Summary Report for the period from 06/01/99 – 05/31/02

Grant No. DE-FG04-99AL66236

Mixture preparation and nitric oxide formation in a GDI engine studied by combined laser diagnostics and numerical modeling.

Profs. Volker Sick and Dennis N. Assanis

Project objectives:

Through the combination of advanced imaging laser diagnostics with multi-dimensional computer models, a new understanding of the performance of direct-injection gasoline engines is pursued. The work focuses on the fuel injection process, the breakup of the liquid into a fine spray and the mixing of the fuel with the in-cylinder gases. Non-intrusive laser diagnostics will be used to measure the spatial distribution of droplets and vaporized fuel with very high temporal resolution. These data along with temperature measurements will be used to validate a new spray breakup model for gasoline direct-injection. Experimental data on near wall fuel distributions will be used for comparison with a model that predicts the spray-wall interaction and the dynamics of the liquid film on the surface. Quantitative measurements of local nitric oxide concentrations inside the combustion chamber will provide a critical test for a numerical simulation of the nitric oxide formation process. This model is based on a modified flamelet approach and will be used to study the effects of exhaust gas recirculation.

Experimental Approaches and Achievements:

A direct-injection fuel spray rig was designed and installed to study a well-characterized spray and provide data for comparison with a new breakup and impingement model. Measurements of the spatial and temporal structure of sprays were conducted with a combination of planar laser-induced fluorescence and planar Mie scattering. This gives access to fuel distribution as well as to relative droplet diameters. A single KrF excimer laser beam was employed to illuminate the spray and the signals were separated with a newly designed filter-beam splitter setup. This filter allows a complete separation of the signals and produces two parallel images that can then be recorded with a single ICCD camera. Other features of the setup are on-line single-shot energy referencing and flexible wavelength selection.

Two sets of experiments were conducted. A first series addressed issues of background signals that occur in engine environments when a reflecting surface lies behind the illuminating laser light sheet. This background signal was determined to be strongly wavelength dependent and an effective suppression is primarily possible when the surface is treated with high pressure water blasting and by optically narrowing the depth-of-field for observation by using a large-aperture imaging lens without additional apertures.

Figure 1: Spray test rig with excimer laser, counter-propagating laser sheet illumination and filter-beam splitter combination.

Illumination of the spray with counter-propagating laser sheets was found to effectively overcome problems with laser beam attenuation by the dense droplet cloud in the spray. Horizontal cross-sections of the spray were investigated and revealed a split-injection behavior of the injector. This is illustrated in figure 2.

Figure 2: Integrated intensities of horizontal cross sections of a spray show split injection behavior of the injection.

A second series of experiments addressed the impingement of sprays on a flat surface. The same setup and techniques as above were employed and yielded detailed information about the changes in breakup once the spray has hit the surface. From the ratio of LIF signals and Mie scattering signals, distributions of relative droplet diameters could be calculated. These data were used to improve a detailed model for impinging sprays.

Figure 3: Distribution of relative droplet diameters of an impinging spray.

A single-cylinder optical SIDI engine was built that allows access to the entire combustion chamber for the observation of spray formation, fuel/air mixing, flame propagation and nitric oxide formation. The introduction and mixing of fuel (iso-octane) with air was studied via a combination of PLIF (planar laser induced fluorescence) and Mie scattering techniques. Features of the in-cylinder flow were characterized with PIV (particle image velocimetry).

The concept of visualizing fuel distributions quantitatively using PLIF relies on the fact that the bulk fuel does not fluoresce upon illumination with UV laser light. A fluorescent tracer is added in percentage concentrations to act as a marker for fuel molecules. Ketones, like acetone and 3-pentanone are frequently used for this purpose [Arnold 1993]. We have chosen to investigate toluene as a tracer because of its unique quenching properties that yield a fluorescence signal that is directly proportional to the fuel/air ratio. Using a KrF excimer laser, emission wavelength 248 nm, yields strong fluorescence signals that are centered at 280 nm. A comparison of absorption and fluorescence spectra in

Figure 4 shows that LIF signals can be collected without the risk of fluorescence trapping when filtered with, e. g. a WG 280 color glass filter.

Figure 4: The spectrally separated absorption and fluorescence spectra of toluene show the suitability of toluene as a LIF marker for fuel measurements.

The equivalence ratio ϕ can then be determined from measured PLIF signals after a calibration with the (metered) amount of fuel injected into the engine. A linear relationship is found with high S/N even at very low ϕ , which is important for the study of stratified charge conditions. This is illustrated in Figure 5.

Figure 5: Calibration of PLIF signals to absolute equivalence ratio numbers.

Figure 6 shows an example of instantaneous ϕ distributions that were measured in the pentroof of the engine very close to the spark plug.

Figure 6: Equivalence ratio maps measured close to the spark plug at 600 rpm. The individual frames were taken in 2 CAD steps starting at 26 CAD BTDC. Note the propagation of the flame in the images. The single image on the right is shown to give the scale of the color coding.

Flow fields were investigated using PIV in an area similar to the one targeted with the PLIF measurements shown in Figure 6. Velocity fields were obtained for a variety of conditions showing a swirling flow even inside the pentroof area. The center of this swirl shifts as the engine speed is changed. Figure 7 shows the averaged flow field for engine speeds of 600 and 2000 rpm.

Figure 7: Ensemble-averaged flow fields ($N=200$) at TDC for 600 rpm (upper panel) and 2000 rpm (lower panel). Note that the center of the swirl motion moves as engine speed is changed.

The nature of the fuel/air mixing process in a SIDI engine requires that this process is studied in three spatial directions and time to get a complete understanding of the mixture preparation. An automated PLIF system was constructed, tested and operated to obtain quasi-3D images of the fuel injection, mixing and combustion progress for the following conditions.

- Engine speed: 600 and 2000rpm
- Fuel: iso-octane
- Equivalence ratio: 1.0
- MAP: 45kPa
- Fuel pressure: 8.5 MPa
- EOI: 270 BTDC
- Ignition: 20 BTDC
- Skip-firing: > 5 cycles
- Swirl valve: fully open/fully closed
- Oil/coolant T: 90C

PLIF of toluene was used to obtain images of the equivalence ratio as described in earlier reports.

Figure 8: Schematic of setup used to obtain quasi 3D distributions of the equivalence ratio by automatically translating the lightsheet optics and the ICCD camera

Figure 9 illustrates the arrangement of the swirl control valve and the orientation of the images presented subsequently. All images are oriented such as when view from a birds-eye view onto the engine. The background photo of the valves etc. is taken from below and was then flipped to illustrate the position of valves, spark plug and injector.

Figure 9: Geometric arrangement for optical measurements.

Figure 10 shows an example of averaged ($N=30$) ϕ distributions that were measured for different swirl settings.

Figure 10: Quasi 3D equivalence ratio maps measured for different swirl settings. Average of 30 individual images

3D movies were created to show the mixing process in all four dimensions which will allow a thorough comparison to models.

Combustion progress can be studied using the same images. As is evident from figure 11, the propagating flame front can be extracted from the equivalence ratio maps. The simplest strategy is to binarize the images and then to define a combustion progress variable that can be compared with modeling results like the ones from the coherent flamelet model described below. However, since DOE decided to discontinue funding for the University Consortium prior to the original contract, this part of the work as well as studies of NO formation was not completed under DOE funding and is excluded from this report.

Figure 11: Maps of the equivalence ratio in different cycles at 8BTDC; spark timing is 20BTDC.

In summary, the fuel injection, evaporation, and mixing as well as combustion throughout the cycle have been experimentally investigated with quasi-3D PLIF imaging for a variety of engine operating conditions that show the influence of engine speed and overall in-cylinder engine flow on these processes.

Modeling Approaches and Achievements

A spray/wall impingement submodel was developed and integrated into the KIVA-3V multidimensional CFD environment to simulate the behavior of a spray impacting normally on a flat plate. The performance of the model was assessed by comparing numerical results to the data obtained from the above-mentioned experiments. The model was validated based upon its ability to predict the radial penetration along the wall, normal penetration from with the wall, and envelope of the spray. The calculations were conducted on a SUN ULTRA 2 Creator 3D workstation.

The spray/wall impingement model conserved the mass, momentum, and energy of an impinging parcel before and after impact. The mass conservation equation allowed for three secondary parcels and one wall film parcel to form after a splashing event. It was assumed that the tangential momentum of the impinging parcel was conserved. The tangential momentum of the three secondary parcels was assumed to equal 70% of the impinging parcel's tangential momentum, while the remaining 30% contributed to the momentum of the wallfilm parcel. Finally, the energy balance accounted for the viscous dissipation of the parcel upon impact using the scaling analysis of Chandra et al (1991) and the kinetic energy of the wallfilm.

An impingement criteria was used to determine the onset of a splashing event. The model treated dry wall and wet wall droplet impact separately. If the impinging parcel impacted a dry surface, the splash criteria of Mundo et al (1995) was used. Otherwise, if the parcel impinged on a surface with a pre-existing film, the splash criteria of Cossali et al (1997) was used. If splashing did not occur, the parcel deposited onto the surface or merged with the pre-existing liquid film. After a splashing event, three secondary parcels and one wallfilm parcel were formed. The normal velocity of the wallfilm parcel was zero. Furthermore, it was assumed that the wallfilm parcel did not turn in the tangential plane affixed along the surface. The size of the three splashing parcels was randomly sampled from a Nukiyama-Tanasawa distribution. The velocity of one of the three secondary parcels was randomly chosen to ensure real solutions when the velocities of the remaining secondary parcels were computed. The trajectory of the splashing parcels from the wall was estimated from the experimental data of Mundo et al (1995). In addition, the secondary parcels could turn in the tangential plane.

The calculations were conducted on a wedge shaped grid of 11.25 degrees. The 40 x 1 x 27 grid contained slightly less than 2500 cells. The grid contained a refined region 10mm from the wall with cells having a 1mm x 1mm projection on the front/back faces of the wedge. Outside of the grid, the cell projection was 2mm x 1mm. The grid is illustrated in figure 12.

Figure 12: Computational mesh used in impingement simulation

The radial and normal penetrations along with the envelope of the spray were compared to experimental results of iso-octane impinging on a flat plate at an injector height of 33mm and injection velocity of 55m/s. The model showed improvements over the current KIVA-3V impingement model as shown in figure 13. In addition, model performed well in estimating the shape of the spray as shown in figure 14.

Figure 13: Comparison radial and normal spray penetration predictions of new impingement submodel and KIVA-3V model with experimental data

Figure 14: Spray envelope comparison of experimental results (pink) and model 0.96ms after the start of injection. The legend represents a measure of fuel vapor concentration

A spray/wall impingement submodel was developed and integrated into the KIVA-3V multidimensional CFD environment to simulate the behavior of a spray impacting solid surfaces. The performance of the model was assessed by comparing numerical results to the data obtained from measurements conducted at the University of Michigan of a hollow cone spray impinging normally onto a flat plate under ambient conditions along with previously published experimental results of a solid cone diesel spray impinging normally onto a plate at elevated temperature. The model was assessed based upon its ability to predict the radial penetration along the wall and normal penetration away from the wall. The calculations were conducted on a SUN ULTRA 2 Creator 3D workstation.

The spray/wall impingement model conserved the mass, momentum, and energy of an impinging parcel before and after impact. Three splashing parcels and one wallfilm parcel were used to represent the shattering of an incoming droplet upon impact with the surface as shown in Figure 15.

Figure 15: Splash of an Impinging Parcel.

It was assumed that the impulsive force on an impinging droplet normal to the surface was dominant allowing one to treat the magnitude of its tangential momentum component constant after impact. The tangential momentum of the three secondary parcels was assumed to equal 70% of the impinging parcel's tangential momentum, while the remaining 30% contributed to the momentum of the wallfilm parcel. Finally, the viscous energy lost by a parcel after impact was modeled by using the model of Mao et al (1997) in conjunction with the maximum spread model of Pasandideh-Fard et al (1996) detailed in equation 1.

$$\frac{d_{\max}}{d_i} = \sqrt{\frac{We + 12}{3(1 - \cos \theta_a) + 4\left(\frac{We}{\sqrt{Re}}\right)}} \quad (1)$$

Hence, the overall energy balance of the impinging parcel could be written as the following:

$$\underbrace{\frac{1}{2} m_i v_i^2}_{E_{ke,i}} + \underbrace{\pi d_i^2 \sigma}_{E_{surf,i}} = \underbrace{0.2 \pi d_i^2 \sigma \frac{We^{0.83}}{Re^{0.33}} \left(\frac{d_{\max}}{d_i}\right)^2}_{E_{visc}} + \underbrace{\frac{1}{2} m_{wf} v_{wf}^2}_{E_{ke,wf}} + \underbrace{\sum_1^3 \frac{1}{2} m_j v_j^2}_{E_{ke,s}} + \underbrace{\sum_1^3 \pi d_j^2 \sigma}_{E_{surf,s}} \quad (2)$$

An impingement criterion was used to determine the onset of a splashing event. The model treated dry wall and wet wall droplet impact separately. If the impinging parcel impacted a dry surface, the splash criterion of Mundo et al (1995) was used. Otherwise, if the parcel impinged on a surface with a pre-existing film, the splash criteria of Cossali et al (1997) was used. If splashing did not occur, the parcel deposited onto the surface or merged with the pre-existing liquid film. After a splashing event, three secondary parcels and one wallfilm parcel were formed. The normal velocity of the wallfilm parcel was zero. Furthermore, it was assumed that the wallfilm parcel did not turn in the tangential plane affixed along the surface. The size of the three splashing parcels was randomly sampled from a Nukiyama-Tanasawa distribution of O'Rourke et al (2000) or Han et al (2000). The velocity of one of the three secondary parcels was randomly chosen to ensure real solutions when the velocities of the remaining secondary parcels were computed. The trajectory of the splashing parcels from the wall was estimated from the experimental data of Mundo et al (1995). In addition, the secondary parcels could turn in the tangential plane. Table 1 shows a comparison of the new model formulation with previous published models.

Table 1: Summary of Features in New and Previous Impingement Models

Feature	KIVA (2000)	Gosman et al (1995)	Rutland et al (1998)	New
Splashing Droplet Sizes From Statistical Distribution	√		√	√
Dry/Wet Wall Splash Criteria	√	√	√	√
Solves the Mass Conservation Equation	√	√	√	√
Solves the Momentum Conservation Equation		√		√
Solves the Energy Conservation Equation	√	√	√	√
Comparison of Viscous Dissipation Model with CFD Results				√
Separate Model for Viscous Dissipation and Wallfilm Energy				√

The hollow cone spray calculations were conducted on the 2D grid shown in figure 16. The grid consisted of 1600 cells with a uniform cell size of 1mm x 1mm throughout.

Figure 16: Computational mesh used for the hollow cone spray impingement simulation.

The radial and normal penetrations along with the envelope of the spray were compared to experimental results of iso-octane impinging on a flat plate at an injector height of 25.7mm and injection velocity of 60m/s. The spray was injected into an ambient pressure and temperature environment. The model showed improvements over the cur-

rent KIVA-3V impingement model as shown in figure 17 and 18 in predicting on-the-wall spray penetrations.

Figure 17: Comparison of the radial penetration predictions of new impingement sub-model and KIVA-3V model with experimental data.

Figure 18: Comparison of the normal penetration predictions of new impingement sub-model and KIVA-3V model with experimental data.

The new spray impact model was also validated using experimental measurements of an evaporating solid cone spray of n-tridecane at 550K impinging normally onto a flat plate at elevated temperature and pressure. The experimental results were published by Senda et al (1995). The computational grid selected for this study is shown in figure 19. The grid consisted of a 10mm refined region above the wall that consisted of 40 cells in the radial direction and 20 cells in the normal direction.

Figure 19: Computational mesh used for solid cone spray impingement simulation.

The ambient environment was nitrogen at a temperature and density of 700K and 12.3 kg/m³, respectively. 2400 parcels were introduced into the computational environment at an injection velocity of 154 m/s. Figure 20 shows the spray development at 0.66, 0.99, and 1.32ms after the start of injection. The new model shows improvements over a group of previous impingement models in predicting the spread rate of the liquid the spray as shown in figure 21.

(a)

(b)

(c)

Figure 20: Spray profiles at (a) 0.66, (b) 0.99, and (c) 1.32 ms after the start of injection. Liquid phase (dark circles) is superimposed onto the vapor phase.

Figure 21: Liquid Phase Penetration of the Impinging Spray Measured by Senda et al. (1995)

The characteristics of a GDI engine require specific computational models to capture the important physics. The combustion process in a GDI engine differs from both PFI and CI engines, therefore, a suitable combustion model needs to be developed. A coherent flame type model was developed at the University of Michigan, incorporated in to the KIVA-3V multi-dimensional CFD framework. The first phase of the model was validated with results from a homogeneous charge PFI Ford Duratec engine. The second phase of the model, which is able to capture stratified mixture combustion, will be demonstrated in a non-moving geometry. Further validation of this model with the data from the experimental part of this study was planned, however, the loss of funding prohibited completion of this work.

The coherent flame model, developed for this study, is based on the flamelet concept, which assumes that the thickness of the chemical reaction zone is thin compared to the length scale of the energy containing turbulent eddies. Then the chemical reaction exists as a collection of wrinkled laminar flame surfaces and the “flame brush” is described in terms of a flame surface density (the flame sheet area per unit volume) Σ . Flame sheet models describe the evolution of this quantity Σ (Boudier et al, Musculus et al, Cheng et al). Under these assumptions, the progress of the combustion reaction can be described as follows:

$$\dot{\omega} = w_L \Sigma \quad \text{with } w_L = \rho_f Y_f S_L$$

with ρ_f and Y_f the fuel density and fuel mass fraction, respectively. The problem is then reduced to solving a balance equation for Σ , accounting for transport, diffusion, production (due to the stretch rate) and destruction (due to mutual annihilation of flamelets, quenching, ...). This equation can be summarized as follows:

$$\frac{\partial \tilde{\Sigma}}{\partial t} + \frac{\partial \tilde{u}_i \tilde{\Sigma}}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\nu_t}{\sigma_\Sigma} \frac{\partial \tilde{\Sigma}}{\partial x_i} \right) + \frac{d \tilde{\Sigma}}{dt}$$

where ν_t is the turbulent diffusivity and σ_Σ is a fixed model parameter. The tilde denotes Favre-averaged quantities. The last term on the right hand side of the equation requires modeling of the production and destruction of flame density, and it is in this term that the most variability between models has been seen in the literature. Summarized briefly, Σ is initiated by the spark ignition, sustained by the turbulent fluid straining, bulk-convected by the charge motion, and consumed locally by a variety of mechanisms. A number of different formulations for the production and destruction terms were implemented, but are beyond the scope of this report.

To accurately model the stratified charge combustion, we need to know the properties of the unburned mixture ahead of the flame. With the standard set of KIVA-3V equations for the different species and energy, once, for example, a lean mixture in a computational cell starts burning, we can no longer distinguish how much oxygen is present ahead of the flame, since the quantity model is the total mass of oxygen in the cell. To accurately model the properties of the unburned mixture ahead of the flame, and hence the progress rate of the combustion reaction, three diagnostic equations are solved, tracking the unburned fuel, unburned oxygen, and the unburned gas enthalpy, as follows:

$$\begin{aligned}
\frac{\partial \bar{\rho} Y_{F,u}}{\partial t} + \frac{\partial \bar{\rho} u_k Y_{F,u}}{\partial x_k} &= \frac{\partial}{\partial x_k} \left(\frac{\mu_t}{\sigma_F} \frac{\partial Y_{F,u}}{\partial x_k} \right) - \bar{\omega}_{F,u} \\
\frac{\partial \bar{\rho} Y_{O,u}}{\partial t} + \frac{\partial \bar{\rho} u_k Y_{O,u}}{\partial x_k} &= \frac{\partial}{\partial x_k} \left(\frac{\mu_t}{\sigma_F} \frac{\partial Y_{O,u}}{\partial x_k} \right) - \frac{S}{\Phi} \bar{\omega}_{F,u} \\
\frac{\partial \bar{\rho} h_u}{\partial t} + \frac{\partial \bar{\rho} u_k h_u}{\partial x_k} &= \frac{\partial}{\partial x_k} \left(\frac{\mu_t}{P_r} \frac{\partial h_u}{\partial x_k} \right) + \bar{\rho} \varepsilon + \frac{\bar{\rho}}{\rho_u} \frac{\partial p}{\partial t} + \bar{Q}_{w,u}
\end{aligned}$$

where s is the stoichiometric ratio, and Φ is the equivalence ratio. With these diagnostic equations, the progress rate of the combustion reaction becomes:

$$\dot{\omega} = w_L \Sigma \quad \text{with } w_L = \rho_f Y_f^u S_L$$

Here, $Y_{F,u}$ and $Y_{O,u}$ are the mass of fuel and oxygen in the unburned gases divided by the total mass. Y_F^u and Y_O^u are the mass of fuel and oxygen in the unburned gas divided by the mass of unburned gas. The above equations allow us to track the mixture ahead of the flame. In addition, we can determine the properties of the mixture behind the flame, allowing us to predict NO_x based on the burned gas temperature, instead of the global cell temperature. Additional features of the model include a spark-ignition model and a wall-flame interaction model, but these are beyond the scope of this report.

To validate the first phase of the model, the closed cycle of a Ford Duratec engine was modeled. The grid used was a regular cylinder with the same bore and stroke, and an adjusted squish height to retain the same compression ratio as the original geometry. The model was applied to five different operating points, as summarized in Table 2. The results, shown in Figure 22, show acceptable qualitative and quantitative agreement of the first phase of the model.

	Case 1	Case 2	Case 3	Case 4	Case 5
Speed (rpm)	2000	2000	2000	2000	3000
Lambda	1.3	0.7	1	1	1
Spark	26	26	0	50	26
Trapped Mass (gram)	0.26	0.25	0.27	0.24	0.22
IVC	109 BTDC	109 BTDC	109 BTDC	109 BTDC	109 BTDC

Table 2: Modeled operating points for Ford Duratec engine.

Figure 22: Phase I Ford Duratec Results

As a first step of evaluating the extended formulation, a cylinder with a stratified mixture as seen in Figure 23, and ignition along the top was modeled. The initial results showed an unphysical behavior of the flame near the walls. This was attributed to the over-prediction of the turbulent dissipation by the Law-of-the-Wall boundary layer treatment in KIVA-3V. The turbulent dissipation is directly proportional to the generation of flame surface due to stretch, and therefore the progress rate was over predicted near the walls. A near-wall stretch correction was implemented, reducing the length scales the flame sees near the walls of the combustion chamber, and the qualitative flame behavior was observed to be physically correct. A summary picture showing different views of the flame can be seen in Figure 24.

Figure 23: Stratified Charge Test Case.

Figure 24: Propagating flame for stratified testcase.

To validate the extended formulation in more detail, it was planned to compare results of a simulation of the optical engine with the experimental results, however, the loss of funding prohibited completion of this work.

References:

Arnold, A., Buschmann, A., Cousyn, B., Decker, M., Sick, V., Vannobel, F., Wolfrum, J., 1993, "Simultaneous Imaging of Fuel and Hydroxyl Radicals in an In-Line Four Cylinder SI Engine," SAE Transactions 102, Sec. 4, pp. 1-9 and also SAE Paper No. 932696 Philadelphia

Boudier, P., Henriot, S., Poinot, T. and Baritaud, T., "A Model for Turbulent Flame Ignition and Propagation in Spark Ignition Engines," 24th Symposium (International) on Combustion/The Combustion Institute, 1992/pp.503-510.

Chandra and C. Avedisian, "On the Collision of Droplet with a Solid Surface", Proceedings Royal Society of London A, Vol 432, pp. 13-41, 1991.

Cheng, W. K. and Diringer, J. A., "Numerical Modeling of SI Engine Combustion with a Flame Sheet Model," SAE Paper 910268, 1991.

G. Cossali, A. Coghe, and M. Marengo, "The Impact of a Single Drop on a Wetted Solid Surface", Experiments in Fluids, Vol. 22, pp. 463-472, 1997.

Mundo, M. Sommerfeld, and C. Tropea, Droplet-Wall Collisions: Experimental Studies of the Deformation and Breakup Process, Int. J. Multiphase Flow, Vol. 21, pp. 151-173, 1995.

Mao, T., Kuhn, D., and Tran, H., "Spread and Rebound of Liquid Droplets upon Impact on Flat Surfaces", AIChE Journal 43(9): 2169-2179 (1997).

Musculus, M. P. and Rutland, C. J., "An Application of the Coherent Flamelet Model to Diesel Engine Combustion," SAE Paper 950281, 1995.

Pasandideh-Fard, M., Qiao, Y., Chandra, S., and Mostaghimi, J., "Capillary Effects During Droplet Impact on a Solid Surface", Physics of Fluids 8(3): 650-659 (1996).

O'Rourke, P.J. and Amsden, A.A., "A Spray/Wall Interaction Submodel for the KIVA-3V Wall Film Model", SAE Technical Paper No 2000-01-0271

Senda, J., Kobayashi, M., Iwashita, S., and Fujimoto, H., "Modeling of Diesel Spray Impingement on a Flat Plate", SAE Technical Paper No. 941894.

Han, Z., Xu, Z., and Trigui, N., "Spray/Wall Interaction Models for Multidimensional Engine Simulation", International Journal of Engine Research 1(1):127-146 (2000).

Naber, J. and Reitz, R., "Modeling Engine Spray/Wall Impingement", SAE Technical Paper No 880107.

Publications to date based on results produced under this contract:

Grover, R.O. and Assanis, D.N., 2001, "A Spray Wall Impingement Model Based Upon Conservation Principles," Fifth International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines, Nagoya, Japan, July 2 - 5, pp. 551-559

Sick, V., Stojkovic, B., 2001, "Attenuation effects on imaging diagnostics of hollow-cone sprays," Applied Optics, 40, (15) pp. 2435 - 2442

Stojkovic, B., Sick, V. 2001, "Evolution and impingement of an automotive fuel spray investigated with simultaneous Mie/LIF techniques," Applied Physics B 72, pp. 1-9

Frieden, D., Sick, V., 2003, "Investigation of the fuel injection, mixing and combustion processes in an SIDI engine using quasi-3D LIF imaging," SAE Technical Paper 2003-01-0068