Modeling of ICE Piston Cooling Gallery Oil Filling Ratio using SPH (Smoothed Particle Hydrodynamics) method.

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ABSTRACT

The piston maximum temperature is a very important characteristic for the development of an internal combustion engine. Several parameters define the piston maximum temperature that must be minimized, and the piston cooling efficiency is one of the relevant issues which is tightly related to the piston cooling gallery filling ratio (FR) that can be improved aiming to optimize the piston heat-transfer efficiency. The virtual modeling of the piston cooling gallery filling is traditionally performed by a transient CFD (Computational Fluid Dynamics) approach, however the availability of the SPH (Smoothed Particle Hydrodynamics) method can achieve good results with a simple approach of model preparation and short processing time leading to confidence project development with accurate of results and attractive cost efficiency. The focus of this work is to validate the SPH technics to predict the FR for a specific condition comparing the simulation results with bench test. Later this modeling approach is applied in a real piston engine application comparing two pistons with different cooling channel designs where is possible to observe the relation of modeled FR with the piston temperature measurements in the engine.

INTRODUCTION

During the development of an internal combustion engine piston, the fill ratio (FR) is a key parameter to reduce piston temperatures through the heat transfer process. Traditionally, this kind of calculation is performed by a transient CFD (Computational Fluid Dynamics) approach, but the evolution of the SPH (Smoothed Particle Hydrodynamics) method brings gains in model preparation and processing time with greater cost efficiency and accuracy of results [1]. In the automotive industry, there are several other applications where this method is used to aid and address design issues, such as gearbox packages [2] and die casting process for example [3].

The focus of this work is to model a piston cooling gallery of a spark ignition internal combustion engine using the SPH technique to predict the oil volume inside the cooling gallery, the so-called Filling Ratio (FR), for a specific engine operating condition.

A study of the available models and parameters was carried out to ensure a satisfactory convergence of the results. Finally, a comparison was made between the SPH simulation results, and the measured results on the test bench, with a good correlation between them.

Figure 1 shows a schematic section where can be seen the piston gallery, the injector nozzle, and the oil jet of an internal combustion engine.

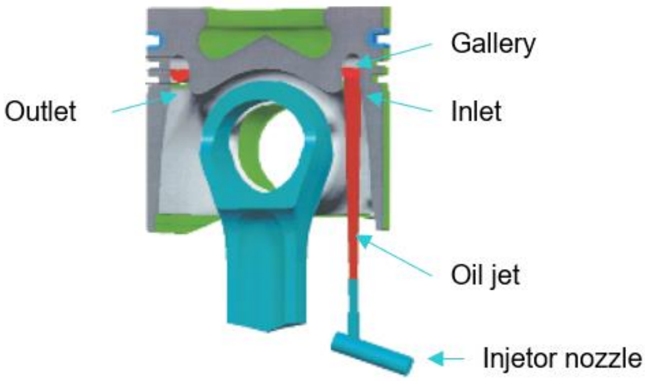

Figure 1. Scheme of the injector nozzle, oil jet and piston gallery.

SIMULATION METHOD AND FUNDAMENTAL EQUATIONS

The SPH particle simulation method is based on a Lagrangian approach instead of the traditional Eulerian method used in CFD simulations.

From the Lagrangian method, the control volume of the fluid is followed through the domain. Although particles can be visualized as discrete, mathematically they behave as a continuum. Each particle property can be expressed through the following volume integral:

$$A(r) = \int A(r')W(r - r', h)dr' \approx \sum_j Aj(rj)VjW(ri - rj, h) \quad (1)$$

Being:

$A(r)$: particle property,

$A(r')$: neighboring particle property,

$(r - r', h)$: Kernel function,

$\sum_j A_j(rj)VjW(ri - rj, h)$: discrete form of the integral, where the index j represents the number of the neighboring particle.

Kernel functions are very important for the SPH approach, as they form the basis of property interpolation.

The discretized Lagrangian form of the Navier Stokes equations that govern the physics of the particle is expressed as follows:

$$a_i = \frac{\partial u_i}{\partial t} = -\frac{1}{m_i}\sum_{j=1}^{N_{nbs}} p_{ij}\left(V_i^2 + V_j^2\right)\nabla W_{ij} + \sum_{j=1}^{N_{nbs}} u_{ij}\left(V_i^2 + V_j^2\right)\frac{u_{ij}}{r_{ij}}\nabla W_{ij} + g + \propto k\nabla C \quad (2)$$

Being:

$\sum_{j=1}^{N_{nbs}} p_{ij}\left(V_i^2 + V_j^2\right)\nabla W_{ij}$: pressure gradient,

$\sum_{j=1}^{N_{nbs}} u_{ij}\left(V_i^2 + V_j^2\right)\frac{u_{ij}}{r_{ij}}\nabla W_{ij}$: viscous term,

g: gravity force,

$\propto k\nabla C$: surface tension.

Equation (2) is the discretized mathematical expression used by the computational code.

The SPH computational code used in this work is the software named nanoFluidX from Altair company [4].

METODOLOGY

In general, the methodology used in the SPH numerical simulation process consists of the following steps:

- Pre-processing, in this stage the mathematical model is prepared, properly manipulating the geometries involved, particle generation, set-up of the boundary conditions and input data as well as the generation of the file that contains all the necessary information that will be submitted to processing.

- Processing, step where the calculation process is performed by the solver. This processing is executed on graphics cards specially dedicated to the calculation (GPU, Graphics Processing Unit) with a substantial increase in computational performance.

- Post-processing, final phase of the methodology in which the results of interest are extracted after the processing step is completed. Here, graphs, tables, figures, and animations can be generated for a correct and intuitive interpretation of the results.

MODELING

Modeling tries to reproduce the physical condition of the real problem to a virtual form considering some specific considerations and appropriated simplifications. Figure 2 represents a test bench in which a prototype of a piston gallery suitably manufactured from a transparent polymeric material is submitted to tests simulating a similar operating condition of an internal combustion engine. The oil filling ratio (FR) is determined through instrumentation and the use of optical methods associated with high-speed imaging software [5].

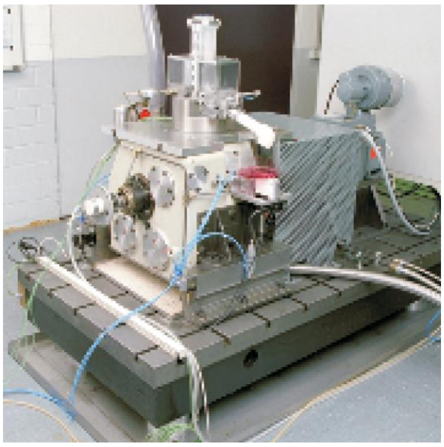

Figure 2. Test bench to measure the FR in piston gallery prototypes.

Details of the geometry and dimensions of the prototype of the piston gallery as well as the oil injection nozzle can be seen in Figure 3.

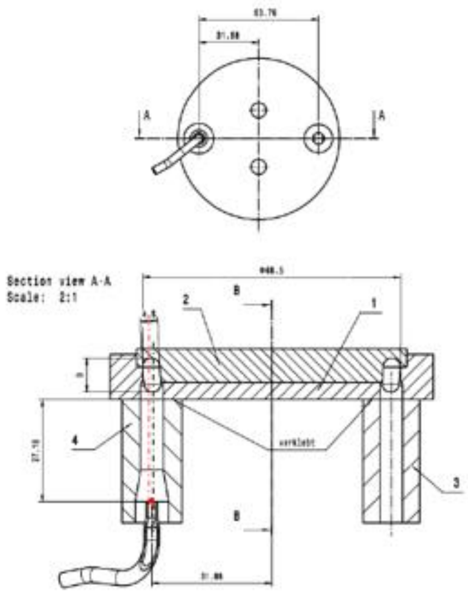

Figure 3. Prototype of the piston gallery to be tested.

Following the methodology previously described in the pre-processing phase, the modeling of the real prototype (figure 3) is carried out using appropriate software so-called Simlab from the Altair company [6]. This modeling faithfully reproduces, in a virtual way, the geometry of the prototype of the piston gallery and the oil injection nozzle through a 3D CAD geometry as shown in figure 4.

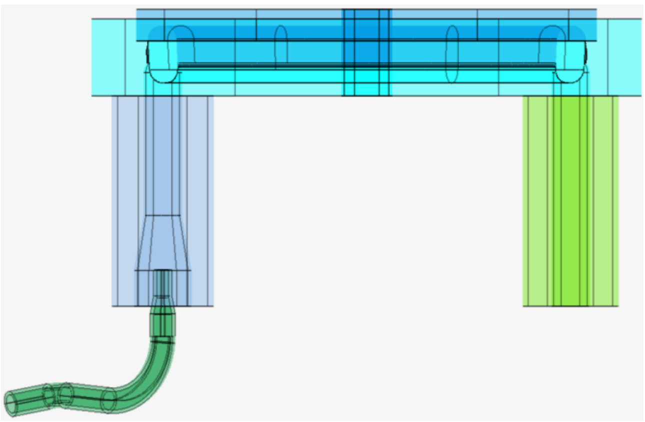

Figure 4. 3D CAD geometry of the prototype of piston gallery with its injector nozzle.

The geometry of figure 4 is in sequence, submitted to a discretization using particles of appropriate size with respect to the dimensions of the CAD model. The most suitable particle size for this case is 0.0004m.

Figure 5 shows the discretization of the geometry using particles.

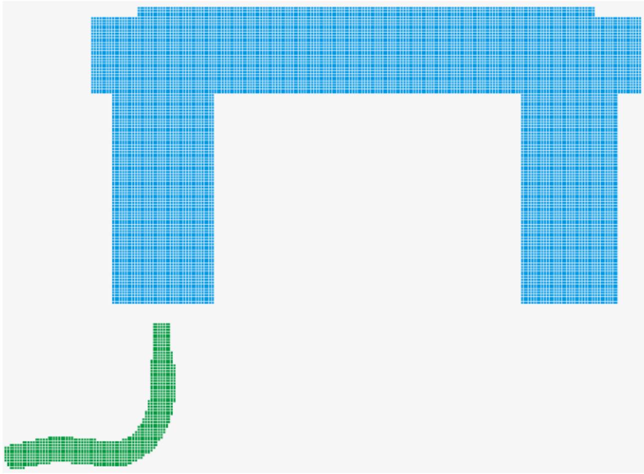

Figure 5. Discretization of the model using particles.

Following the model preparation procedure, the next step is to configure the connecting rod-crank reciprocating movement to the piston gallery prototype according to the geometric dimensions of the mechanism. This movement is put in the form of an appropriate file that represents the actual movement for a given rotation.

Once the desired movement is set up, the materials and fluids involved for each component used are defined. In this case, for the gallery component, the assigned material is a type of polymer and for the injector, steel. The oil fluid is defined with the same specifications used on the test bench. The inlet and outlet ports of the piston gallery prototype are defined with sensors that will measure oil flow and velocity, among other parameters.

The boundary conditions of the oil jet, such as flow rate or exit velocity are also defined.

Table 1 below summarizes the main input data and boundary conditions of the model.

Table 1. Main input data and boundary conditions.

Speed [rpm]	3988
Stroke [mm]	92.4
Conrod length [mm]	149
Injector nozzle volumetric flow [l/min]	2.5
Kinematic viscosity of oil [m2/s]	6.6×10^{-6}
Oil density [kg/m3]	829

During the model set-up, some considerations inherent to the simulation approach were also fixed, such as:

Transient analysis, that is, the solution is given as a function of the time variable.

Single-phase analysis, in this study only the liquid phase of the fluid oil was defined. Air fluid iteration was not considered.

The thermal model that would enable the solution of the temperature distribution of the prototype of the piston gallery was disabled, since the focus of this work is only the prediction of the FR.

The physical simulation time was set to 2.0 seconds. Parameters related to solution convergence and stability were also defined.

Once the entire set-up is completed, the file containing all the information inherent to the model is generated and will be submitted to processing.

PROCESSING

The process to obtain the solution with the desired results is performed in a machine environment that uses LINUX operating system. The processor is a graphics card (GPU, Graphics Processing Unit) with dedicated features for high-performance mathematical calculations.

The processing time will depend on the complexity of the model, size and total number of particles generated during modeling as well as the number of GPUs used. Processing ends when the convergence criteria are satisfied.

RESULTS

As mentioned before, once the solution is converged, the simulation stop, and several output files are generated. These files contain several results that must be manipulated using appropriate software. The name given to this phase is post-processing.

For the handling of the result files and subsequent generation of graphics and animations that facilitate their understanding and interpretation, an open-source software called ParaView [7], and a commercial software called Hyper Graph from the Altair company were used.

The main result is the filling ratio (FR) of oil into the piston gallery under the conditions tested on a test bench and reproduced in the computational model. The FR is given by the ratio between the volume of oil introduced by the injector nozzle inside the piston gallery and the gallery volume itself. The relationship is shown in equation (3).

$$FR\,[\%] = \frac{volume\ de\ \acute{o}leo\ dentro\ da\ galeria\ do\ pist\tilde{a}o}{volume\ da\ galeria\ do\ pist\tilde{a}o}\,X100 \quad (3)$$

During the analysis of the results, investigations were made comparing two interaction scheme models available in the software, the Weigthed and the Riemann interaction schemes. Figure 6 shows the comparison of the FR curves as a function of time (crank angle) between both models. The Weighted model (green curve) presented a FR trend to increasing and diverging with the previously known measured result. The Riemann model shows improved stability presenting a better correlation to the experimental result; therefore, the Riemann interaction scheme was selected for predicting the FR.

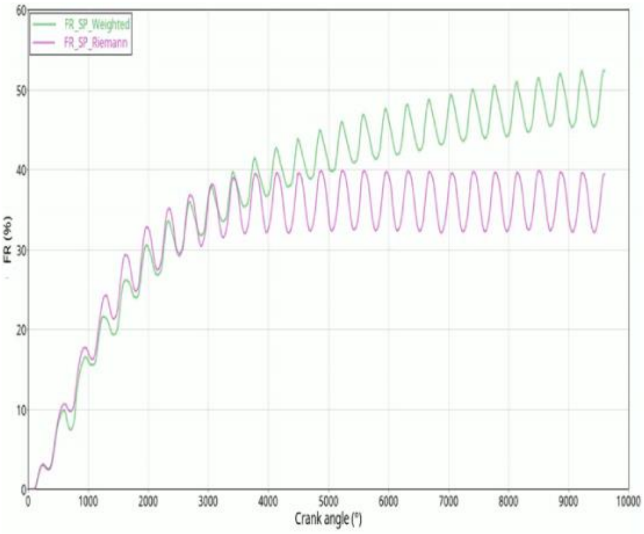

Figure 6. Comparison between Weighted and Riemann solution schemes.

Once the Riemann model was chosen, the simulation ran for a longer time until convergence and stability of the result. Figure 7 illustrates the result of the stabilized FR curve. It should be noted that the sinusoidal oscillations of the curve are because of the relative speed between the prototype of the piston gallery in its reciprocal movement and the constant speed of the oil jet. The numerical value of the FR was obtained by the arithmetic mean of the results between the positions of 35.000 degrees and 48.000 degrees of the crankshaft, equivalent to 1.5 and 2.0 seconds respectively of the physical simulation time, where a better stability of the curve can be appreciated. Thus, the simulated FR value was 40%.

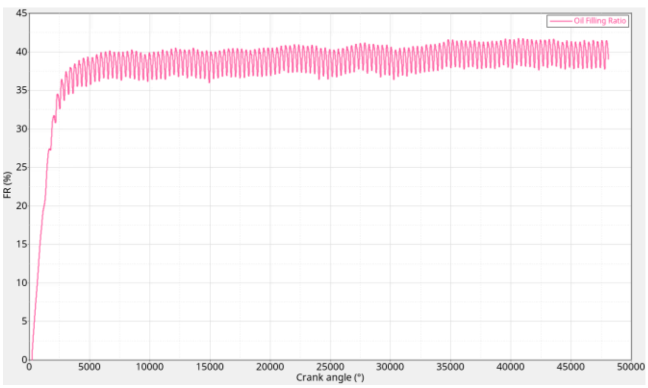

Figura 7. FR curve as a function of crank angle.

Figure 8 illustrates a snapshot of the animation generated by the ParaView software showing the oil velocity during the filling cycle in the virtual prototype of the piston gallery. It is interesting to visualize the oil output from the injection nozzle on the right side, its behavior inside the gallery due to the inertial effects of the movement and its output to the outside on the left side of the picture. It is important to point out that for the purposes of an efficient thermal exchange, the oil must not completely fill the volume of the gallery, since its movement / agitation increases the heat transfer coefficient by convection, facilitating the removal of heat from the piston that is transferred to the oil. Optimal FR values are in the range between 30 and 60% [5].

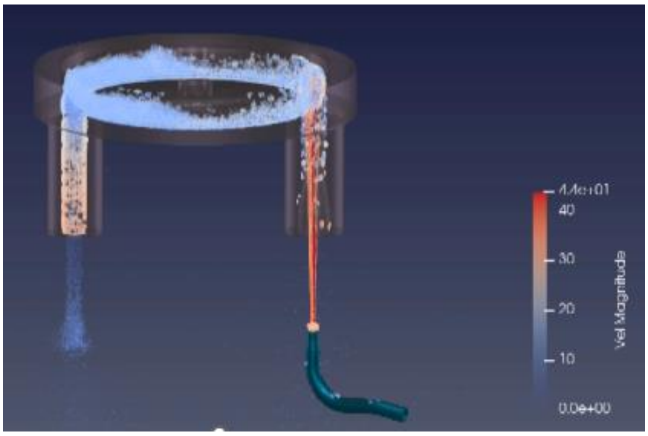

Figura 8. Screenshot of oil filling animation.

VALIDATION OF THE SIMULATION RESULTS

To validate the simulated FR result, it is necessary to compare it with the measured experimental result obtained on the test bench shown in figure 2.

As mentioned before, the measured result is obtained by optical methods associated with a software that manages the images captured in a very small-time intervals during the operation of the bench. Briefly, the method is described as follows: the images show, in different frames, an area of the piston gallery (yellow frame in figure 9) filled with oil, this area is related to the gallery area without filling. The bench software takes care of correlating all the images over time and calculates the FR. The FR measured value by this method was 41% under the operating conditions described in table 1.

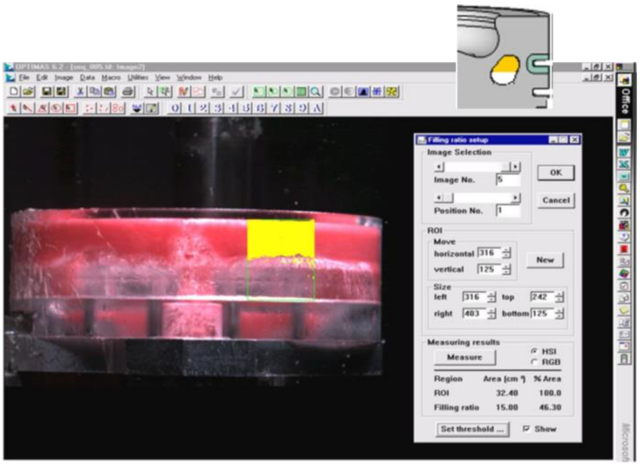

Figure 9. Determination of FR on the test bench.

Table 2 shows the comparison between the measured and simulated FR results showing a good correlation between them with a difference of 2.4%.

Table 2: Comparison between measured versus simulated FR result.

	Prototype of piston gallery filling ratio (FR)
Measured	41%
Simulated	40%
Difference	2.4%

CONCLUSION

The use of advanced tools of numerical simulation by SPH (Smoothed Particle Hydrodynamics) approach available today in the market, made possible the virtual simulation of a relatively complex problem such as the physics of oil filling a piston gallery with interesting gains in pre-processing and processing time in comparison to traditional simulation techniques like CFD.

The FR results obtained with the SPH simulation approach correlated very well with the experimental results provided by the test bench, with an acceptable margin of error between them of 2.4%.

This validation allowed the use of the SPH approach that was later applied to a real engine application comparing two different piston gallery designs where was observed the relation of the FR simulated results with the piston temperature measurements in the engine with a good correlation as expected.

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