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# Fluid Mechanics of Distillation Trays (II): Prediction of Flow Fields on Some Practically Important Sieve Trays

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# FLUID MECHANICS OF DISTILLATION TRAYS (II): PREDICTION OF FLOW FIELDS ON SOME PRACTICALLY IMPORTANT SIEVE TRAYS†

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## ABSTRACT

Separation processes account for 6% of the annual US energy expenditure, 50% of which is consumed by distillation alone. Therefore, it is not too surprising that distillation, the work horse of the chemical process industry, is under attack by emerging technologies based on membranes and adsorption, whose proponents claim enormous potential savings in energy expenditure. Moreover, the massive scale of use plus the energy intensiveness implies that even small improvements in the efficiency of distillation processes can result in large gains in energy savings. Such improvements can come from developing a fundamental understanding of the fluid mechanics of tray columns, which has heretofore been lacking and is the subject of this paper. The flow on a distillation tray is governed by the equations of mass and momentum conservation in three-dimensions. These equations are reduced here to a set of two-dimensional equations by averaging them across the depth of the fluid film flowing across the tray. The depth-averaged equations are then solved

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by a Galerkin/finite element technique. The evolution of film height and flow fields are determined for three types of trays that are commonly found in the laboratory and in actual plants: rectangular trays, circular trays, and so-called race track trays. Sample results include development and growth of eddies or zones of recirculation on various types of trays, variation of film height with position on a tray, and effect of tray geometry, flow rate, and physical properties on tray holdup. Occurrence of eddies and large height variations on trays can have detrimental consequences in vapor-liquid contacting operations. Therefore, the new rigorous computations should prove indispensable in developing column designs that avoid or minimize them.

## INTRODUCTION

Lockett *et al.* (1), among others, have shown that vapor flow is virtually unmixed in large diameter, industrial-scale columns. Therefore, knowledge of liquid flow patterns on trays in such columns, which is the main goal of this paper, should be enough to determine the Murphree tray efficiency from the point efficiency.

In a previous paper (2), we have outlined a technique based on averaging the governing set of three-dimensional conservation equations across the thickness of the froth, which reduces them to a set of two-dimensional equations, to determine the flow on distillation trays and their downcomers. In (2), steady and time-dependent solutions are presented for situations in which the flow is invariant in a direction perpendicular to the main flow direction on the tray. In this paper, we remove the restrictions placed on the flows of (2) and consider the effect of tray geometry on the tray hydraulics.

Specifically, three tray types are considered in this paper, as shown in Figure 1: (a) a square or rectangular tray, (b) a circular or round tray, and (c) a race track tray. In Figure 1, inlet and outlet downcomers of length $D_1$ and $D_5$ and transition regions between the downcomers and the tray of lengths $D_2$ and $D_4$ have been projected onto the plane of the tray for convenience of plotting. Although square and circular trays are both simple to

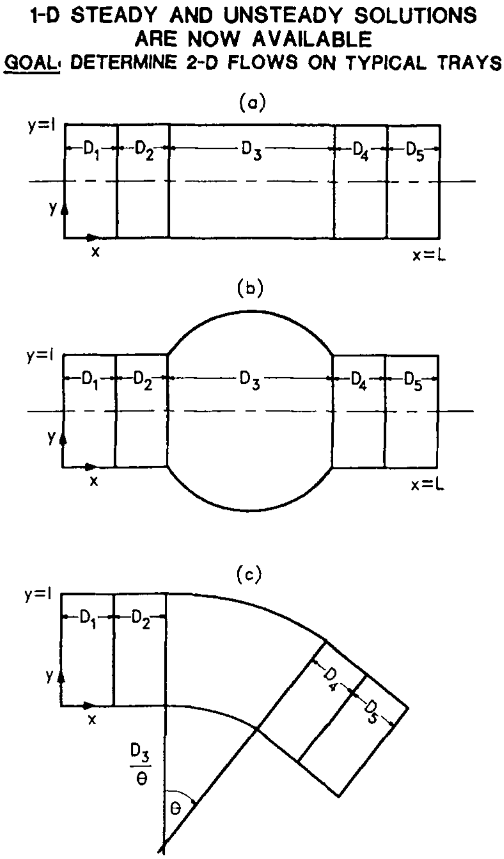


FIGURE 1. Some widely used trays: (a) a square or rectangular tray, (b) a circular or round tray, and (c) a race track tray. Here lengths shown are dimensionless and have been scaled by the (dimensional) length of the width of the inlet downcomer.

visualize, a race track tray is at first glance geometrically complex. However, a race track tray is readily obtained by taking a pie slice and removing a portion of the pie that touches its center, as shown in Figure 1(c). The inner and the outer edges of a race track tray are arcs of circles each of which subtends an angle $\theta$.

To date, with the exception of (3) and (4), modeling of flows on practical trays has been performed in an *ad hoc* manner. By way of example, Porter *et al.* (5) and Lockett *et al.* (6) have assumed that a rectangular flow region of uniform velocity exists between the inlet and outlet downcomers of a circular tray and that the flow in the curved region outside this area is stagnant. Others (see, e.g., (7)) have assumed that the flow on their trays can be divided into regions: in one of these, the flow is in the direction of bulk flow and in the other, near the column edge, the flow is entirely stagnant. Unfortunately, the line of demarcation between the two regions is unknown and can only be adjusted *a posteriori* to agree with experimental observations. Another goal of this paper is to develop the capability to predict *a priori* the line of demarcation between regions of bulk flow and regions in which the fluid is stagnant, or recirculating as a confined eddy, by numerical analysis without resort to experiments.



## THEORY AND COMPUTATIONAL ANALYSIS

Isothermal, steady flow of a fluid on a distillation tray and its downcomers is governed by the continuity and momentum equations:

$$\nabla \cdot \underline{v} = 0 \tag{1}$$

$$\rho \underline{v} \cdot \nabla \underline{v} = -\nabla p + \nabla \cdot \underline{\underline{\tau}} + \rho \underline{g} \tag{2}$$

where $\underline{v}$ is the velocity vector, $\rho$ is the density, $p$ is the pressure, $\underline{\underline{\tau}}$ is the stress tensor, and $\underline{g}$ is the gravitational acceleration. The density $\rho$ as well as the viscosity $\mu$ of the fluid are taken to be constants throughout this paper.

Because the local froth height $h$ is much less than the lateral tray dimensions, say $L$, the governing three-dimensional equations, Eqs. (1) and (2), can be averaged across the film depth to eliminate terms involving the vertical component of the velocity and derivatives with respect to the vertical direction, to give "averaged" two-dimensional equations (8) . If the asymptotic thickness of the film in the inlet downcomer sufficiently far upstream of the flat portion of the tray is $h_o$, then the condition for these shallow flow equations to hold is that $\epsilon \equiv h_o/L \ll 1$, as shown in (2, 8).

The flow on a tray and its downcomers is determined by three dimensionless groups, a Reynolds number, $Re$, a capillary number, $Ca$, and the dimensionless asymptotic film thickness, $\epsilon$, and, depending on the type of tray shown in Figure 1, on several dimensionless geometrical factors and length scales (all made dimensionless by the width of the downcomers). In what follows, attention is focused on situations in which the asymptotic film thickness $\epsilon = 0.1$ and the capillary number $Ca = 0$.

## RESULTS

Figure 2 shows the height profile on a circular tray when $Re = 1,000$. In Figures 2 and 3, flow variables are shown over only one half of the domain as a circular tray has a two-fold symmetry about the plane $y = 1/2$ of Figure 1(b). A pronounced region of local steepening of the height profile, or a hydraulic jump (9), is apparent in Figure 2 near the centerline. Such local regions of rapid height variation have already been predicted in one-dimensional flows (2). However, Figure 2 shows that the hydraulic jump dies off as one moves from the centerline of the tray to its outer edge where the tray meets the column wall.

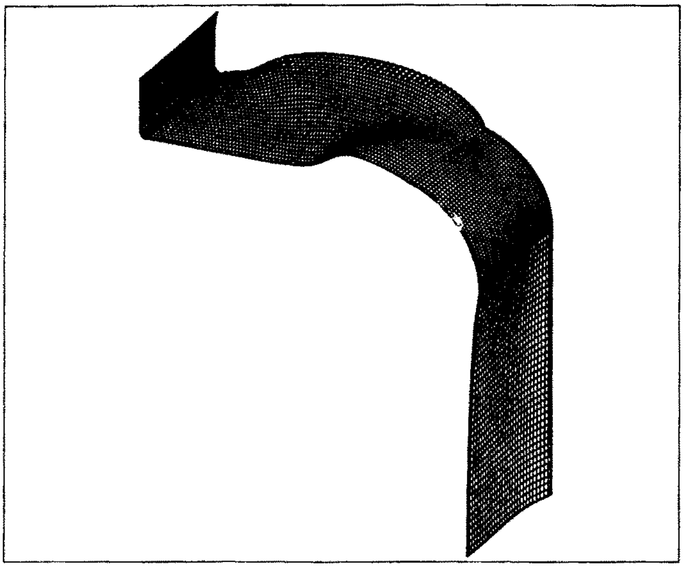

FIGURE 2. Height profile on a circular tray predicted by solution of the 2-D depth-averaged equations. Here $Re = 1,000$, $Ca = 0$, and $\epsilon = 0.1$.

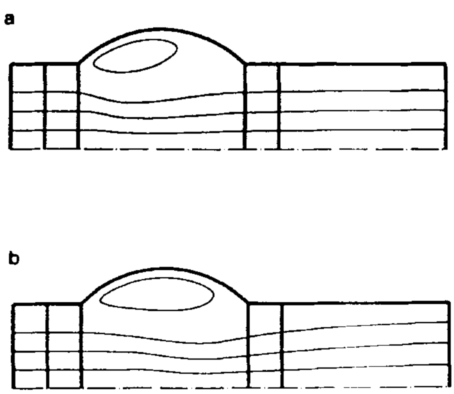


FIGURE 3. Effect of Reynolds number on streamlines on a circular tray predicted by solution of the 2-D depth-averaged equations: (a) $Re = 700$ and (b) $Re = 1,000$. Here $Ca = 0$ and $\epsilon = 0.1$.

Figure 3 shows the effect of increasing $Re$ on the flow on a circular tray. The streamlines shown in Figure 3(a) and (b) demonstrate that a nearly rectangular flow region of virtually uniform velocity exists between the inlet and outlet downcomers of a circular tray, as experimentally observed in (5) and (6). However, Figure 3 makes plain that it is not simply in the curved region outside this area that the flow is stagnant, i.e. a zone of fluid recirculation exists. Evidently, the extent of this stagnant zone is a strong function of Reynolds number and it can extend beyond the the curved region of the tray, an important design consideration.

Figure 4 shows streamline patterns on two race track trays when $Re = 1,000$: in (a), the angle of the arc of the race track tray is $10^o$ and in (b), it is $70^o$. Although the variation of froth height on such trays is another matter, the angle of the arc evidently has little effect on streamlines on race track trays. It is noteworthy that stagnant zones of fluid recirculation are absent from this type of tray at any value of the angle of the arc.

Figure 5 shows the effect of $Re$ and tray geometry on tray holdup. Were the fluid on the tray stagnant, the holdup would equal the asymptotic film thickness $\epsilon = 0.1$. First, for various tray types, the holdup decreases as Reynolds number increases, a result that accords with intuition. Second, the holdup is increased when account is taken of the finiteness of the tray. Third, among various tray types, the race track trays have the highest holdup.

Figure 6 shows the effect of $Re$ and geometry on the height profile on various tray types. For purposes of illustration, the height profiles shown are those along the centerline of the trays. First, as Reynolds number increases, the hydraulic jump moves from the region of the tray near the inlet downcomer to that near the outlet downcomer. Second, finiteness of the tray

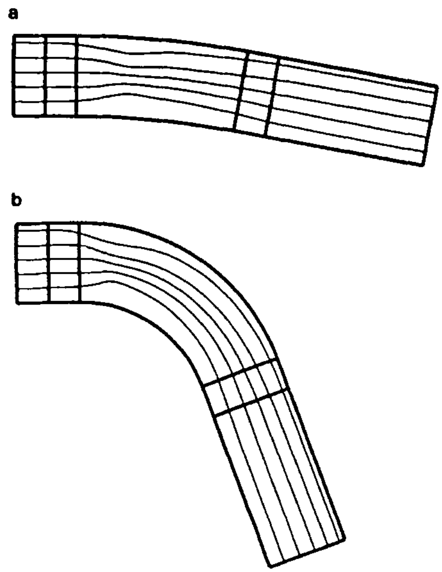


FIGURE 4. Effect of the angle of the arc on streamlines on a race track tray predicted by solution of the 2-D depth-averaged equations: (a) angle of arc $\theta = 10°$ and (b) $\theta = 70°$. Here $Re = 1{,}000$, $Ca = 0$ and $\epsilon = 0.1$.

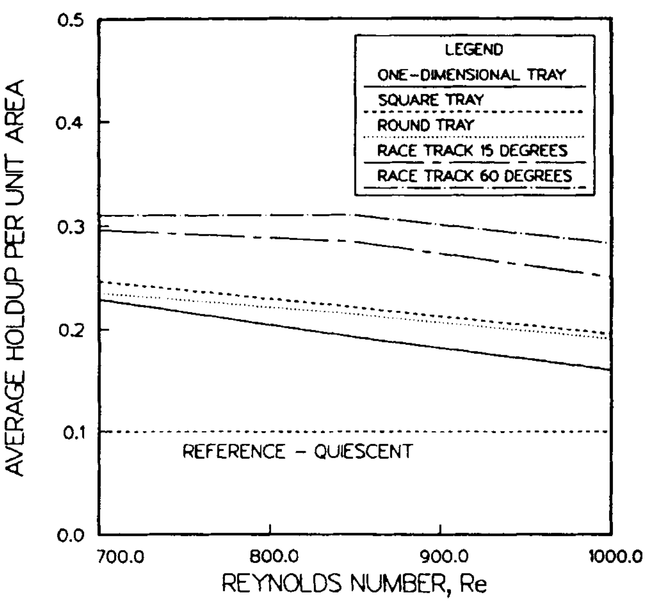


FIGURE 5. Effect of Reynolds number and geometry on tray holdup. Here $Ca = 0$ and $\epsilon = 0.1$.

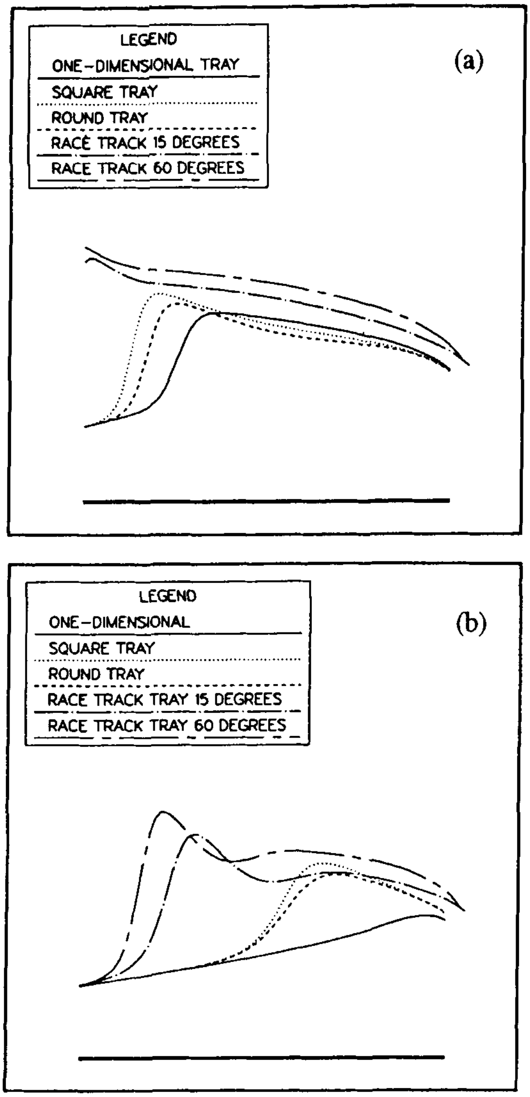


FIGURE 6. Effect of Reynolds number and geometry on height profile along the centerline of the tray: (a) $Re = 700$ and (b) $Re = 1,000$. Here $Ca = 0$ and $\epsilon = 0.1$.

causes the hydraulic jump to shift upstream of the outlet downcomer relative to the situation in which the flow is invariant in the $y$-direction.

## CONCLUSIONS

According to the results reported in the previous section and in a related paper (2), the Galerkin/finite element method is a powerful and accurate technique for theoretical prediction of flow fields and film height profiles on distillation trays. Moreover, in contrast to previous works on modeling flows on distillation trays (3, 4), the present analysis is not restricted to unreasonable values of the parameters or simple tray geometries.



Research is underway to extend the present study in two directions in the near future. Although a great deal of emprical and experimental knowledge of flow on distillation trays is available (see, e.g., (10)), these results were obtained when computational techniques such as those presented in this paper were not available to guide the experiments. Thus one current goal is to perform careful flow visualization experiments, with the setup depicted in Figure 7, to complement the computations. A second emerging thrust is directed at developing a better understanding of the dynamics of bubble formation on distillation trays. Preliminary computational studies on bubble formation (11) have already uncovered fascinating physics that is likely to have consequences in fields as different from distillation as rheology and interfacial phenomena.

Further extensions of the single-phase fluid mechanical theories presented in this paper and in (2) are also needed to model multi-phase, hole activity, and mass transfer effects, among others. Prado and Fair (12) have already begun to consider such realistic complications in the modeling of

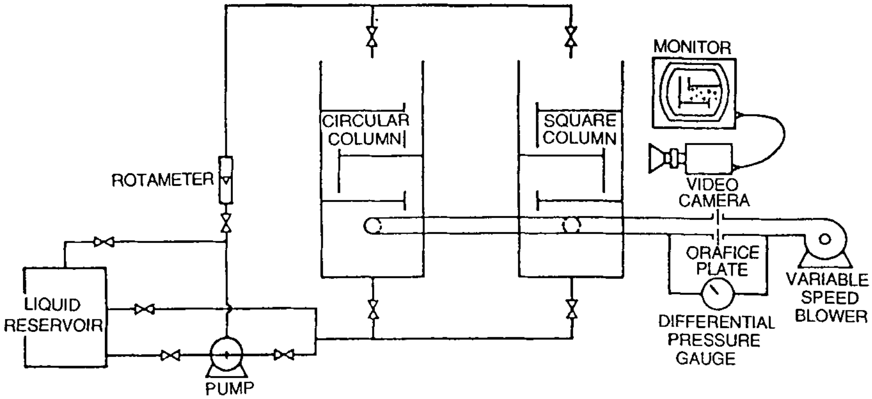


FIGURE 7. Experimental setup for fundamental studies of fluid mechanics of distillation trays.



the performance of distillation trays albeit taking a more empirical approach than those presented here and in (2) for describing the hydrodynamics. Successful marriage of fluid mechanical theories presented here and in (2) with the effects considered in (12) is among the ultimate goals of this research.

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