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Evaluation of Overflow Wet Rinsing Efficiency

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Abstract

A description of the flow field in an overflow wafer rinse process is presented. This information is being used in an initiative whose principal objective is to reduce the usage of water in wafer rinsing. The velocity field is calculated using finite-element numerical techniques. A large portion of the water does not contribute to wafer rinsing.

Introduction

Rinse steps account for as much as 60% of the ultra-pure water (UPW) used in a fab. Billions of gallons can be used by a single fab in one year [1]. The large quantities of water are an important manufacturing expense. Moreover, in some locations, water usage is an environmental concern. Yet, as the complexity of chips and the size of wafers increase, UPW usage could increase significantly. Thus, there is strong motivation to increase the efficiency of rinse processes.

The principal objective of this work is to reduce UPW consumption in overflow rinse tanks. Other objectives are to reduce rinse time, improve rinse uniformity, and improve overall wafer cleanliness.

Our approach is to use experiments and numerical analysis to characterize the fluid dynamics of an idealized rinse tank that is operating in a steady-state overflow mode. As will be shown, characterizing the fluid dynamics provides a clearer understanding of how to accomplish the objectives. In particular, the analysis allows undesirable aspects of the flow field to be identified. Design considerations can then be focused on improving the undesirable aspects to produce an improved rinse tank.

Conventionally, fluid dynamics is viewed as the most important aspect of rinsing, since it often affects other important phenomena. For example, if the removal of a contaminant from the surface of a wafer is purely diffusive, the removal rate still depends strongly on the flow field. Moreover, once a contaminant is removed from the wafer, fluid dynamics strongly influences the transport of the contaminant out of the tank. Thus, although other phenomena are important, fluid dynamics is the dominant physical mechanism in general rinsing processes.

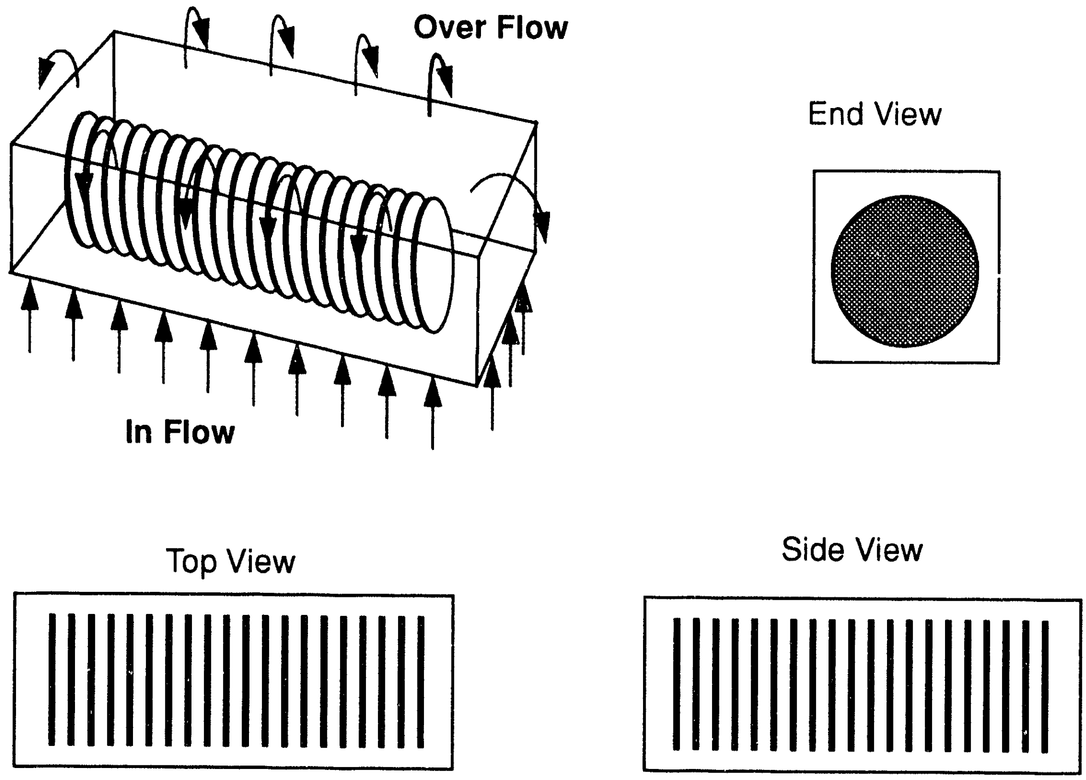

Figure 1 Schematic view of an idealized wafer rinsing. Water flows in from the bottom of the tank, and flows over the sides of the tank.

Two previous analyses in this area are by Tonti [2] and Rosato, *et al.* [3]. Tonti assumed that the transport of a contaminant from a wafer surface and across a fluid boundary layer is purely diffusive. That is, the velocity was assumed to be zero within the fluid momentum boundary layer. The effect of non-zero fluid motion is accounted for only after the contaminant diffuses to the outer edge of the fluid momentum boundary layer.

Rosato, *et al.* assume that a contaminant layer on a wafer diffuses instantaneously and uniformly throughout the rinse tank. As contaminated water flows out of the tank, and uncontaminated water flows into the tank, diffusion continues to be infinitely fast so that the contaminant distribution remains uniform, but becomes more and more dilute with time.

The results from the present investigation allow the effect of fluid motion on diffusive flux from a surface to be considered, which has been omitted in the previous analyses. Our approach also takes into account combined convective and diffusive transport at all points in the fluid, which is also omitted in the previously mentioned analyses. The results presented here include only the first step in our investigation, which is to describe the velocity field of the water. In work presently underway, the velocity fields described herein are being used to determine the transport of contaminants and particles, under the assumption that they are sufficiently dilute such that the fluid velocity field is unaffected.

Idealized Cascade Overflow Rinse Tank

Several features of an overflow rinse tank are idealized to facilitate numerical simulation of the flow field. The principal idealizations are:

- Wafers are modeled as having zero thickness since the real thickness (approximately 1 mm) is much smaller than other important length scales in the problem. This approximation greatly simplifies the numerical grid.
- The free surface flowing out of the tank is modeled using a either a zero-normal - traction boundary condition, or a "rigid lid" approximation. In the rigid lid approximation, the free surface is modeled as a flat surface on which the velocity perpendicular to the lid is zero, and the velocity tangential to the lid is non-zero. These approximations allow the calculation to be much less expensive than if the free surface were to be resolved numerically. Several additional analyses not described here show that these approximations do not affect the flow between the wafers.
- The flow into the tank (from the bottom) is approximated as a uniform vertical velocity. In reality, the water issues from the holes in the bottom of the tank. As a result, small jets are formed which could significantly affect the penetration of the fluid into gaps between wafers if the wafers are sufficiently close to the bottom of the tank. Numerical simulation of such phenomena would require significant additional effort, with questionable benefit in terms of additional information. Experiments are planned to evaluate the accuracy of this approximation.
- The wafers are assumed to be perfectly aligned. For example, if two wafers lean toward one another, the flow between them will be greatly reduced. Thus, the assumption of perfect wafer alignment provides for maximum flow between wafers.

Governing Equations for Fluid Flow

The equations governing the motion of a Newtonian fluid with density ρ and viscosity μ are conservation of linear momentum,

$$\rho\left[\frac{\partial \underset{\sim}{u}}{\partial t} + (\underset{\sim}{u} \bullet \nabla)\,\underset{\sim}{u}\right] = -\nabla P + \mu \nabla^2 \underset{\sim}{u} \tag{1}$$

where P is the fluid pressure and $\underset{\sim}{u}$ is the velocity vector. For the problem of interest, the density is constant which yields the incompressibility constraint on the velocity field,

$$\nabla \bullet \underset{\sim}{u} = 0. \tag{2}$$

The fluid pressure is determined from this constraint. The fluid is assumed to be isothermal, and the velocity field is assumed to be unaffected by the presence of any contaminants or particles. To consider transport of a continuous phase contaminant, the appropriate transport equation is

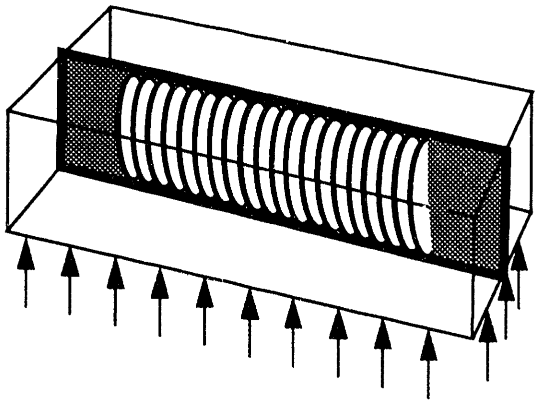

Figure 2 Visualization of the plane on which two-dimensional calculations are performed for a stack of wafers.

$$\frac{\partial c}{\partial t} + (\underline{u} \bullet \nabla) c = \nabla \bullet (\alpha \nabla c) . \quad (3)$$

Boundary conditions will be shown for individual analyses. Below, velocity fields are presented which are numerical solutions to Eqns. (1) and (2), as obtained using the commercial finite element program FIDAP. [4]

Two-Dimensional Results

The two-dimensional results presented below approximate the motion in a tank containing 50 wafers. Only the motion on the centerline of the wafers is considered. The smallest flowrate occurs on the centerline of the wafers, and therefore represents worst-case rinsing. The computational domain is shown in Figure 3. The flow enters the bottom of the tank with a specified uniform velocity, and exits the top of the tank as specified with a zero-normal-traction boundary condition. This approximation is appropriate on the centerline of the wafers since the flow is also symmetric in the direction perpendicular to the page. The velocity on the wafers and the tank walls is zero, as is appropriate for an impermeable surface and a viscous fluid.

Figure 4 a,b,c shows the streamlines for three cases in which the inlet area for the flow is varied from the entire area across the tank bottom, to the area under half of the wafers. The streamlines show that in each case much of the flow goes around, rather than through the wafers, the result being that there is very little flow on the centerline of the wafers. A comparison of the vertical velocity at the mid-height of the centerline of the wafers is also shown to further illustrate that much of the flow goes through the gap between the tank wall, rather than between wafers.

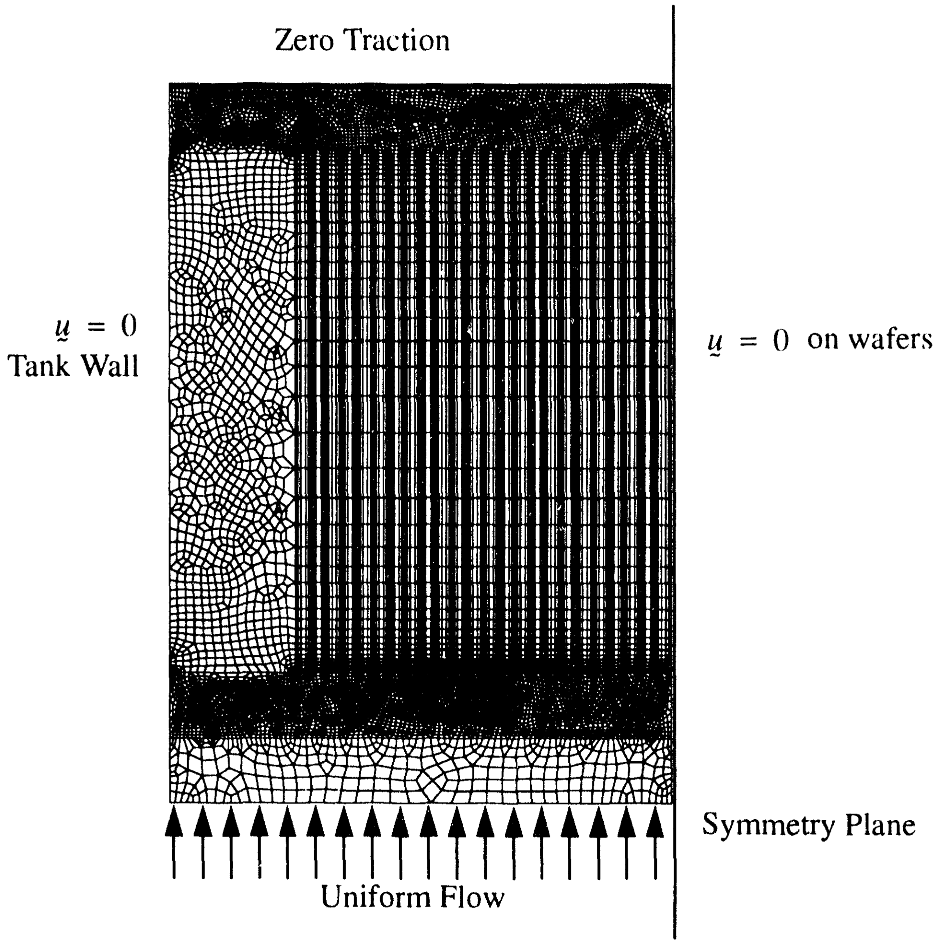

Figure 3 Finite element grid for two-dimensional analysis of flow on the center plane of a rinse tank containing 50 wafers. By symmetry, only the 25 wafers of the left half are considered.

In the results shown in Figure 4, the fluid essentially flows straight out of the top of the tank, as an approximation to flow in a direction perpendicular to the page. To show that this approximation has negligible effect on the flow, an additional calculation was performed in which only two wafers adjacent to the tank wall were considered, and all the flow was required to exit the side of the tank, as shown in Figure 5. The streamlines indicate the same result seen previously: most of the flow goes around the wafers, indicating that the effect of the outflow condition on the flow between the wafers is negligible. The dominant physics is that the flow resistance associated with the narrow gap between two wafers is much larger than the flow resistance associated with the gap between the tank wall and the last wafer. As a result, fluid flows preferentially around the wafers.

0.1 Three-Dimensional Results

Consider the flow entering below the gap between two wafers. If the flow perpendicular to the wafer surfaces were eliminated, all the flow entering below the gap between two wa-

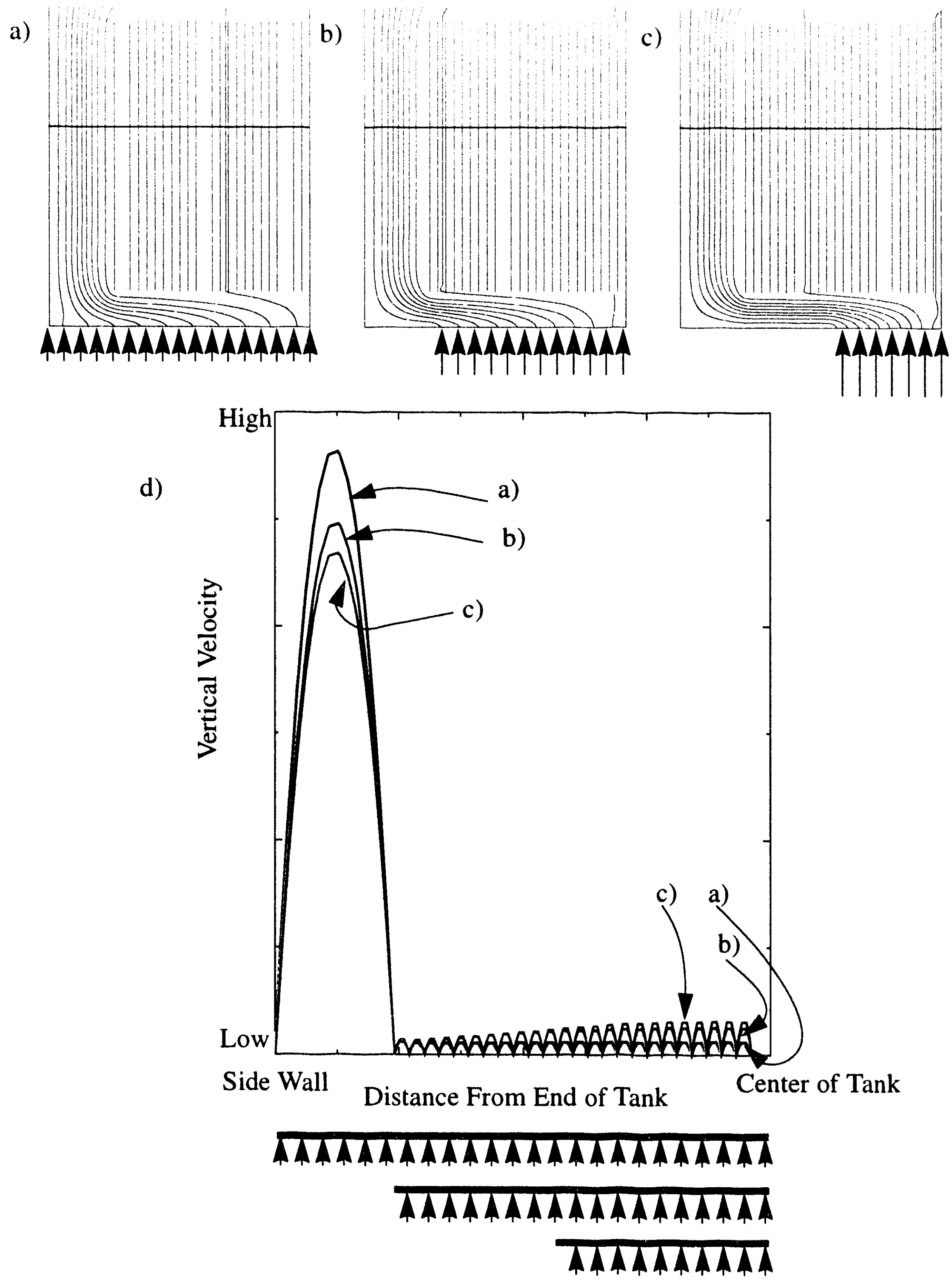

Figure 4 Flow on the centerline of 25 wafers in an idealized rinse tank. The inlet area is varied as shown, keeping the mass flow rate constant. Streamlines shown in a, b, and c indicate that much of the flow goes around the wafers. d) shows the vertical velocity distribution on the horizontal lines in a, b, and c.

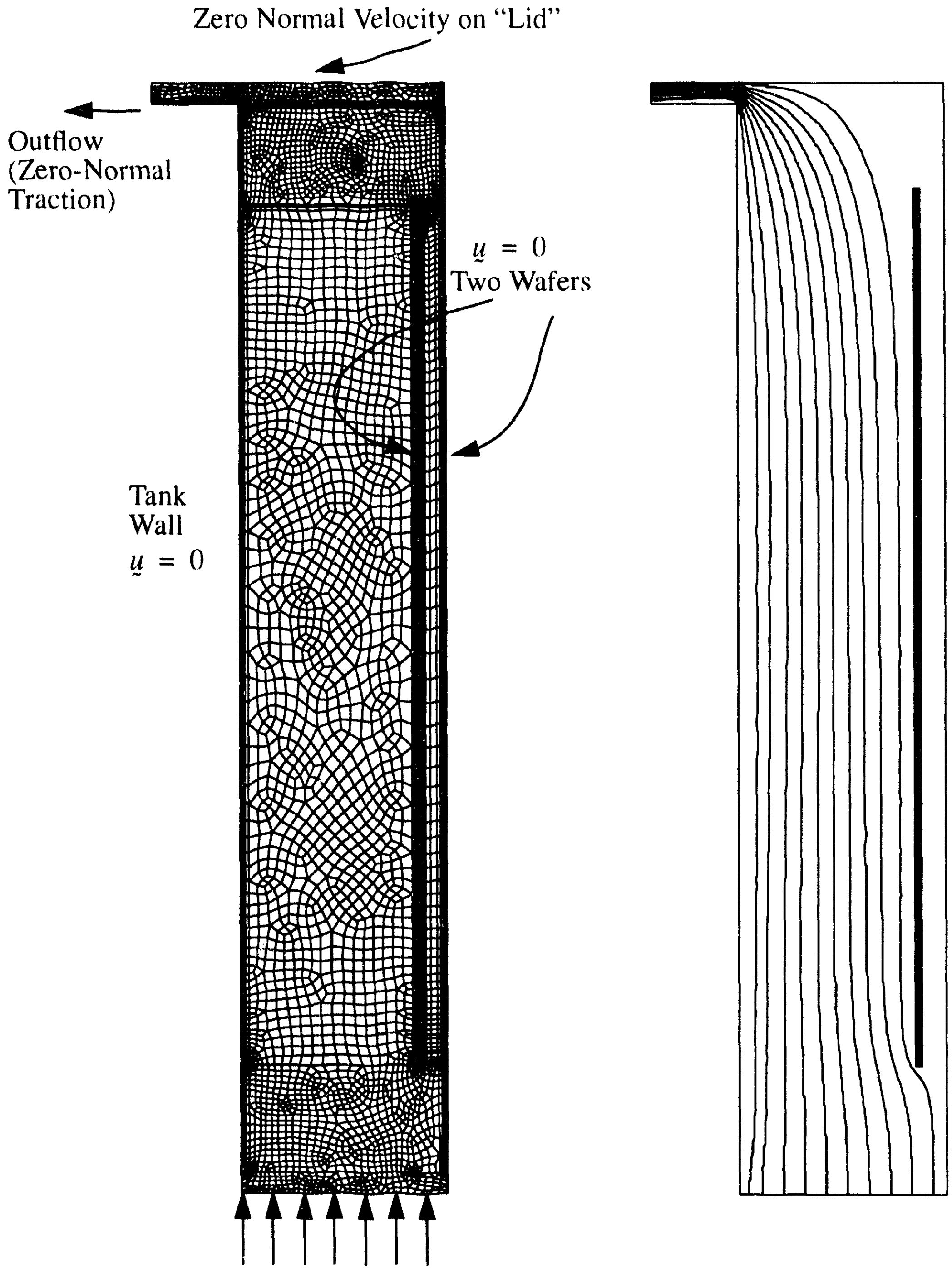

Figure 5 Finite-element grid and streamlines for flow on the centerline of two wafers adjacert to a tank wall, with flow out of the tank specified to be the in the horizontal direction.

fers would have to flow through that gap. This situation is considered in the three-dimensional analysis described next. The three-dimensional computational domain for the gap between two wafers is shown in Figure 6. The streamlines in three planes parallel to the wafer are also shown. The streamlines do not remain straight and parallel from top to bottom. This indicates that some of the flow is diverted around the wafers and through the gap between the wafer edges and the side wall. It is also noted that the flow field in the gap has been shown to be well-described using the two-dimensional Hele-Shaw flow approximation. [5]

Conclusions and Future Directions

Numerical results were presented which describe the flow in an idealized rinse tank containing a stack of wafers. Two-dimensional results identify the gap between the end of the tank and the wafers on the end of the stack (the wafer-wall gap) as being critical to the flow rate on the vertical centerline of wafers. The results show that most of the water flows through the wafer-wall gap rather than through the gaps between wafers. Three-dimensional results show that some of the flow is also diverted through the gap between the edge of the wafers and the side wall. We conclude that much of the water flowing through the tank does not contribute to rinsing of any wafers. Improved rinsing efficiency, which is the objective of this work, can be obtained by focusing design efforts to reduce the undesired flow though the gaps between tank walls and wafers.

Future work in this area includes performing a three-dimensional analysis of an entire tank, performing experiments with flow visualization, and comparing the numerical and analytical results. Particular attention will be paid to assessing the accuracy of the uniform inlet assumption. Additionally, the velocity fields presented here will be used to examine the transport of contaminants (liquid layers and particles) in the tank to gain insight in how the velocity field might be adjusted to improve rinsing and reduce water consumption.

Acknowledgment

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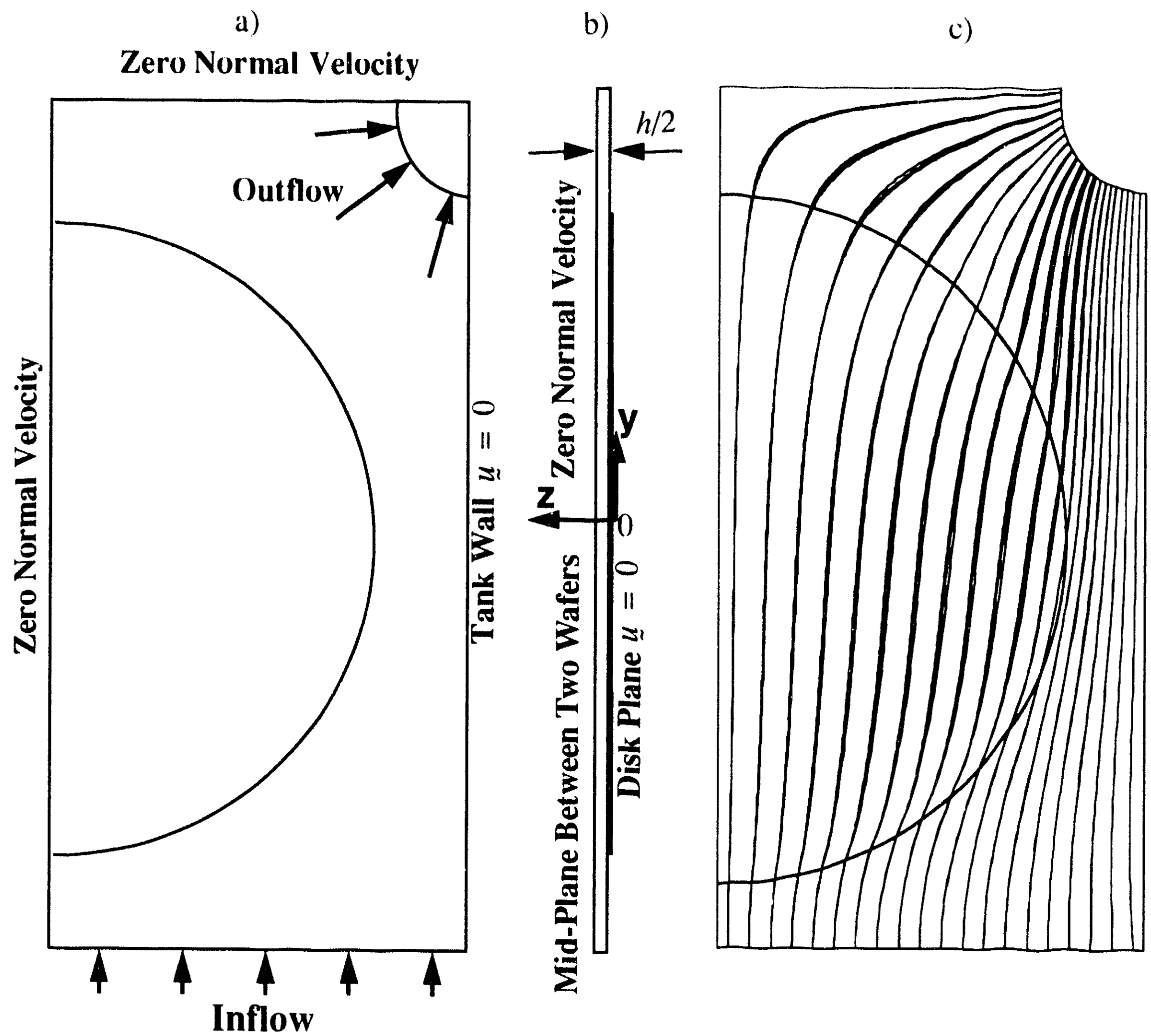

Figure 6 Three-dimensional flow between two wafers in the center of an idealized tank. The plan view of the computational domain is shown in a), side view in b). The no-slip condition is applied only on the disk and the side wall. The outflow boundary, moved inward to ease the computational burden, approximates an isobar. c) shows streamlines in three z-planes, $z = h/2$, 0.2 $h/2$, and 0.05 $h/2$, where $h/2$ is the half-width of a the gap between two wafers, and $z = 0$ is the surface of a wafer. The streamlines are essentially coincident in each plane.

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