to knock. The raison for such a behavior can be found by observing the shape of the melting front. Figs 9 and 10 represent the liquid fraction curves when respectively 5 % and 10 % of the PCM has melt. In the case of the low knock intensity, the vertical heat transfer near the top of the wall cylinder is quite significant compared to the radial heat transfer. This is confirmed by the direction of the isothermal curves close to the cavity (Fig. 11 a). Thus, the mushy region is diagonally moving. In this case, an important part of the heat flux from the combustion chamber crosses the PCM by heat conduction without contributing to the melting process.

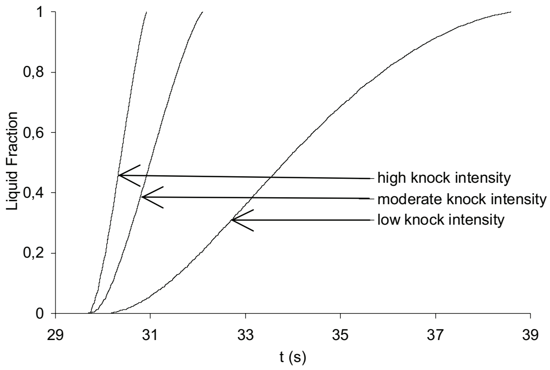


Fig. 7 Average liquid fraction in the cavity as a function of time

If the knock intensity is high, the heat transfer becomes more horizontal close to the top of the cylinder (as shown by the isothermal curves plotted in Fig. 11 b)). Thus, the mushy zone tends to become vertical. In this situation all the heat coming out from the combustion chamber is utilized in order to melt the material. This explains that, when knock intensity is increased, the melting velocity is increased in a higher rate than the wall peak heat flux.

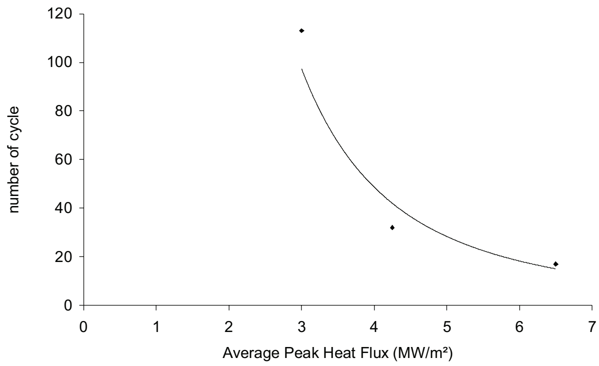
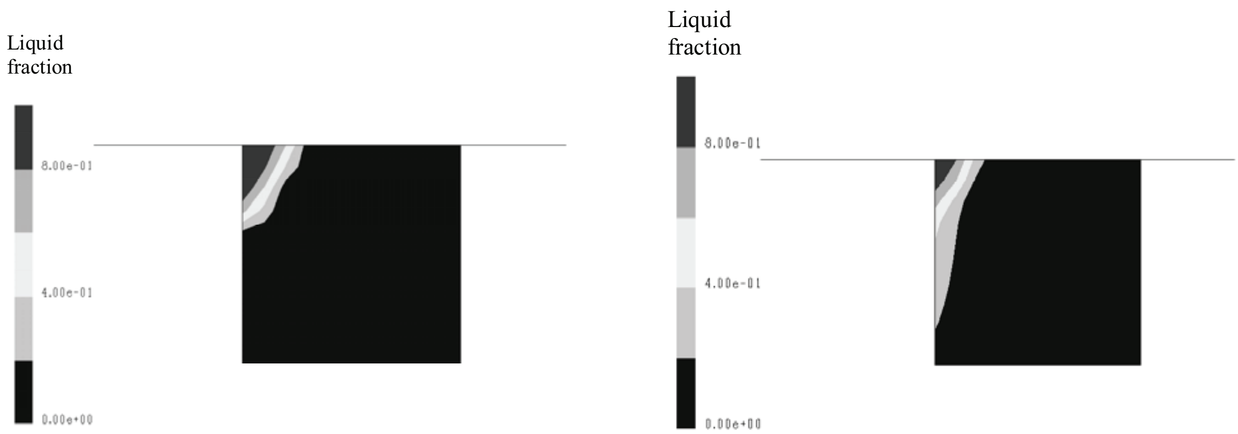
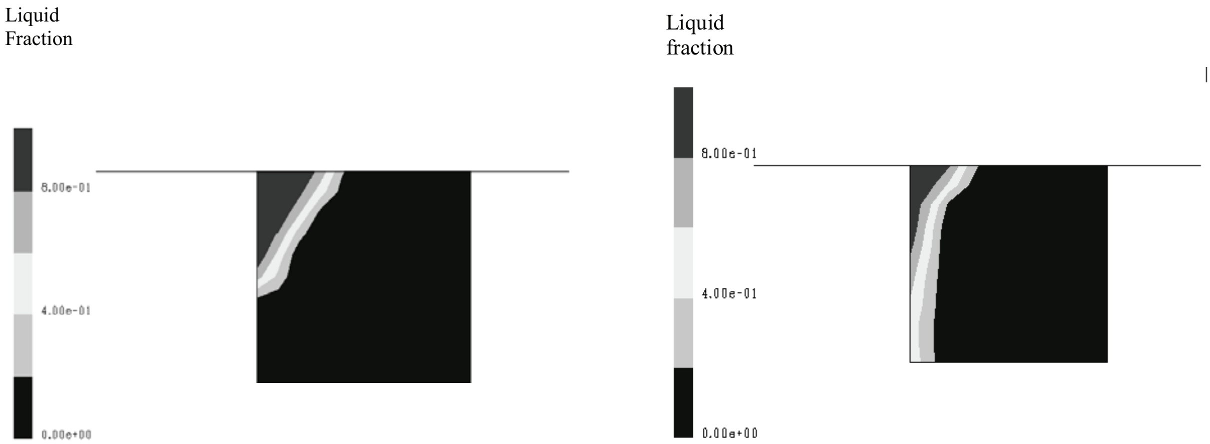


Fig. 8 Number of engine cycles between the knock occurrence and the end of the melting



a) b)

Fig 9 Melting fronts at 5 % a) low knock intensity b) high knock intensity



a) b)

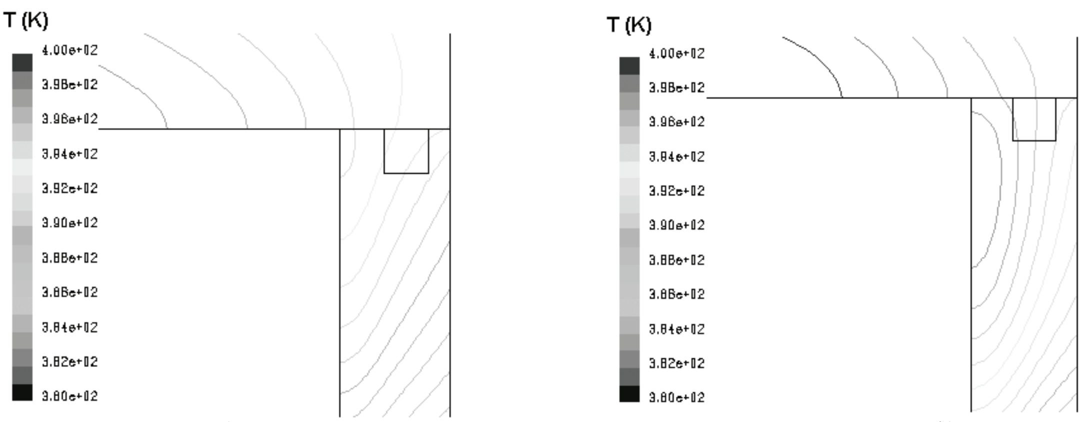
Fig. 10 Melting fronts at 10 % a) low knock intensity b) high knock intensity

Conclusions and perspectives

The present paper proposed a new technique for knock detection in a gas SI engine. It is based on the increase in heat transfer between the combustion chamber and the wall cylinder when knock occurs. The melting of a metallic Phase Change Material is proposed to detect knock occurrence because melting is easy to detect with industrial sensors. The feasibility of this new method was numerically investigated. From the different results, we can especially retain:

- if the knock is persistent, the PCM totally melts even if the knock intensity is low,
- in the studied configuration, the duration of the melting process is included in a range 17-120 engine cycles depends on the knock intensity,
- small increase in the wall heat flux due to cyclic variation should not be interpreted as knock occurrence because they are not persistent,
- Melting velocity increases with a higher rate than the peak heat flux when knock intensity is increased. This is due to the change in the melting front shape.

However, this new technique can be used only if the engine is at full load. In an other case, melting of the PCM could occurs because of an increase in the engine load and not because of knock occurrence. Consequently, further work is now carried out by analyzing the effect of knocking combustion on the exhaust gas temperature. This temperature is decreased when knock occurs. This would certainly complete usefully the information obtained from the wall heat transfer study in order to develop a new method for the knock detection in a large range of engine tunings.



a) b)

Fig. 11 Isothermal curve at the end of a knocking cycle a) low knock intensity b) high knock intensity

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