A Cellular Automata Approach for Modeling Multiphase Flow Tribology

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INTRODUCTION

Thin-film multiphase flows are present in numerous tribological applications such as chemical mechanical polishing (CMP) and artificial hip joints. Traditionally, there have been two ways to model multiphase flows. The first of these approaches is the Eulerian-Eulerian approach, in which the phases are modeled as inter-penetrating continua. This approach is computationally efficient but does not provide discrete particle locations. It has been applied to many engineering problems such as fluidized beds.1 The other approach, known as the Eulerian-Lagrangian approach, treats the dispersed phase as individual particles interacting with a fluid continuum. This approach, which typically uses the discrete element method (DEM) to model the particle phase, becomes computationally demanding, especially for high particle counts. The Eulerian-Lagrangian approach has also been applied to several engineering applications such as CMP2 and artificial hip joints.3

This work aims to produce a computationally fast, first-order, Eulerian-Lagrangian multiphase flow modeling technique through the combination of computational fluid dynamics (CFD) and lattice-based cellular automata (CA). Additionally, this work aims to demonstrate the tribological capabilities of this approach by extending it to perform wear analysis.

EULERIAN PHASE FLUID MODELING

To model the Eulerian phase, the Chorin projection method was used to numerically approximate the Navier-Stokes equations.4,5 The current model uses a finite-differencing scheme in two-dimensions to discretize the fluids governing equations. These include the momentum equations (1)–(2) and the continuity equation (3).

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + \rho g_x
\]

(1)

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \rho g_y
\]

(2)

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

(3)
LAGRANGIAN PHASE MODELING: CELLULAR AUTOMATA (CA)

In the newly developed Eulerian-CA model, the Lagrangian phase is modeled using the lattice-based CA approach. CA is a modeling technique for obtaining fast first-order approximations by using rule-based mathematics and/or physics-based equations to model physical processes. The newly developed Eulerian-CA model incorporates basic CA principles, as summarized in Ilachinski, for modeling particle dynamics.

Space in the Eulerian-CA model is discretized into a two-dimensional rectangular grid. Each grid space is surrounded by eight neighboring cells which make up its local interaction neighborhood. Time is discretized such that the fastest moving particle, or boundary, moves one grid space per time step. In this model, particle interactions are processed by equations based on Newtonian physics.

PARTICLE-FLUID COUPLING

For simplicity in this initial development of the Eulerian-CA method, only the fluid's effect on a particle is modeled and not vice-versa. This occurs through a Stokes drag force, which causes the particles to move based on the fluid velocities at the particle center. To accommodate separate fluid and CA time steps, a CA movement interval, equal to the ratio of the CA time step to the fluid time step, is used to update CA particle positions.

RESULTS

Figure 1 displays the results for a study comparing the computational efficiency of the Eulerian-CA approach to that of the traditional Eulerian-DEM approach. Figure 1 shows that as the number of particles being simulated increases, the Eulerian-CA method exhibits an increasing CPU time savings.

To examine the capabilities of the Eulerian-CA method to study wear processes, an investigation was performed on the effect of fluid inlet velocity on the wear of a surface inside of a Couette flow geometry, as shown in Figure 2.

To calculate the material removed from the wear surface, Archard's wear equation (Eq. (4)) was used. In Eq. (4), \( k, F, \) and \( s \) represent the wear coefficient, indentation force, and sliding distance, respectively.

\[
\text{Material Removed} = k(F)s 
\]

As can be seen in Figure 3, the results from the Eulerian-CA model qualitatively agree very well with a general erosion formulation from Williams. Both sets
of results show that the material removed increases more rapidly as the fluid inlet velocity is increased.

CONCLUSIONS
In this work, an Eulerian-CA model has been developed to predict the behavior of multiphase flow tribo-systems. A study on the method’s computational efficiency has shown that the Eulerian-CA method provides a high potential for CPU time savings. Preliminary wear studies have demonstrated the potential of the Eulerian-CA model to be extended to simulate erosive wear processes. These initial results suggest that the Eulerian-CA model could be useful as a fast first-order supplement to a full Eulerian-Lagrangian simulation or as a means of simulating particle tribo-systems, which are too computationally demanding for other modeling approaches such as Eulerian-DEM.

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REFERENCES