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## MODELING OF PARTICLE WALL INTERACTION AND FILM TRANSPORT USING EULERIAN WALL FILM MODEL

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### ABSTRACT

The growing awareness of pollutant emissions from gas turbines has made it very important to study fuel atomization system, the spray wall interaction and hydrodynamic of film formed on engine walls. A precise fuel spray spatial distribution and efficient fuel air mixing plays important role in improving combustion performance. Cross-flow injection and film atomization technique has been studied extensively for gas turbine engines to achieve efficient combustion. Air blast atomizer is one of these kind of systems used in gas turbine engines which involves shear driven prefilmer secondary atomization. In addition to gas turbine combustor shear driven liquid wall film can be seen in IC engines, rocket nozzles, heat exchangers and also on steam turbine blades.

In our work we have used Eulerian Wall Film (EWF) [1] model to simulate the experiment performed by Arienti et al. [2]. In the Arienti's experiment liquid jet is injected from a nozzle from the top of the chamber. Droplets shed from the jet surface due to primary and later secondary atomization in the presence of high shearing cross flowing air. Further liquid fuel particles hit the wall to form film, film moves subjected to shear from the gas phase. Liquid film can reatomizes due to subgrid processes like stripping, splashing and film breakup. In current study we have validated Arienti et al. [2] experimental data by modeling complex & coupled physics of spray, film and continuous phase and by accounting complex subgrid processes.

### INTRODUCTION

In aeronautical gas turbine engines for a 'more efficient' combustion, high quality of the fuel spray requires. Fine droplets generally evaporate fast and help to achieve efficient mixing and combustion. A precise characterization of the spray drop size distribution is very important to predict the flame structure and topology.

In pre-filming air blast atomizer (Fig. 1) which is widely used in gas turbine system first fuel is atomized by a pressure nozzle. Later droplets hit the pre-filmer wall and form a thin liquid film. Gas stream accelerates the liquid film by shear forces along the pre-filmer wall. Due to high shear at gas-film interface

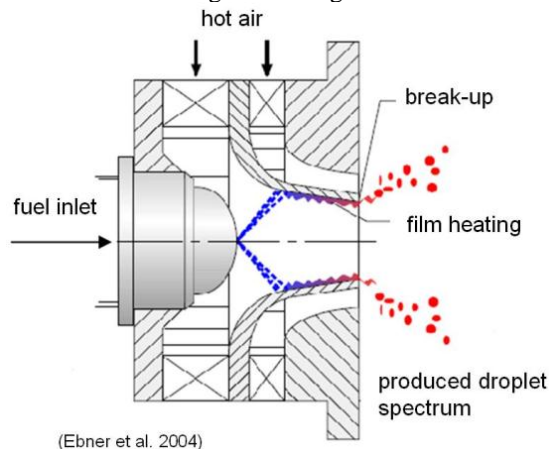


Fig 1. Airblast atomizer (Ebner et al. [3])

Instabilities the pre-filmer secondary atomization occurs. The rest of the fuel droplets get evaporated and mixed downstream. Pre-filming airblast atomizers exhibit stable performances for a wide range of fuel flow rates, and a low pressure loss [4]. Currently such atomizers are being investigated for use in lean burn combustors which promise the additional advantages of fuel efficiency and low pollution, particularly NOx.

Experimental investigations of shear-driven film flow and film evaporation are one of the most important tasks in development of modern gas turbine combustor. For this reason, various researchers have studied film and droplet formation from the impingement of a spray onto a film in the absence of a crossflow of air [5], as well as in the presence of crossflow [6,7].

Since thin liquid film is of interest in many other engineering applications as well, several researchers have work towards CFD modeling of this phenomenon. O'Rourke & Amsden[8] developed a Lagrangian approach to model wall films. Wittig et al.[9] modeled motion and evaporation of shear driven liquid films. Ebner et al. [3] modeled the liquid films under the effect of accelerated air flow conditions. Chaussonnet et al. [10] employed large eddy simulation for the bulk flow along with the film modeling. Senda & Fujimoto [11] implemented a film model for the impinging sprays on the wall in diesel engines.

Arient et al. [2] carried out experiments on where the liquid jet is crossflow-atomized in a rectangular channel so that a film forms on the wall opposite to the injection orifice. The film eventually breaks up at the downstream exit of the channel. Experimental data of film thickness, drop size distribution and drop velocity was reported and later validated with numerical simulation [12].

Arienti et al. [12] propose a model for film formation and breakup based on data from experiments and direct numerical simulations. AtoMIST (Atomization Model Interfaced with Surface Tracking) method used in their study is based on the time-dependent description of the liquid phase as well as on local atomization submodels that operate directly on the jet and film surfaces. The main simplification of AtoMIST consists in transforming liquid elements of the jet or film surface into Lagrangian parcels (by atomization) and vice versa (by impingement) directly at the tracked liquid surface. They included various submodels like column breakup, film breakup, shear stripping and splashing to accurately predict the wall film and atomization physics. Ebner et al. [3] have also validated data of accelerated film flow experiment using their in-house code with improved boundary layer approach. This work was on film flow through diffuser and nozzle.

## NOMENCLATURE

$\rho_l$	= Liquid Density
$\sigma$	= Surface tension
$h$	= Film height
$\nabla_s$	= Surface gradient operator
$\vec{V}_l$	= Mean film velocity
$\vec{V}_p$	= Velocity of particle stream
$\dot{m}_s$	= Mass source per unit wall area due to droplet collection, film separation, film stripping
$\dot{m}_p$	= Mass flow rate of particle stream
$P_{gas}$	= Gas Flow Pressure term
$P_h$	= Pressure term due to gravity component normal to the wall surface
$P_\sigma$	= Pressure term due to surface tension
$\vec{g}_\tau$	= Gravity in the direction parallel to the film
$\vec{\tau}_{fs}$	= Shear Stress
$\nu_l$	= Liquid viscosity
$\dot{q}$	= Momentum source term due to droplet collection or separation
$We_f$	= Film Weber number
$We_{critical}$	= Critical Weber number for film separation
$\theta$	= Edge angle
$\theta_{critical}$	= Critical edge angle for film separation

## EULERIAN WALL FILM (EWF) MODEL [3]

As shown in Fig. 3 the whole process of atomization and film formation and breakup can be described as below

1. **Primary Atomization:** In-nozzle effects (cavitation, turbulence induced disturbances) and instabilities on liquid-gas interface lead to ligaments break up and drop formation.
2. **Secondary Atomization:** Droplets become unstable under the action of forces induced by their motion relative to the continuous phase and undergo further fragmentation
3. **Particle collection and film formation:** During atomization process or afterwards, a fraction of the spray impinge on the wall and form the film.
4. **Film transport:** Film moves due to shear from the continuous phase.

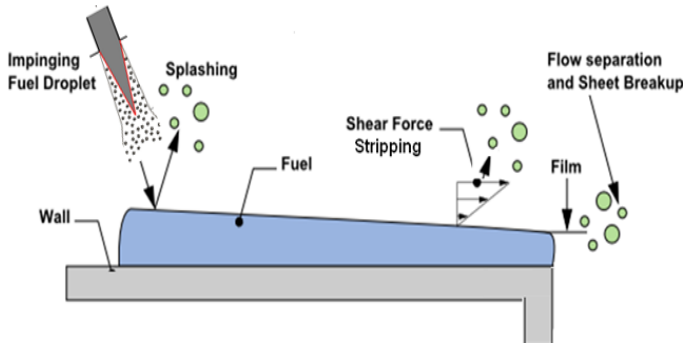


Fig 3. Subgrid processes involved in EWF model

5. **Splashing:** Impinging drops can remove liquid from the film by splashing.
6. **Stripping:** Drops can shed from the film surface due to high shear at film-continuous phase interface
7. **Separation:** The liquid reaches the end of the film wall, where the competition of surface tension and shear results in the formation of new ligaments and drops.

EWF model of ANSYS Fluent 15.0 solves two dimensional thin film of liquid on a wall surface which forms after collection of droplet. This film can further reatomized and shed particles due to splashing, stripping & separation. EWF model has been coupled with discrete phase particles (spray droplets) and continuous phase (crossflow). There are other film physics which are accounted in EWF model like viscous and kinetic heating, film heat transfer with continuous phase and wall, film evaporation & condensation. Also this model is suitable for collection efficiency calculation. Collection efficiency calculation is the first and important step in any icing analysis is to investigate the effectiveness of a body in collecting the water droplets in the atmosphere. EWF model can be coupled with Eulerian-Lagrangian(DPM) and Eulerian-Eulerian multiphase frame work of ANSYS Fluent Solver. EWF model assumes that film always flows parallel to the surface so normal component of film velocity is zero. The film is assumed to have a parabolic velocity profile & bilinear temperature profile across its depth.

## 1. Mass, Momentum Equations for Wall Film

Eulerian Wall film model solves conservation of mass for a two dimensional film in a three dimensional domain using transient explicit formulation. The conservation equation is:

$$\frac{\partial h}{\partial t} + \nabla_s \cdot [h \vec{V}_l] = \frac{\dot{m}_s}{\rho_l} \quad (1)$$

Where  $\rho_l$  is the liquid density,  $h$  the film height,  $\nabla_s$  the surface gradient operator,  $V_l$  the mean film velocity and  $\dot{m}_s$  the mass source per unit wall area due to droplet collection, film separation, film stripping.

Conservation of film momentum is given,

$$\frac{\partial h \vec{V}_l}{\partial t} + \nabla_s \cdot (h \vec{V}_l \vec{V}_l) = -\frac{h \nabla_s P_L}{\rho_l} + (\vec{g}_\tau) h + \frac{3}{2\rho_l} \vec{\tau}_{fs} - \frac{3v_l}{h} \vec{V}_l + \frac{\dot{q}}{\rho_l} \quad (2)$$

Where

$$P_L = P_{gas} + P_h + P_\sigma$$

$$P_h = -\rho h (\vec{n} \cdot \vec{g})$$

$$P_\sigma = -\sigma \nabla_s \cdot (\nabla_s h)$$

The terms on the left hand side of Equation (2) represent transient and convection effects, respectively. On the right hand side, the first term includes the effects of gas-flow pressure, the gravity component normal to the wall surface (known as spreading), and surface tension; the second term represents the effect of gravity in the direction parallel to the film; the third term is the viscous shear force at the gas-film interface; the fourth term represents the viscous force in the film, and the last term is associated with droplet collection or separation. Note that in arriving at the shear and viscous terms on the RHS, a parabolic film velocity profile has been assumed.

Since the film considered here is thin, the lubrication approximation (parallel flow) is valid and therefore these equations are solved in local coordinates that are parallel to the surface.

## 2. Film sub models

The Eulerian wall film model can interact with the discrete phase model (DPM) through source terms to the film equations. During the interaction with the DPM model, the discrete particles are collected to form a wall film. The discrete particles can splash when interacting with a film boundary, creating additional particles. Additional particles can be created when the film separates from the wall, or when the shear stress is sufficient that large particles can be stripped from the film. Mass leaving the film surface by separation or stripping is accounted through source terms to the film equations.

### 2.1. DPM Collection

Discrete particle streams or discrete particles hitting a face on a wall boundary are absorbed into the film. When particles are absorbed, their mass and momentum are added to the source terms in Equation (1) and Equation (2), continuity and momentum equations, respectively. The mass source term is given by

$$\dot{m}_s = \dot{m}_p$$

Where  $\dot{m}_p$  is the flow rate of the particle stream impinging on the face. The momentum source term is

$$\vec{q}_s = \dot{m}_p \cdot (\vec{V}_p - \vec{V}_l)$$

Where  $\vec{V}_p$  denotes the velocity of the particle stream and  $\vec{V}_l$  denotes the film velocity.

## 2.2. Splashing

During the interaction with the DPM model, the discrete particles are collected to form a wall film. The discrete particles can splash when interacting with a film boundary, creating additional particles. The wall particle wall interaction is based on the work of Stanton [13] and O'Rourke [14].

## 2.3. Film Stripping

Film stripping occurs when high relative velocities exist between the gas phase and the liquid film on a wall surface. At sufficiently high shear rates, Kelvin-Helmholtz waves form on the surface of the film and grow, eventually stripping off droplets from the surface. The film can strip if based on two criteria 1) Critical Wall Shear and 2) Critical film Weber number. The model for this behavior in the current implementation of the wall film model is based on work by Lopez de Bertodano, et al. [15] and Mayer [16].

## 2.4. Film Separation

The film can separate from an edge if two criteria are met – first that the angle between faces is sufficiently large and second if the film inertia is above a critical value. If separation occurs, a source term in the film equation is used to remove mass and momentum from the face corresponding to the edge upstream of where the separation occurs. Once separation occurs, EWF model calculate the number and diameter of the shed particle stream at an edge, based on work by Foucart [17], O'Rourke [18] and Friedrich [19].

## ARIENTI et al [1] EXPERIMENT:

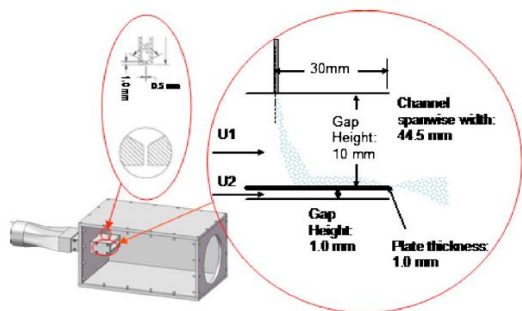


Fig 2. Injector and test section geometry in the experiment [1]

In this study we have chosen Arienti et al. [2] experiment for validation of EWF model. Arienti et al. [2] did experiments for different flow conditions. In current work we have chosen condition with air velocity 82 m/s and spray jet velocity 12.7 m/s. A sketch of the test section and liquid injection nozzle which was used by Arienti et al. [2] is shown in Fig. 2. The primary flow channel, 10 mm tall by 44.5 mm wide, is separated by a thin wall from a second small air channel. The secondary channel is not used in this initial study. The nozzle is fabricated from an aluminum rod to the dimensions of 0.5 mm in diameter, 1 mm in length, and total inlet orifice chamfer of 90 deg. The nozzle is installed flush with the upper wall of the primary flow channel.

## COMPUTATIONAL DETAIL

ANSYS FLUENT 15.0 has been used for all simulations. Fig. 4 shows the computation domain. Air enters at 82 m/s and Jet velocity is 12.7 m/s. Outlet is exposed to atmospheric condition. For side surfaces symmetry boundary conditions have been used. Mineral spirits is used as model fluid for spray droplet. It has density  $\rho_l = 780 \text{ kg/m}^3$ , dynamic viscosity  $\mu = 0.00085 \text{ kg/m s}$  and surface tension  $\sigma = 0.024 \text{ N/m}$ .

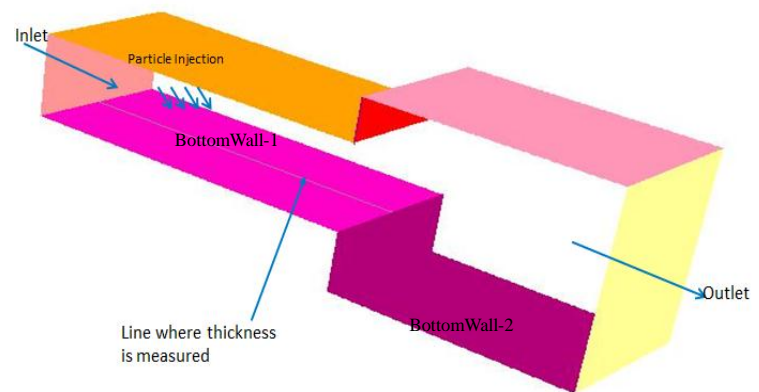


Fig. 4 Computational Domain

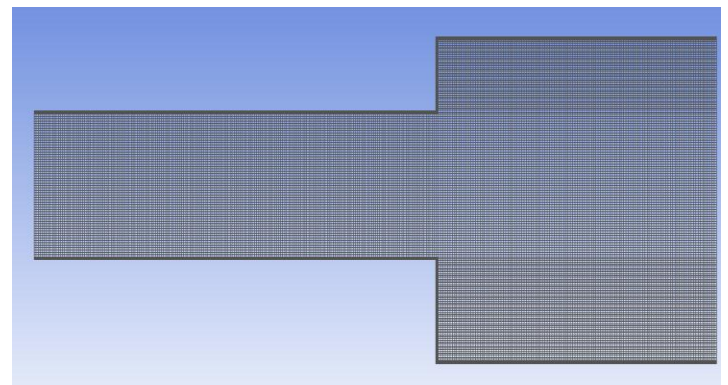


Fig. 5 Mesh Distribution in mid plane

Mesh count is  $2.5 \times 10^6$  hexahedral cells. Mesh distribution is shown in Fig. 5. Near the wall inflation layer has been created to predict accurate wall shear. Realizable k epsilon model has been used along with Enhance wall treatment to model the boundary layer. Wall Yplus one was achieved with the inflation layers. Grid independent study for film solution was performed with various surface mesh sizes to make sure the wall film height becomes grid independent. Global residuals convergence were achieved below  $10^{-3}$  for all equations.

Turbulent continuous phase flow field solved using pressure based coupled solver and secondary droplet phase solved using DPM approach with unsteady particle tracking method. Simulations have been carried to study effects of various EWF models and compared results with experimental data. For each simulation mass imbalance less than 1% has been achieved. The convergence is ensured by monitoring the film mass as function of time. The results are considered converged when this monitor stabilizes.

### Dispersed Phase Description

Spray droplets are tracked in Lagrangian framework by the parcel approach, with each parcel representing several physical droplets with the same diameter and velocity. For modeling the spray accurately capturing the primary breakup and the secondary breakup of the spray droplets are very important.

Primary breakup is responsible for the droplet size distribution and initial velocity at the exit of the nozzle. In this study Plain orifice atomizer model is used to model the spray nozzle. In the current study TAB breakup model is used to accurately predict the secondary breakup of the liquid droplet. This method is based upon Taylor's analogy [20].

### RESULTS & DISCUSSION

In the experiment spray is injected from the top of the chamber under high shearing air cross flow. Under such situation spray bends and hits the surface to form film, also fraction of the spray mass goes down stream without hitting wall. Before analyzing the wall film thickness and velocity it is important to examine the spray appearance and continuous phase pressure and velocity field. Fig. 6 shows the spray appearance under the cross flow condition without any subgrid processes. At nozzle initial particle velocity and diameter has been calculated due to primary breakup and further down secondary breakup occurs. Small size particles flow with continuous phase and large size particle hits wall and form the film.

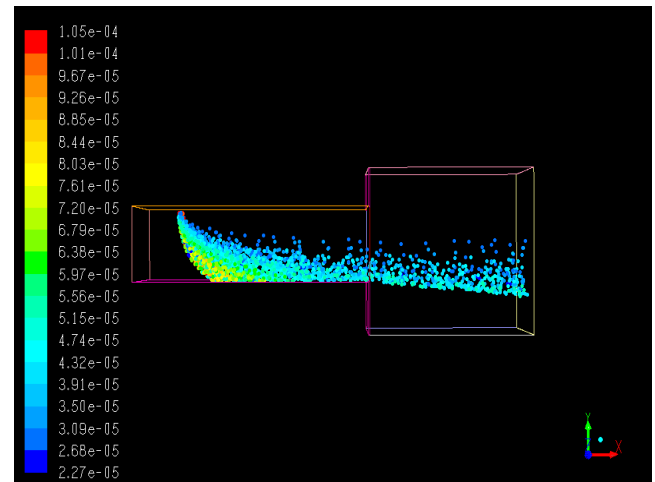


Fig. 6 Particle Track colored by Particle Diameter (m)

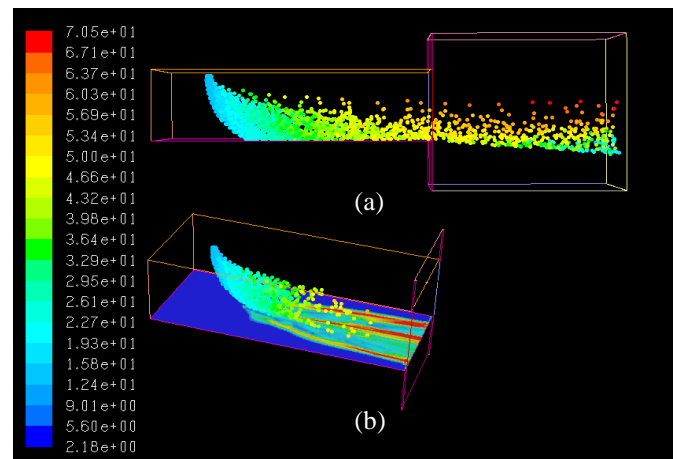


Fig. 7 (a) Particle Track colored by Particle Velocity (m/s)  
(b) Filtered Particle along with Film thickness contour

Fig. 7 shows that spray particles gain momentum due to interaction with continuous phase. Also how particle and wall interaction leads to film formation and transport can be seen.

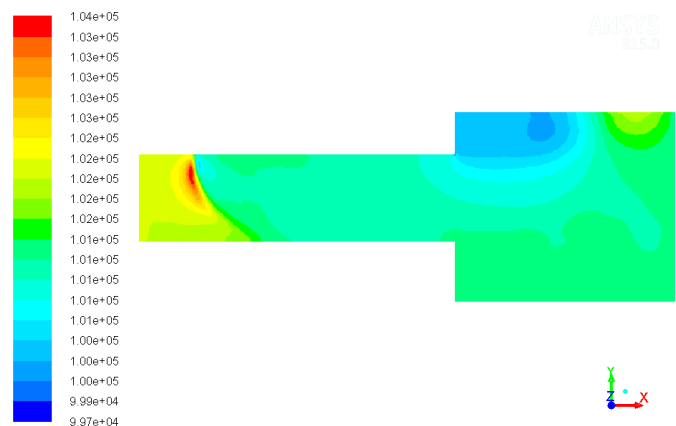


Fig. 8 Contour of Pressure (Pa)

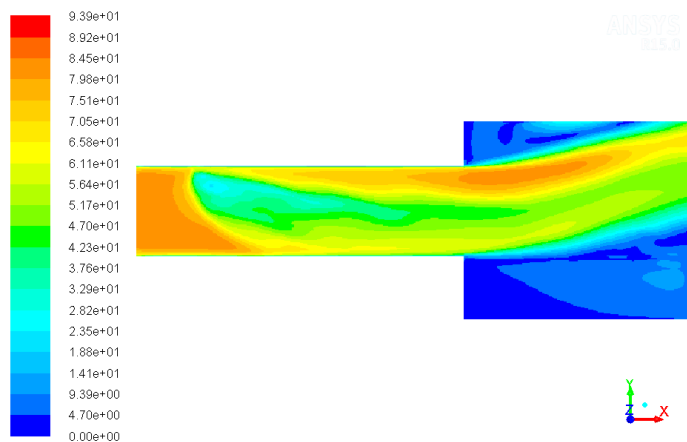


Fig. 9 Contour of Velocity Magnitude (m/s)

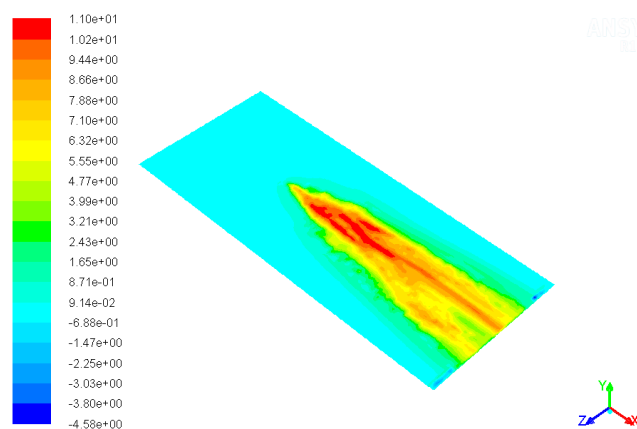


Fig. 12 Film X Velocity (m/s) on Bottom Wall-1

High pressure field is created just before the spray due to hindrance from the spray. Low pressure recirculation regions are also seen after the step and it looks strong in top corner because of the change in height of top and bottom steps.

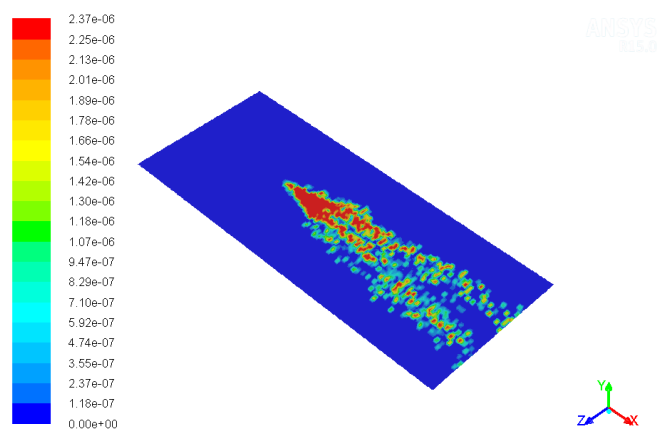


Fig. 10 Film DPM Mass Source (kg/s) on Bottom Wall-1

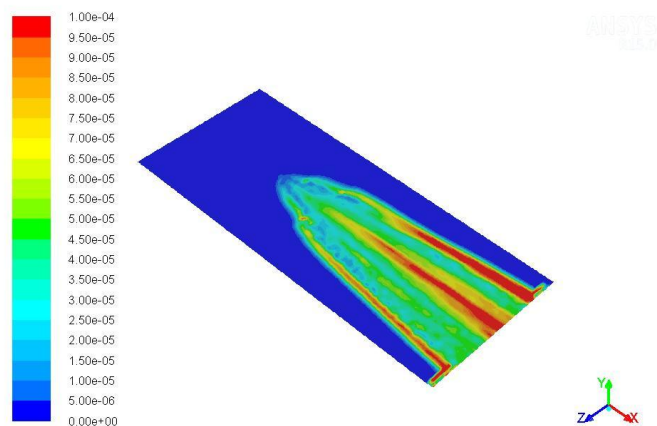


Fig. 11 Film Thickness (m) on Bottom Wall-1

Fig. 10 shows impact zone of particles where particle are collected to form the film. Particle mass collection is high at the location where jet impinges of the wall. Deposited particle mass form the film and film gets transported due to shear from the gas phase.

Fig. 11 shows Wall Film thickness on Bottom Wall-1. Film thickness contours looks on expected line except at the corners near step where high film thickness values can be seen. The reason for the buildup of thick film is the back flow of gas phase over the edge, which slows down the film flow and forces the film liquid to flow sideways. When this side-flowing film reaches the symmetry boundary, it got nowhere to go, causing film build-up. Fig. 12 shows negative X-Velocity at the side corners near step.

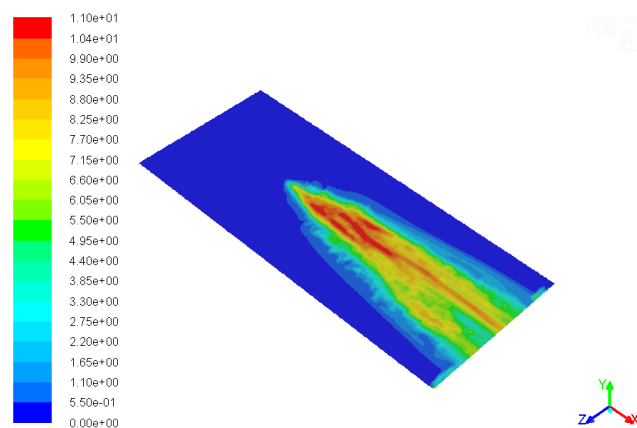


Fig. 13 Film Velocity Magnitude (m/s) on Bottom Wall-1

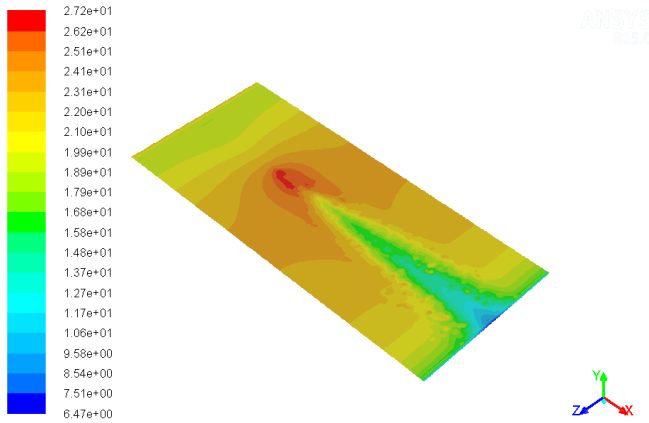


Fig. 14 Wall Shear Stress (N/m<sup>2</sup>) on Bottom Wall-1

Fig. 13 shows Film Velocity Magnitude contour which looks consistent with wall shear stress Fig. 14. Film velocity increases as wall shear increases and then decreases as shear stress reduces downstream.

When liquid droplet hits the surface to form wall film some of the particles get absorbed in the film and some splashes based on the criterion described in the literature [13][14]. Also under high shearing condition some of the particles are stripped from the surface of the film.

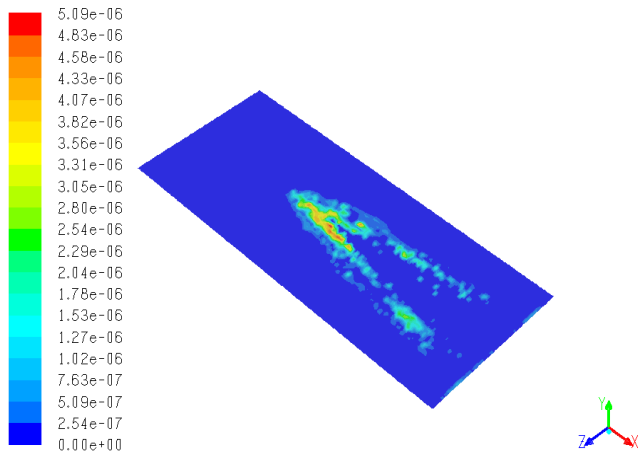


Fig. 15 Film Stripping Mass Source (kg/s) on Bottom Wall-1

In current study film submodels are accounted step by step and its impact on film thickness is studied. Generally stripping happens in the region of high shear compared to surface tension. Fig 15 shows the zone of film from where film stripping occurred due to high shear.

Also as film flows downstream at the step film breaks (separate) to shed new droplets. Separation criteria is based on the work by Foucart [17], separation can occur at an edge if a critical angle,  $\theta$ , is exceeded and a Weber number based on the

film,  $We_f$ , is above a minimum value. Film weber number is defined as below:

$$We_f = \frac{\rho_l h |\vec{V}_l|^2}{\sigma}$$

and  $\sigma$  is surface tension of the film. The separation criteria become,

$$\begin{cases} \theta > \theta_{critical} \\ We_f > We_{critical} \end{cases}$$

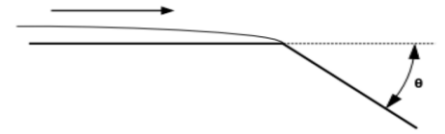


Fig 17 shows a comparison of film thickness plot along the centerline on Bottom Wall-1 for three different cases with experimental data. Without submodel film increases steadily and reaches close to 90μm as per experimental data but without submodel simulation over predict the film thickness. Splashing does not seem to be affecting the film thickness. In the zone of 5 to 15 mm filmer distance there is high shear which leads to film stripping so simulation with stripping shows very good match with experimental data.

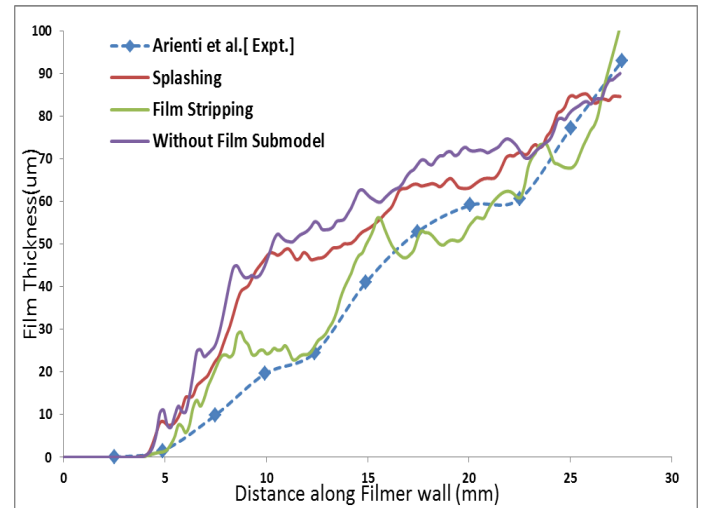


Fig. 16 Film thicknesses along the centerline of Bottom Wall-1

Numerical challenges have been faced to choose appropriate criteria for stripping when film, flow and particle solution was coupled. Film solution was showing unstable behavior as film courant number was going to very high value. To overcome these challenges we used adaptive time stepping option available with EWF model and made sure that film courant number does not cross 0.2. For stripping case we froze the flowfiled and solved only for film and particle field.

## CONCLUSION

Eulerian Wall Film (EWF) Model can be coupled with DPM model to predict particle wall interaction and film atomization. It has a very good post processing capability which helps to analyze the flow field in detail. Various submodels like splashing, stripping and separation enables accurate modeling of complicated physics associated with film. EWF model shows good match with film thickness experimental data. Thus EWF model can be used for the design and optimization of system where liquid film plays an important role. Modeling challenges still exist in providing a firm basis to the atomization criteria tried in this work. Results of this work are currently being used for further refinement and by adding accurate stripping criteria and film breakup model.

## ACKNOWLEDGMENTS

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## REFERENCES

1. ANSYS FLUENT Theory Guide, ANSYS 15.0, 2013
2. Shedd, T., Corn, M. L., Arienti, M., and Soteriou, M. C., 2009, "Liquid Jet Breakup by an Impinging Air Jet," Forty-Seventh AIAA Aerospace Sciences Meeting. Paper No. AIAA-2009-0998
3. J.Ebner, P. Schober, O. Schafer, R.Koch and S. Wittig. "Modeling of Shear Driven Liquid Wall Films: Effect of Accelerated air flow on the film propagation". Progress in Computational Fluid Dynamics, Volume 4, Nos. 3-5, 2004
4. Lefebvre, A. H., (1989). *Atomization and Spray*, Ed. Norman higier
5. Mathews, W. S., Lee, C. F., and Peters, J. E., 2003, "Experimental Investigations of Spray/Wall Impingement," *Atomization Sprays*, **13**, pp. 223–242.
6. Panao, M. R. O., and Moreira, A. L. N., 2005, "Experimental Characterization of an Intermittent Gasoline Spray Impinging Under Cross-Flow Conditions," *Atomization Sprays*, **15**, pp. 201–222.
7. Kiura, T., Shedd, T. A., and Blaser, B. C., 2009, "Investigation of Spray Evaporation and Numerical Model Applied for Fuel-Injection Small Engines," *SAE Int. J. Engines*, **1**, pp. 1402–1409.
8. P. J. O'Rourke and A. A. Amsden. "A Particle Numerical Model for Wall Film Dynamics in Port-Fuel Injected Engines". SAE Paper 961961. 1996.
9. S.wittig, J. Himmelsbatch, B.Noll, and H.J. Feld, "Motion and Evaporation of Shear Driven Liquid Film in Turbulent Gases".
10. G. Chaussonnet, E. Riber, O. Vermorel, B. Cuenot, S. Gepperth, and R. Koch, "Large Eddy Simulation of a prefilming airblast atomizer". ILASS – Europe 2013.
11. J. Senda and H. G. Fujimoto, "Multidimensional Modeling of Impinging Sprays on the Wall in Diesel Engines".ASME-2009.
12. M.Arienti et al., "Modeling Wall Film Formation and Breakup Using an Integrated Interface-Tracking/Discrete-Phase Approach", *Journal of Engineering for Gas Turbines and Power*, March 2011, Vol. 133 / 031501-1.
13. D. W. Stanton and C. J. Rutland. "Modeling Fuel Film Formation and Wall Interaction in Diesel Engines". SAE Paper 960628. 1996.
14. P. J. O'Rourke and A. A. Amsden. "A Spray/Wall Interaction Submodel for the KIV A-3 Wall Film Model". SAE Paper 2000-01-0271. 2000.
15. M.A. Lopez de Bertodano, C. S. Jan, S.G. Beus. "Annular Flow Entrainment Rate Experiment in a Small Vertical Pipe". *Nuclear Engineering and Design*. 178. 61-70. 1997.
16. S. Mayer, "Theory of Liquid Atomization in High Velocity Gas Streams". *ARS Journal*. 31. 467–473. 1961.
17. J. A. Foucart, Private Communication
18. P. J. O'Rourke and A. A. Amsden. "A Particle Numerical Model for Wall Film Dynamics in Port-Fuel Injected Engines". SAE Paper 961961. 1996.
19. S. M.A. Friedrich, H. Lan, J. L. Wegner, J. A. Drallmeier, and B. F. Armaly. "A Separation Criterion with Experimental Validation for Shear-Driven Films in Separated Flows". *Journal of Fluids Engineering*.130., May 2008
20. G. I. Taylor. "The Shape and Acceleration of a Drop in a High Speed air Stream, Technical Report". In the Scientific Papers of G. I. Taylor. ed., G. K. Batchelor. 1963