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SIMULACION MULTIDIMENCIONAL DE TRANSFERENCIA DE CALOR EN UN COMPRESOR DE COMBUSTION INTERNA EN EL ENCENDIDO

MULTIDIMENSIONAL SIMULATION OF HEAT TRANSFER IN AN INTERNAL COMBUSTION COMPRESSION-IGNITION ENGINE

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Abstract: To perform the simulation of fluid flow, fuel spray and combustion in an internal combustion engine, the boundary conditions in the engine's geometry require that a temperature be specified in the internal solid/fluid interface; it is difficult to measure experimentally. To obtain the borders' temperature values, a multidimensional simulation of a single-cylinder compression-ignition engine is performed, using solid walls in the Converge CFD software, with combustion and fluid/solid conjugate heat transfer. Considering that, the time scales of heat transfer in the solid are greater than those on the fluid, in the simulation the super cycling approach is used for the solution of conjugated heat transfer problems. 25 cycles are simulated for the engine, where combustion is considered using the rate of heat release as a function of crank angle, obtained from combustion with a kinetic mechanism for n-dodecane ($C_{12}H_{26}$). In the final cycle, when the heat transfer reaches the permanent regime, the temperature is obtained as a function of crank angle for the solid walls that make up the engine, which is used as boundary conditions in new simulations.

Keywords: Ignition-compression engine, conjugate heat transfer, combustion, simulation

1. INTRODUCCIÓN

The internal combustion ignition-compression engine is a high efficiency engine and therefore generates fuel economy. In this type of engine, once the fuel is injected, the formation of fuel-air mixture begins when the compression stroke ends, and the formation characteristics of this mixture have a strong influence on the combustion and the formation of emissions. The injection process and the thermodynamic conditions of compressed air generate the fuel mixture's auto ignition, initiating the combustion and the release of heat.

In the internal combustion engine, the piston alternates its position with a linear movement between two points defined as top dead center (TDC) and bottom dead center (BDC), and this linear movement generates the crankshaft's rotation by a crank-crank mechanism.

The heat release rate depends on the fuel spray evolution; fuel the evaporation and the process of mixing fuel with air. The release of heat produced in the cylinder gases thermodynamic state a variation, which is used in the form of work on the engine's crankshaft. Combustion in diesel engines is an important factor, and in this process there are sub-processes involved like fuel injection, mixture formation, ignition, pollutants formation and nitrogen oxides (NOx), these sub-processes can act simultaneously (Merker, Schwarz, & Teichmann, 2011), (Gamboa, Flórez, & Conteras, 2019).

Diesel fuel is commonly used in compression-ignition engines is a petroleum derivative made up of hydrocarbons, it contains 8 to 38 carbon atoms in its chain. In this type of engines, the use of biodiesel, which is obtained by transesterification of vegetable oil, has been implemented (Demirbas, 2008).

For the fuel spray's numerical analysis atomization and combustion process, all variables involved in the engine must be considered, and the admitted air flow is an important factor, which is related to the pressure and temperature before and after the intake valve with the intake valve's characteristic area (John, 1998).

The heat transfer between the fluid inside the cylinder and the walls is a phenomenon that influences the fluid's thermodynamic state, where heat is transferred between the gas and the walls by convection, conduction and radiation as shown in Fig 1, where T_g is the temperature of the gas, $T_{w,g}$ is the gas side's temperature of the wall, $T_{w,c}$ is the temperature of the cooling fluid side's wall and T_c is the temperature of the cooling fluid.

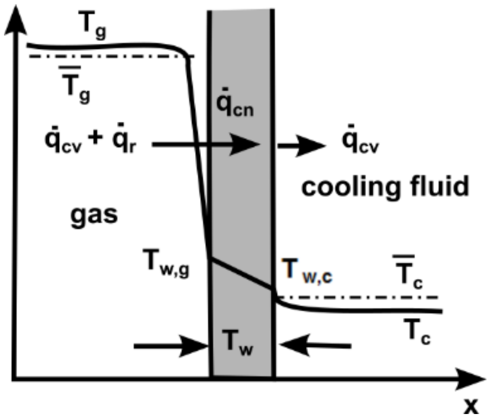

Fig. 1. Heat transfer mechanisms in the engine
***Source**: Adapted of Heywood [3].*

The flow inside the cylinder has interaction of turbulent layers, boundary layer and recirculation regions, having fluctuations from one cycle to another in the engine. To obtain numerically the field of speed, temperature and fluid's pressure it is necessary to solve a system of different equations which are: conservation of mass equation, equation of momentum, equation of energy and equation of state (Richards, Senecal, & Pomraning, 2014).

The Fig. 2 show the three-dimensional geometry used for the simulation, which is formed by intake duct, cylinder, piston, exhaust duct, intake valve and exhaust valve.

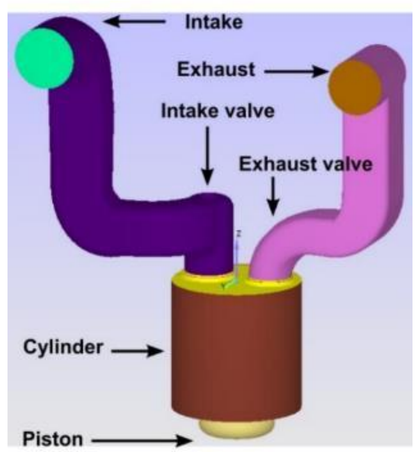

Fig. 2. Engine geometry
***Source**: Authors.*

The engine's characteristics are listed in Table 1.

Table 1: Engine's characteristics

ITEMS	SPECIFICATION
Classification	Diesel, 4 times, 1 cylinder
System injection	Direct

Cylinder diameter	115 mm
Displacement cylinder	115 mm
Capacity	1194 cm3
Compression	17,3
Potency	14,7 kW / 2200 rpm

The geometry shown in Fig. 1 considers as borders the fluid inlet, fluid outlet and the wall of the following components: cylinder, piston, headstock, injector, inlet valve, exhaust valve, inlet duct and exhaust duct. As boundary conditions in the engine walls, the average temperature in the solid components that make up the borders or the solids' internal surfaces temperature as a crank function angle is necessary. To obtain this temperature in each solid component and be able to simulate the phenomena inside the cylinder, such as spray combustion, it is necessary to perform experimental tests on the engine (Torregrosa, Bermúdez, Olmeda, & Fygueroa, 2012), which are expensive, another option is the numerical simulation of heat transfer in the engine, and this could be done to obtain those temperatures at lower cost.

The following sections describe the methodology used and heat transfer numerical simulation in the engine results considering combustion, in order to obtain the average temperature in each of the engine's solid walls.

2. NUMERICAL MODELLING

The engine's heat transfer analysis requires the fluid flow's solution inside the engine considering combustion, heat transfer in the solution, solid walls and the fluid.For bulleted lists.

2.1. Modelling Fluid Flow.

The fluid in the engine is considered to be compressible and transient, and to obtain the fields of speed, pressure and temperature inside the engine, it is necessary to solve a system of conservation equations and equations of state. The flow is turbulent with small scales of length, speed and time. Given the parameters of kinematic viscosity (υ) and the rate of dissipation of turbulent kinetic energy (ε). These small scales are called Kolmogorov scales.

The equations that describe the turbulent flow are the Navier-Stokes equations in non-stationary and three-dimensional form, which need a solution in small scales of time and space to obtain a description of the flow in detail.

The solution equations' system of in turbulent flow inside the engine during the heat transfer simulation, this is carried out by means of the Navier-Stokes methodology equations averaged by Reynolds (RANS) (Adrian, 2013). In compressible flow, as well as the fluctuations of speed and pressure, it is necessary to take into account the fluctuations of density and temperature, therefore, the average of Favre is used to express any of the fluid's properties as the sum of a mean value and variation, both pondered by mass(Kenneth Kuan-yun Kuo & Acharya, 2012; Wilcox, 1993). The corresponding equations in terms of Favre for compressible fluid are: Equations of mass Conservation Equation. (1), Momentum Conservation Equation. (2), Energy Conservation Equation. (3), and State Equation. (4) (Richards et al., 2014; Wilcox, 1993).

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u_i}}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{\rho}\widetilde{u_i}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u_i}\widetilde{u_j}}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \widetilde{u_i}}{\partial x_j} + \frac{\partial \widetilde{u_j}}{\partial x_i}\right) - \frac{2}{3}\mu\frac{\partial \widetilde{u_k}}{\partial x_k}\delta_{ij}\right] + \frac{\partial}{\partial x_j}\left(-\bar{\rho}\widetilde{u_i'' u_j''}\right) \quad (2)$$

$$\frac{\partial \bar{\rho}\tilde{e}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u_j}\tilde{e}}{\partial x_j} = -\frac{p(\partial \widetilde{u_j})}{\partial x_j} + \sigma_{ij}\frac{\partial \widetilde{u_i}}{\partial x_j} + \frac{\partial}{\partial x_j}\left(K\frac{\partial \tilde{T}}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(\bar{\rho}D\sum_m \tilde{h}_m \frac{\partial Y_m}{\partial x_j}\right) + S \quad (3)$$

$$\tilde{p} = \bar{\rho}R\tilde{T} \quad (4)$$

where σij is the tension tensor. In this system of equations an additional term called Reynolds Tensor is obtained, which consists of six additional scalar unknowns in the system of equations, generating a problem for the solution. The Reynolds Tensioner is defined by Equation. (5).

$$R_{ij} = -\bar{\rho}\widetilde{u_i'' u_j''} \quad (5)$$

The equations' solution system using RANS, is carried out using the turbulent viscosity model k-ε RNG (Renormalization Group) based on the solution of turbulent kinetic energy transport equations (k) and the dissipation rate of turbulent kinetic energy equation (ε), with modeling9 of the turbulent viscosity by Equation (6) (Wilcox, 1993).

$$\mu_t = C_\mu \rho \frac{k^2}{\epsilon} \quad (6)$$

For the numerical solution of the equations, the Converge CFD Software is used, which is a computational fluid dynamics program that uses the finite volume method, developed mainly for internal combustion engines, with an automatic structured orthogonal mesh generator based on parameters given by the user.

2.2. Mode Heat Transfer Modelling

In the analysis of heat transfer in the engine walls, the complete geometry of the engine shown in Fig. 1 this is used with solid walls without refrigeration ducts. The simulation is carried out in the Converge CFD software using the conjugate heat transfer model (Conjugate Head Transfer), since heat transfer occurs in solids and fluids. With the Conjugate Head Transfer methodology, the solid part temperature fields and engine fluids are resolved simultaneously considering combustion.

To simulate heat transfer in solids and liquids simultaneously, it must be considered that the time scales of heat transfer in solids are greater than those in fluids; therefore, the super cycling methodology is used for transfer problems of conjugated heat, which in general terms is like this:

a. The equations in fluid and solid are solved, but the heat transfer data in solid is not stored from the simulation‘s beginning up to a time called "super cycle's start time". When the super cycle's start time is reached, values for heat transfer coefficient (HTC) and temperature in each wall cell in the solid/fluid interface for each time interval is stored. The equations in fluid and solid continue to be solved, storing HTC data and temperature in the cells near the interface up to a time called "super cycle's status interval".

b. When the super cycle's status interval time is over, a pause in the fluid solver is performed and a mean HTC and temperature are calculated on each cell near the interface based on the previously stored values. The calculation of heat transfer in solid is made at this time with the mean values of HTC and temperature, considering stable state.

c. After performing the calculation of heat transfer in the solid, the solid's temperature represents the temperature in steady state, and this temperature is considered a temperature peak at the start of a new super cycle.

d. After the temperature's calculation in the solid, the fluid solver is started again to solve the fluid and solid equations again for a time equal to the super cycle state interval, and the process is continued according to the super cycles established in the simulation.

The simulation is performed for an engine speed of 1800 rpm using the crank angle in degrees with a variable time interval as a time advance parameter: a minimum time equivalent to 2.0E-8 seconds and a maximum time of 4.9E -5 seconds.

The flow characteristics in the engine are dependent on the mesh size which makes is difficult to choose. For this, the fluid's pressure dependence and the turbulent kinetic energy, in relation to the mesh size is verified using base meshes of size 6, 4 and 3 mm and in each case Adaptive Mesh Refinement (AMR) is applied. A scale of 2 inside the cylinder for the fluid. Both for the pressure and for the turbulent kinetic energy, the result is that for mesh sizes of 4 and 3 mm the behavior of these parameters keeps the same tendency and values almost next, therefore, a base mesh of 4 mm is used.

The boundaries that make up the system are the walls of the cylinder, the piston (mobile boundary), the head, the injector, the intake valve (mobile boundary), the exhaust valve (mobile boundary), the intake duct and of the exhaust duct.

In addition, there is the fluid inlet frontier and the fluid outlet on the engine. As boundary conditions in the engine's fluid input, experimental data of atmospheric pressure and temperature is used as a function, this species correspond to the components of the air. The boundary conditions at the oulet are considered as experimental data for the species, temperature and atmospheric pressure.

For the fluid, the initial conditions in the intake duct are considered to have an average temperature taken from the experimental data at the inlet, atmospheric pressure and species corresponding to the air. In the exhaust pipe as initial conditions, the measured temperature for the exhaust gases, the atmospheric pressure and the species measured experimentally in the exhaust are considered. In the engine cylinder, the initial condition of engine pressure corresponds to the measurement experimentally, the temperature obtained theoretically using experimental pressure data and the species are considered the same experimentally measured in the exhaust.

In the heat transfer simulation, data storage starts at 60°, and a super cycle state interval of 60° is defined. A total of 25 engine cycles are simulated, divided into 5 simulations of 5 cycles each, considering that the final conditions obtained in each previous simulation correspond to the initial conditions of the following simulation. The combustion is considered using the rate of release of heat in the engine, obtained from simulation of combustion of n-dodecane (C12H26) using a kinetic mechanism of 102 species and 420 reactions.

The initial temperature conditions in the solid regions for the simulation of the first 5 cycles are taken from general data used in Converge CFD sessions for compression ignition engines. The initial conditions of temperature, pressure, turbulent kinetic energy, turbulent kinetic energy dissipation rate and species for the fluid are taken from the results of the n-dodecane combustion simulation.

The temperature contour conditions in the external wall that make up the engine geometry are given in heat flux per unit area (q''). By means of an initial engine simulation where n-dodecane combustion is considered, the area of heat transfer (Aint) and the heat flow (Q̇) from the fluid in the interior, for each degree of rotation from the engine's crank, towards the inner wall on each of the engine's solid components to obtain the heat flow per unit area. The simulation considered to obtain this initial heat transfer data is performed using the non-thick engine's walls; the heat transfer is given from the fluid volumes adjacent from each wall to the solid surfaces, as has been obtained by other researchers for diesel engines (Taghavifar, Taghavifar, Mardan, Mohebbi, & Khalilarya, 2015). In figure 3 the heat flow per unit area from the fluid to the internal surface of each of the engine components is shown, as a crank angle function, considering that the top dead center where combustion occurs corresponds to 0°, and in This crank angle gives the highest heat transfer due to the release of energy given by combustion (Spitsov, 2013)

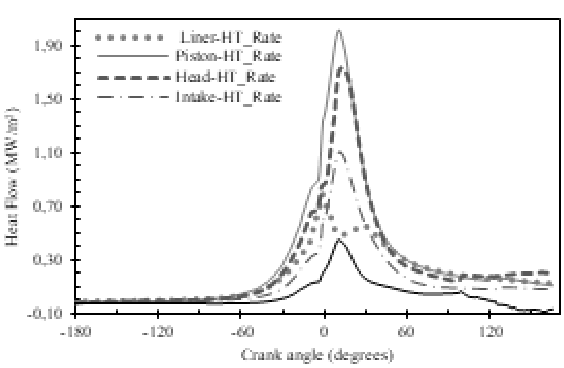

Fig. 3. Heat flow per unit area on engine internal surfaces.
***Source**: Authors*

The heat flux per unit area on the external surfaces of each engine component as a crank angle function is obtained considering the heat transferred and the external area. The external area of each component is obtained through the *Converge CFD* software.

In *Converge CFD*, for each external engine surface, the heat flux per unit area is assigned as a condition of temperature contour as a crank angle function for a complete cycle, which starts at -360° and ends in 360°. The materials used for the solid are steel and aluminum.

3. RESULTS

Obtained heat transfer simulation results for the first five (5) cycles of the engine are analyzed according to the crank's angle in order to see the temperature variation from one cycle to another. In this simulation, the value of q_{ext}'' is obtained in the different solids and these values are used as a boundary condition in the external walls for a new simulation of heat transfer.

Fig. 4 shows the average temperature in each fluid region as a crank's angle function for the first 5 cycles of the engine. In this figure it is observed that the temperature in the fluid presents variations from one cycle to another, mainly at maximum temperatures. Temperature variation from one cycle to another represents the engine's transient state in terms of its temperature in each component.

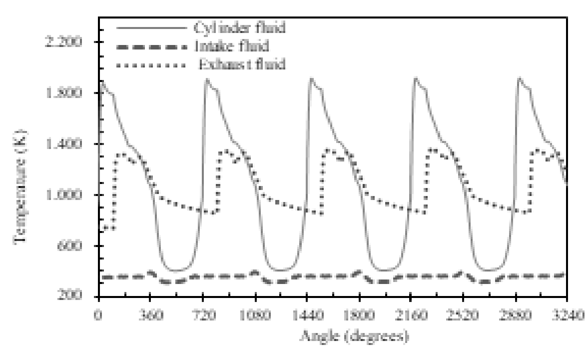

Fig. 4. Average temperature in fluid regions for the first 5 cycles.
***Source:** Authors*

The solid components of the engine have lower temperature variations from one cycle to another compared to the fluid, as shown in Fig. 5. In this figure it can be seen that the solid components are increasing their temperature, as they occur new cycles of the engine, and this increase from one cycle to another is not as considerable when compared to that of the fluid (Mirko, 2014).

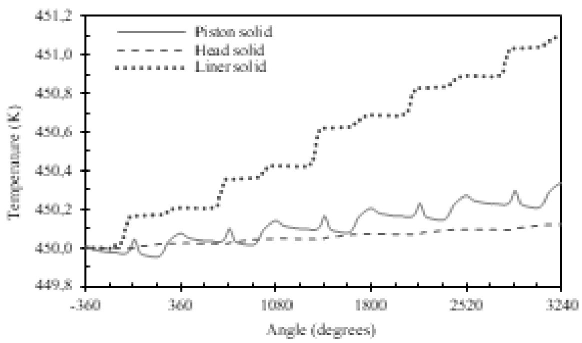

Fig. 5. Average temperature in solid regions for the first 5 cycles.

Source: *Authors*

The temperature's behavior in solids for the initial engine cycles is mainly due to effects produced by combustion. Analyzing the solid boundary's temperature in the solid / fluid interface, allows to see the variation as a crank angle's function from one cycle to another as shown in Fig. 6.

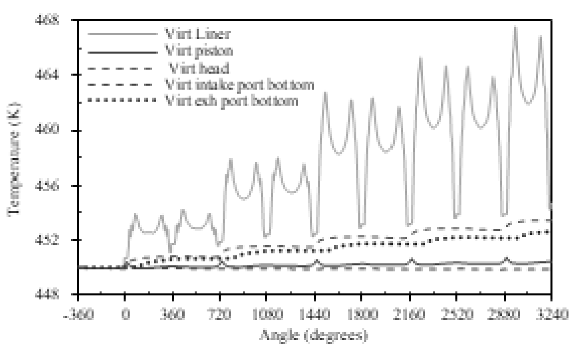

Fig. 6. Average temperature at the solid boundary in the solid / fluid interface for the first 5 cycles.

Source*: Authors*

In figure 6 it can be seen that the average solid wall temperature in the internal engine's region begins to increase from one cycle to another influenced mainly by the high temperature in the combustion process.

In the results' analysis obtained from the engine's first 5 cycles simulation, in general terms it is observed that the temperature of both the solid and fluid components in the engine suffer a variation from cycle to cycle, tending to increase. From the results obtained in the engine's first 5 cycles simulation, the following data is obtained and to be used in a new simulation: initial temperature conditions in the fluid, initial temperature conditions in the solids, boundary conditions in the walls external with new values q''_{ext} .

Fig. 7 shows the average temperature in the solid engine components for the five final cycles. In this figure it is possible to see that the cylinder, the piston and the head have temperatures with values close to each other and that the temperature variation between one cycle and another is small. For the intake valve and the exhaust valve, the greatest variation in temperature occurs in the crank angle where there is combustion, since these elements are smaller than the other three solids.

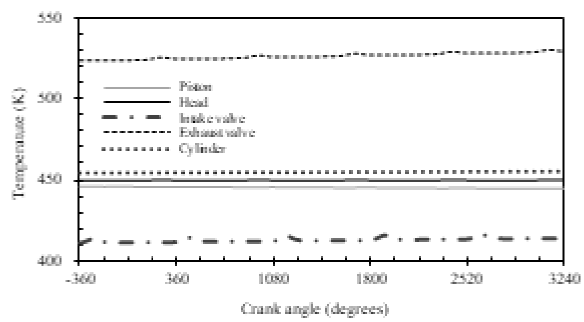

Fig. 7. Average temperature in solid regions for the last 5 cycles.

Source: *Authors*

Table 2 specifies the average engine's solid temperature in the last cycle, and according to the data generated in the simulation and those observed in Fig.7, these temperatures in the final cycles do not show considerable cycle variation to cycle.

Table 2: Average temperature of the solids in the final cycle

Solid	Temperature (K)
Piston	445
Cabezote	450
Admission valve	414
Scape valve	529
Cylinder	455

At the solid boundary of the solid / fluid interface, according to Fig. 8, the temperature's behavior from one cycle to another does not show considerable variations when compared with the behavior of these same borders in the five initial cycles (See Fig. 6). The greatest variation of temperature in the same cycle occurs in the cylinder's internal surface, considering that this internal surface has a variable heat transfer area according to the piston's movement, with a maximum area where the piston is in the BDC and a minimum area when the piston is in the TDC. The other engine's internal surfaces do not exhibit these oscillations in their temperature, and it is also considered that their surface area of heat transfer is constant. The temperatures in each of the engine's solid components depend on the combustion in an engine, considering that the ignition and the advance of the flame front occurs in certain points inside the cylinder (Yuanhong & Song-Charng, 2011).

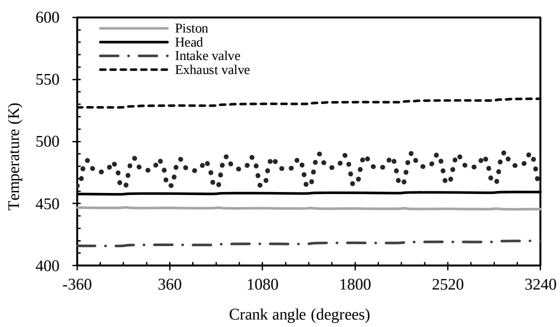

Fig. 8. Average temperature at the solid boundary in the solid / fluid interface for the last 5 cycles.

***Source**: Authors*

The variation in the area of heat transfer from the internal cylinder's surface can be seen in Fig. 9, where a temperature profile of each of the solid and fluid regions in the cylinder is represented, on the Exhaust stage in the engine. In this figure it is observed that the highest temperature corresponds to the fluid that is being expelled towards the exhaust duct. The average fluid regions' temperature present large variations in the same cycle, because the fluid's temperature depends on each of the cycle's stages, mainly during admission, compression and combustion.

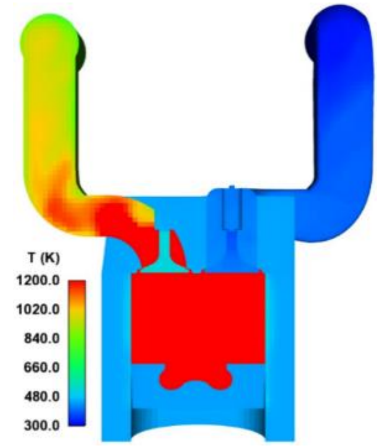

Fig. 9. Temperature profile in the different regions of the engine in the exhaust stage.

***Source**: Authors*

4. CONCLUSIONES

The multidimensional simulation of heat transfer in an internal combustion engine is carried out, considering combustion and it is observed that in the results of the last five engine cycles no variation in the engine's average temperature of the solid components is detected.

By means of this methodology, the average temperature is obtained to be used as a boundary condition in the simulation of spray and spray combustion processes where the non-thick engine walls are used as shown in figure 2.

The solid's internal temperature surface (solid/fluid interface) is considered an important data to be used as a boundary condition with temperature depending on the crank's angle, mainly in simulations where it is necessary to take into account that the internal surfaces' temperature varies depending on the crank's angle.

An additional analysis using the results given by the Converge CFD software is to measure the energy loss by heat transfer in the engine for one cycle, in order to perform the energy balance in the engine.

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