feedback from the authors, industry provided data for three nozzle combinations. The switch time for each of these three engine designs was optimized, and the resulting best points are shown in Fig. 4. The results indicate that the best of these combinations leads to an empty weight of 196,500 lb, which is somewhat better than the fixed nozzle results. The results also indicate that even better results are probably possible with larger expansion ratios.

Concluding Remarks

A study of several design options for the Russian RD-704 tripropellant engine for use on a SSTO vehicle has been conducted. The results indicate that there may be some benefit from a two-position nozzle. To gain this benefit, however, the nozzle must be extended before the switch from tripropellant operation to hydrogen-only operation.

References

[1]Martin, J. A., "Effects of Tripropellant Engines on Earth-to-Orbit Vehicles," *Journal of Spacecraft and Rockets*, Vol. 22, No. 6, 1985, p. 620.

[2]Calouri, V. A., Conrad, R. T., and Jenkins, J. C., "Technology Requirements for Future Earth-to-Geosynchronous Orbit Transportation System," NASA CR 3266, Boeing Aerospace Co., Seattle, WA, June 1980.

[3]Martin, J. A., and Kramer, R. D., "Evaluation of Proposed Rocket Engines for Earth-to-Orbit Vehicles," JANNAF Propulsion Meeting, Oct. 1990.

[4]Venkatasubramanyam, G., and Martin, J. A., "Alternate Vehicles for Engine/Vehicle Optimization," AIAA Paper 93-227, June 1993.

[5]Venkatasubramanyam, G., and Martin, J. A., "Continuing Propulsion Evaluations for SSTO," AIAA Paper 94-3158, June 1994.

[6]Braun, R. D., Powell, R. W., Lepsch, R. A., Stanley, D. O., and Kroo, I. M., "Comparison of Two Multidisciplinary Optimization Strategies for Launch Vehicle Design," *Journal of Spacecraft and Rockets*, Vol. 32, No. 3, 1995, p. 404.

[7]Brauer, G. L., Cornick, D. E., and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST)," Program Summary Document, NASA CR-2770, Feb. 1977.

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Draining of Liquid from Tanks of Square or Rectangular Cross Sections

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Nomenclature

d = diameter of drain hole
H_c = critical height, i.e., the height at which the vortex is formed
H_i = initial height of liquid column in container

Introduction

WHEN liquid drains from a container through a centrally placed orifice (drain), a dip forms on the free surface of the liquid that almost instantaneously develops into a vortex with an air core extending to the bottom port. The air core reduces the effective cross-sectional area of the drain outlet.[1–4] The height at which the vortex is formed is the critical height H_c, and because of the formation of the vortex, the flow rate reduces considerably. The phenomenon is of practical relevance in the fuel feed systems in spacecrafts and rockets. It has also been observed that there is considerable augmentation of the vortex because of initial rotation imparted to the liquid in the container. Ramamurthi and Tharakan[4] have suggested shaped discharge ports for suppressing the vortex formation.

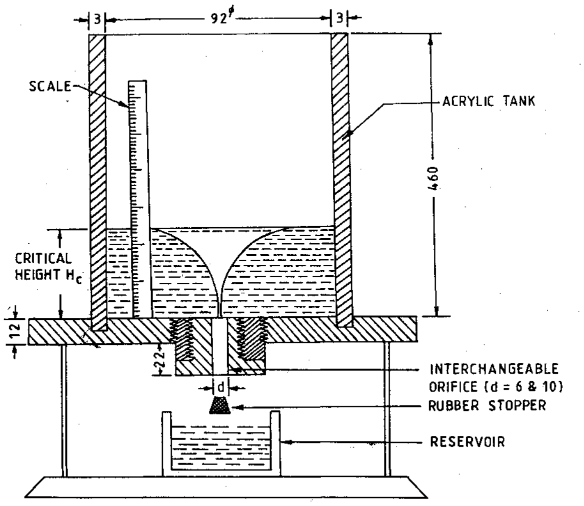

Fig. 1 Experimental setup.

In the present study, experimental results are presented for two cross-sectional shapes (square and rectangular), and the results are compared with those for a circular cross section. For all of the tank cross-sectional shapes, the outlet drain is of circular cross section. The beneficial influence of these shapes over the circular cross section with regard to the vortexing phenomenon is highlighted.

Experimental Arrangement

For studies with the circular cross section, an acrylic tank of 92-mm inside diameter (wall thickness of 3 mm) and 460-mm height with provision for interchangeable drain holes (diameter d) is used (Fig. 1). For investigations with the other cross sections, cylindrical tanks with square (81.5 × 81.5 mm) and rectangular (100 × 66.5 mm) cross sections, both having the same cross-sectional area and height as those of the circular one and made out of 3-mm-thick acrylic sheet, are used. For each cross-sectional shape (i.e., circular, square, and rectangular), experiments are carried out with drain holes of diameters 6 and 10 mm, centrally located at the bottom of the tanks along the vertical axis. Figure 1 shows the arrangement for the circular cross section. The liquid used is water at room temperature.

Initial experiments with the circular container showed that disturbances mainly in the form of rotational components influence the vortex formation considerably. Because of the disturbances, the critical height H_c increases considerably compared with the case when the liquid is initially stationary. Experiments are carried out quantifying the initial rotation imparted to the liquid. The quantification is done by controlled stirring of the liquid in the tank (with the drain port closed by the rubber stopper; Fig. 1), by using varying numbers of revolutions of a stirrer over a constant period of time. After imparting the rotation, the rubber stopper is removed and the draining started. The process is carried out for each of the three cross-sectional shapes used. The results are obtained keeping the initial height H_i of the liquid column same for all runs.

Results

Experiments are conducted with $H_i = 300$ mm for all cases. This height is chosen so that the critical height and the duration for complete draining could be recorded conveniently. The results pertaining to the influence of rotation on the critical height are shown in Fig. 2 and those on the duration of draining in Fig. 3. In each figure, the results for all three cross-sectional shapes used, i.e., circular, square, and rectangular, are included. Also shown in the figures are the values for the case without rotation. The latter were obtained after allowing the liquid column to be stationary for a sufficiently long time (so that there were no disturbances) and then removing the rubber stopper to start the draining.

Referring to Fig. 1, it is seen that the critical height H_c is only a very small fraction of H_i ($H_c/H_i \approx 0.025$) for the stationary case,

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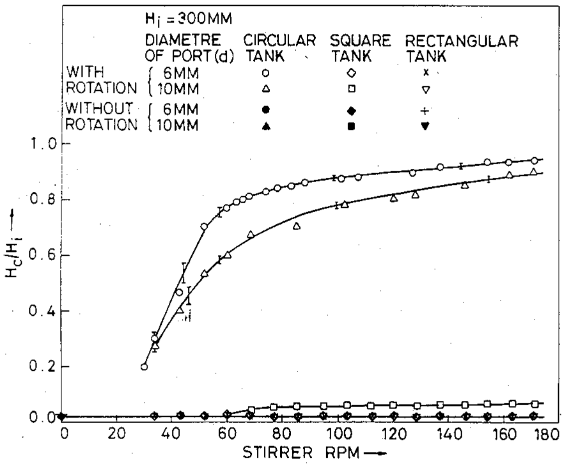

Fig. 2 Influence of rotation on vortex formation.

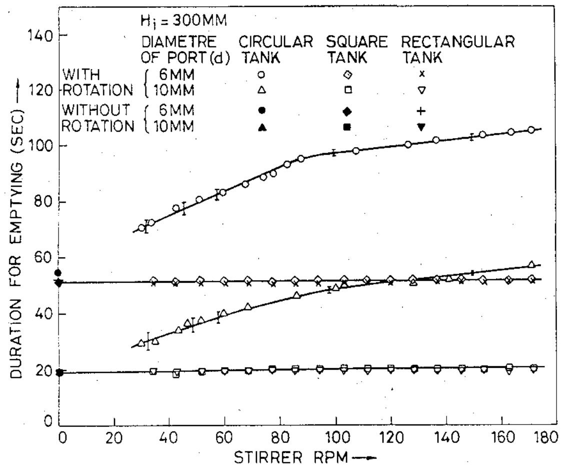

Fig. 3 Influence of rotation on duration for emptying.

i.e., without rotation (H_c = 6 and 8 mm for d = 6 and 10 mm, respectively). Further, this value of H_c/H_i is the same for the circular, the square, and the rectangular cross sections. With rotation, the value of H_c/H_i shows a large increase for the circular tank. For this shape, the critical height of vortex formation increases almost linearly with the stirrer's revolutions per minute up to 60, beyond which it shows a gradual increase. There is some dependence on the port diameter d, with slightly higher values of H_c/H_i occurring for the smaller port size. It is observed that the critical height with rotation can be as high as 40 times that for the case without rotation for the circular cross section.

Very interestingly, rotation appears to have negligible influence on the value of H_c/H_i for the square and the rectangular cross sections. The critical height, at all values of the stirrer's revolutions per minute, remains the same as that for the stationary case. There is only a very marginal increase ($H_c/H_i = 0.06$) for the square cross section for the case $d = 10$ mm. Thus, there is no augmentation of the vortex for the square and the rectangular shapes unlike that for the circular tank.

The preceding features are reflected in Fig. 3, which shows the duration for complete draining of the tanks. With no rotation, 19 s are required for complete draining when the port size d is 10 mm and 53 s for $d = 6$ mm. Significantly, these values remain the same for all of the three cross sections. But with rotation the draining time increases for the circular cross section because of the formation of vortex and its extension into the drain hole. The effective port size reduces and more time is required for complete draining of the tank. For this cross-sectional shape, the duration required is seen to increase at a rapid rate, up to 100 rpm. For higher values of the stirrer's revolutions per minute, there is only a marginal increase. But for the tanks with square and rectangular cross sections the duration required for complete draining at various stirrer revolutions per minute remains the same as that for the stationary case. The nonvariance of the duration required for draining both with and without rotation results because no vortex is formed in these cases, and thus there is no encroachment on the drain port area.

The main reason for the suppression of vortex formation (in spite of imparting varying degrees of initial rotation) in the tanks with square and rectangular cross section, compared with that for the circular cross section, appears to be the changed boundary conditions. The four sharp corners present in the square and the rectangular shapes, coupled with the nonaxisymmetry of the sections, seem to prevent the development of rotational motion. Whatever rotation is imparted appears to get dissipated very quickly, with the result that there is no vortex augmentation for these shapes unlike in the case of the circular tank. The explanation given is only tentative, and further studies are required to obtain a better understanding of the interesting features observed. Nevertheless, the results presented indicate the obvious advantage of using nonaxisymmetric cross sections like square and rectangular in practical situations. With equal area of cross section and under stationary conditions, the duration for complete draining for these shapes is the same as that for the circular shape, indicating that the rate of outflow is not affected because of the changed cross-sectional shape. In the case of the circular tank, any environmental disturbance can be expected to augment the vortex formation and affect the feed rates but such disturbances will hardly have any influence in the case of square and the rectangular tanks. The feed rates for the latter can be expected to remain unaltered, which will be a major benefit. But the limitation of using the square and the rectangular cross-sectional shapes in the practical design of propellent tanks could be the presence of sharp corners, which give rise to regions of stress concentration. However, the results presented can be employed in the future for improved design of antivortex or vortex suppression baffles.

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References

[1]Abramson, H. N., Chu, W. H., Garza, L. R., and Ransleben, G. E., "Some Studies of Liquid Rotation and Vortexing in Rocket Propellant Tanks," NASA TN D-1212, Feb. 1962, pp. 1–35.

[2]Pasley, G. F., "Propellant Vortexing in a Spinning Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 18, No. 5, 1981, pp. 418–426.

[3]Zhou, Q. N., and Graebel, W. P., "Axisymmetric Draining of a Cylindrical Tank with a Free Surface," *Journal of Fluid Mechanics*, Vol. 221, Dec. 1990, pp. 511–532.

[4]Ramamurthi, K., and Tharakan, J. T., "Shaped Discharge Ports for Draining Liquids," *Journal of Spacecraft and Rockets*, Vol. 30, No. 6, 1992, pp. 786–788.

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