Conjugate Heat Transfer for Internal Combustion Engine Application using KIVA code

E. Urip, S. L. Yang, and O. Arici

Mechanical Engineering –Engineering Mechanics Department
Michigan Technological University
Houghton, Michigan 49931

Abstract

Heat transfer is one major important aspect of energy transformation in spark ignition (SI) engines. Locating hot spots in a solid wall can be used as an impetus to design a better cooling system. Fast transient heat flux between the combustion chamber and the solid wall must be investigated to understand the effects of the non-steady thermal environment. A numerical model to solve heat conduction equation inside the solid part of the engine has been developed and implemented into the KIVA code. A 5.4 L V8 Ford engine is used as the engine model to test the modified KIVA.

Introduction

In most common internal combustion (IC) engines, air-fuel mixture is the medium used to produce mechanical work through chemical reaction. For typical four-stroke reciprocating engines, the mixture in the combustion chamber is compressed and then ignited, resulting in a tremendous increase of pressure and temperature. Pressure difference between the combustion chamber and the ambient forces the piston to move up and down, producing mechanical work. The second law of thermodynamics states that a certain amount of heat generated from the combustion products must be rejected. Coolant is typically used in the engine cooling jacket as a medium of accommodating the heat rejection. An insufficient heat removal rate could result in higher thermal stress in the engine.

An improved cooling system can potentially reduce the thermal stress, resulting in a longer engine lifetime. A smaller electronically controlled pump, which requires less power, can now be used to substitute the old inefficient mechanical pump to improve engine efficiency. This can be accomplished by understanding the physical processes occurring in the engine itself. Fast transient heat flux from the combustion products to the cylinder liner and transient heat loss to the cooling passages are important factors affecting the heat transfer process in IC engines. The objective of this study is to predict transient thermal behavior in the solid part of the engine. It should be noted that steady state condition will never be attained in this type of application due to the moving pistons and valves; therefore from an engineering point of view, it is good enough to consider the cyclic or periodic thermal behavior in the engine as an appropriate direction to look for hot spots.

A numerical model to solve heat conduction equation has been developed and validated in Ref [1]. Implementation of the model into the KIVA code to couple the solid

and the fluid phases has been carried out by employing energy balance at the fluid-solid interface.

Numerical Model

Heat conduction equation in the solid part of the engine is described by the following equation:

$$\frac{\partial(\rho I)}{\partial t} = \nabla \bullet [K \nabla T] \tag{1}$$

Discretization of Eq. (1) closely resembles the KIVA code for later coupling. Discretizing the temporal and spatial terms after applying volume integral, through Reynolds transport theorem and divergence theorem to Eq. (1), gives:

$$\rho V C_P^n \frac{T^{n+1} - T^n}{\Delta t} = \sum_a K_a^n \nabla \left[(1 - \Phi_D) T^n + \Phi_D T^{n+1} \right]_a \bullet \vec{A}_a \tag{2}$$

The summation term on the right hand side of Eq. (2) is done on all six faces of a hexagonal finite volume. Φ_D is the implicitness variable and is a function of local diffusion number, C_D, and is given in Eq (3). Second order term in Eq. (3) can be found in Ref [2].

$$C_D = \nu \frac{\Delta t}{\Delta X^2}$$

$$\nu = \frac{K}{\rho C_P} \tag{3}$$

The conjugate Residual Method (CRM) is used as the iterative scheme to solve the resulting implicit equation[3].

Fluid-Solid Interface

Heat transfer process at the fluid-solid interface is presented using Figure 1, and the KIVA code terminology is used to describe the equations. Heat transfer process between the two phases is accomplished by balancing the energy equation at the interface, and is given in Eq. (4). T_s is the solid cell temperature (cell center quantity), and T_a is the fluid-solid interface temperature (face center quantity). Geometric coefficient, "a_{12}, a_{23}, a_{34}", in Eq (4) is solved according to Ref [2] such that the cell to the right of the solid cell is a ghost cell (see Figure 1).

$$q_k = q_c$$

where

$$q_k = -K \left[\nabla T_s \bullet \vec{A} \right] \tag{4}$$

$$q_c = h_f | \vec{A} | [T_f - T_a]$$

and

$$-K \left[\nabla T_s \bullet \vec{A} \right] = -K \left[a_{12}(T_s - T_a) + a_{23}(T_2 - T_3) + a_{34}(T_3 - T_4) \right]$$

Convective heat transfer h_f is obtained from the *law-of-the-wall* heat transfer model[4], and is given by:

$$h_f = \frac{\rho_f \nu_f C_{Pf}}{Pr_{lf}} \frac{F}{y};$$

where

$$F = \begin{cases} \dfrac{R^{'} Pr_{lf} * RPR}{1/\kappa \ln R^{'} + B + 11.05(Pr_{lf} * RPR - 1)} & R^{'} > 11.05 \\ 1.0 & R^{'} < 11.05 \end{cases} \qquad (5)$$

and

$$R^{'} = \frac{C_\mu^{.25} K_f^{0.5} y}{\nu_{lf}}$$

Thermal coupling between the solid and fluid phases is done in the *lawall* subroutine of the KIVA code.

Special treatments are applied to the fluid-solid interface on the cylinder liner, and are automatically utilized when a moving boundary is detected. Two cases are identified and shown in Figure 2. In Case 1, the effective area for the *Fourier's law* in Eq (4) is x1-i1 whereas for the *Newton's law of cooling* is x1-x2. In Case 2, the energy balance is applied at two interfaces namely, Solid1-Fluid and Solid2-Fluid. In the first interface energy balance, the effective area for both *Fourier's law* and *Newton's law of cooling* is x1-x2. In the second energy balance, the effective area for the *Fourier's law* is x2-i1 and the effective area for the *Newton's law of cooling* is x2-x3.

Grid Generation and Engine Operating Conditions

The computational mesh is generated using GRIDGEN® and a modified version of the K3Prep. The generated fluid mesh has about 196,000 grid points whereas the solid mesh has about 132,000 grid points. The solid mesh only covers the cylinder wall as shown in Figure 3. By default the modified KIVA code will apply the constant temperature wall boundary to the fluid mesh that the boundaries are not in contact with in the solid mesh, in this case cylinder head and ports, see Figure 3.

Engine speed is set to constant 3000 RPM and is simulated for two engine cycles (1440 crank angles). Both inlet and exhaust ports boundary are maintained at a constant one atmospheric pressure. The fluid is initially at STP condition, and a stoichiometric mixture is assumed in the inlet port. Cast iron thermal property is assumed[1] for the solid and is initially at 350.15 K. Adiabatic wall boundary is applied on the solid wall surface that is not in contact with the fluid mesh. Ignition is initiated at approximately ten degrees crank angle before top dead center.

Results and Discussion

Temperature contour of both fluid and solid phases is presented using XZ planes at Y=0 cm, see Figure 4. Figure 4(a), (b), and (c) show the temperature contour for the first engine cycle and Figure 4(d), (e), and (f) are for the second engine cycle. It is expected

that fluid flow field will vary between engine cycles due to the transient temperature in the solid region and the initial condition in the fluid region. In order to obtain useful results, one needs to run the simulation for couple thousands of engine cycles until both fluid and solid phases reach periodic steady state. In this study, it took approximately seven days to simulate in cylinder flow with conjugate heat transfer for total of two engine cycles on an Intel Pentium 4 3.06 GHz PC, and it becomes very impractical to simulate the periodic steady state for this type of problem.

Since the convective heat transfer coefficient calculated in Eq (5) is only a function of the flow field and the fluid properties, and is also expected to have small variation between engine cycles, it is good to assume constant h_f and T_f in Eq (4). These two quantities are allowed to vary in space and crank angles (0° – 720° crank angles but repetitive between engine cycles). In other words, the boundary condition on the fluid-solid interface between 1440° and 2160° crank angles (third engine cycle) can be used to obtain periodic steady state solution in the solid. The above assumption is not yet implemented into the KIVA code and only serves as a temporary solution due to the present computing power.

Acknowledgements

References:

1. **E. Urip, K. H. Liew, S. L. Yang, and O. Arici,** "Numerical Investigation of Heat Conduction with Unsteady Thermal Boundary Conditions for Internal Combustion Engine Application", ASME International Mechanical Engineering Congress and RD&D Expo, November 2004.
2. **Amsden, A. A., O'Rourke, P. J., and Butler, T. D.,** 1989, "KIVA-II: A Computer Program for Chemically Reactive Flows with Sprays," Los Alamos National Laboratory Report LA-11560-MS, Los Alamos, NM.
3. O'Rourke, P. J. and Amsden, A. A., 1986, "Implementation of a Conjugate Residual Iteration in the KIVA Computer Program," Los Alamos National Laboratory report LA-10849-MS.
4. **Amsden, A. A.,** 1997, "KIVA-3V: A Block-Stuctured KIVA Program for Engines with Vertical or Canted Valves," Los Alamos National Laboratory Report LA-13313-MS, Los Alamos, NM.
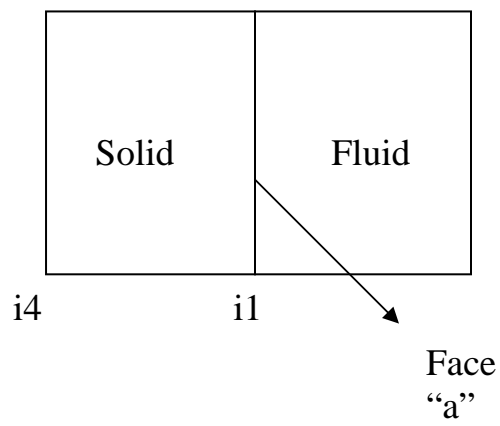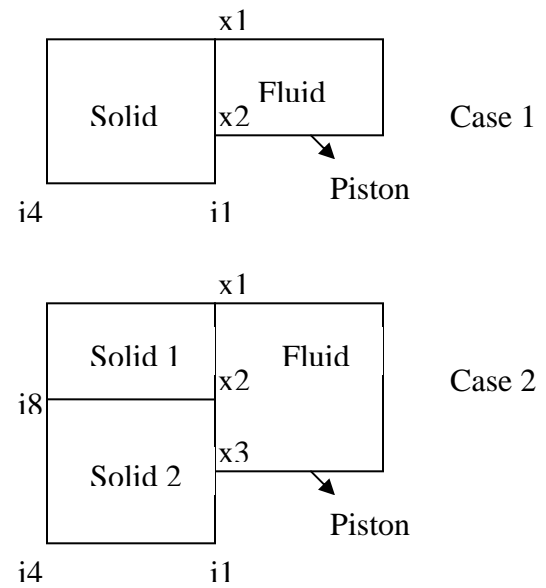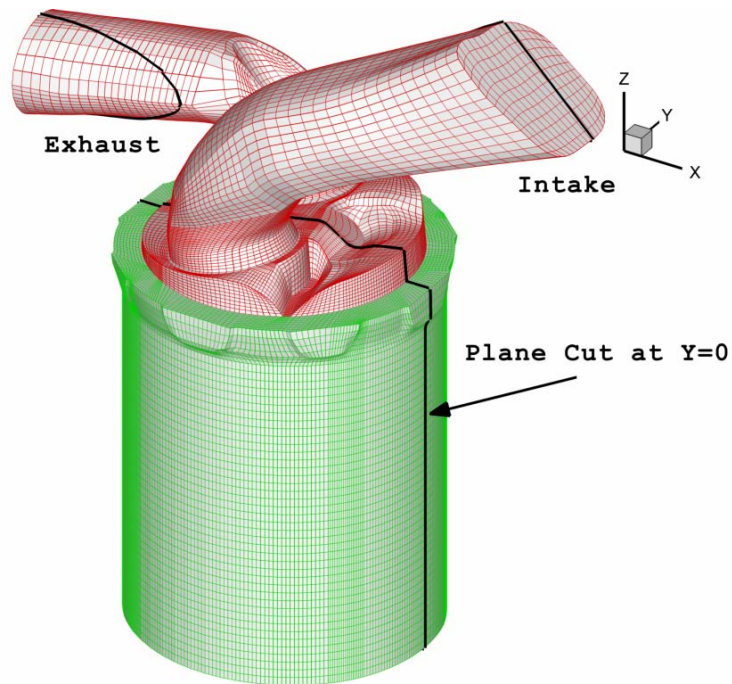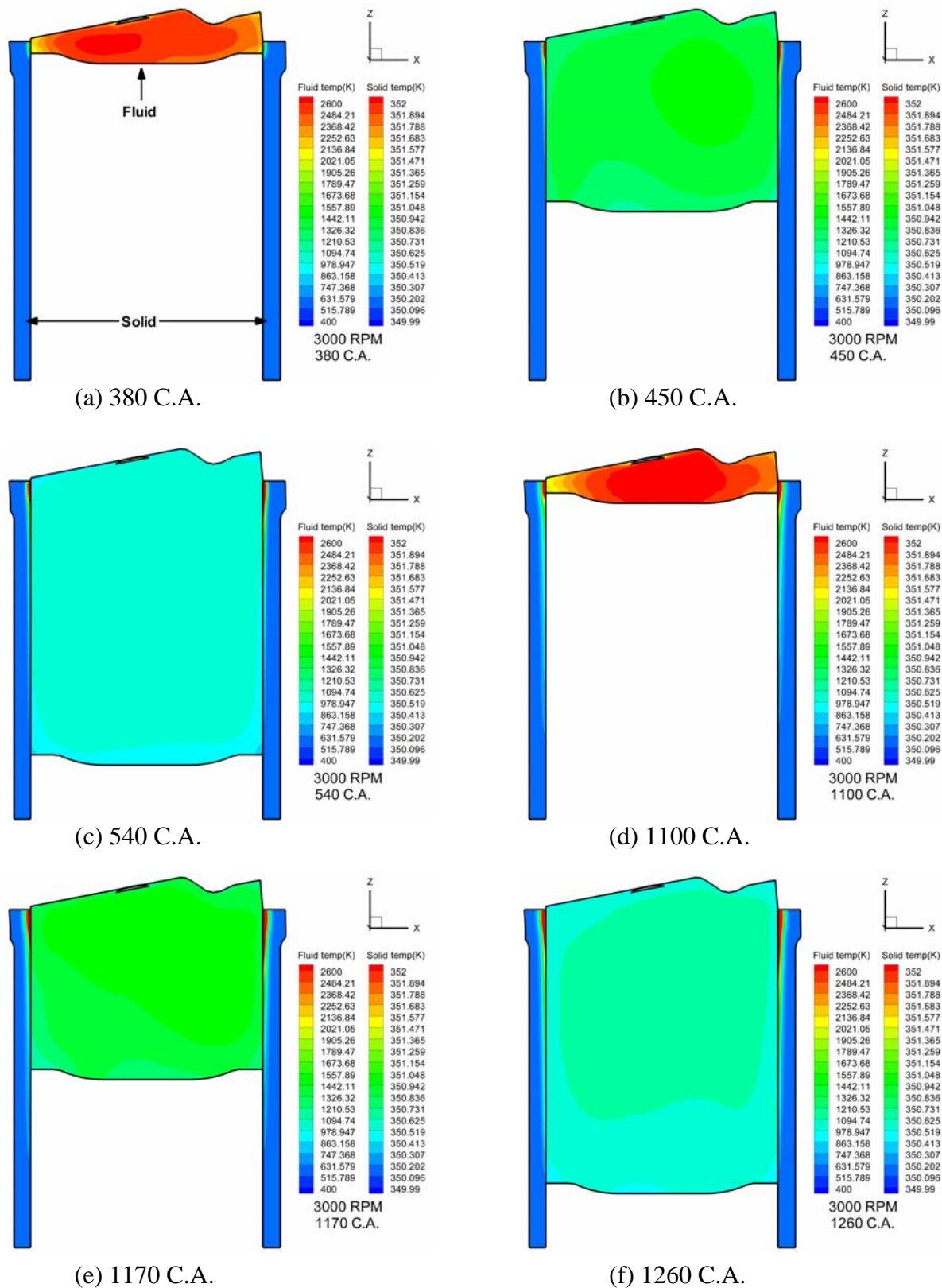
Figure 1

Figure 2

Figure 3

(a) 380 C.A.

(b) 450 C.A.

(c) 540 C.A.

(d) 1100 C.A.

(e) 1170 C.A.

(f) 1260 C.A.

Figure 4 temperature contour at Y=0 cm (3000 RPM)