D_i = diameter of the impeller
d = impeller blade width
F = feed flow rate
N = impeller speed
n = number of data points for any run
Q = impeller pumping capacity
t = time
V_T = volume of stirred tank
H_i = height of impeller from the bottom of mixing tank
H_L = height of liquid level in the mixing tank

LITERATURE CITED

1. Hubbard, D. W., and H. Patel, paper presented at AIChE 62nd Ann. Meeting, Washington, D. C. (Nov. 1969).
2. Keairns, D. L., and F. S. Manning, *AIChE J.*, **15**, 660 (1969).
3. Manning, F. S., D. Wolf, and D. L. Keairns, *ibid.*, **11**, 723 (1965).
4. Patel, H., M. S. thesis, Michigan Technol. Univ. (1968).
5. Wolf, D., and F. S. Manning, *Can. J. Chem. Eng.*, 137 (June 1966).

Reduction of Thermal Stratification by Nonuniform Wall Heating

L. B. EVANS, E. S. MATULEVICIUS, and P. C. PAN

Massachusetts Institute of Technology, Cambridge, Massachusetts

The phenomenon of thermal stratification, which occurs when a confined fluid is heated through the sidewalls of its enclosure, has been the subject of a number of recent investigations (*1* to *6*), and the fundamental mechanisms are well understood. In a thermally stratified fluid an axial temperature distribution is established in the bulk of the fluid, and the temperature at the top can exceed the mixed-mean temperature by a considerable amount. The axial temperature distribution can be predicted (*5, 6*) with reasonable confidence for well-defined geometries subjected to a uniform sidewall heat flux.

In many engineering applications, particularly those involving storage of cryogenic fluids, thermal stratification is undesirable. A rocket propellant tank, for example, must be designed to withstand the vapor pressure of the warmest liquid in the tank. The extent to which the temperature of the warmest liquid at the surface exceeds the mixed-mean temperature will depend upon the severity of thermal stratification. Several studies (*7* to *11*) have been undertaken in an effort to develop techniques for reducing thermal stratification, but the methods reported have not been generally successful.

The experiments described here were carried out to determine the effect of a nonuniform sidewall heat flux on the thermal stratification phenomena. A most remarkable effect was observed which may have direct application to the control of thermal stratification.

EXPERIMENTS

The experimental apparatus (*6*), shown schematically in Figure 1, was a rectangular cavity 8 in. wide, and 2 ft. deep, filled to a height of 2 ft. with water as the test fluid. The motion of a dye tracer introduced into the water could be observed through transparent front and rear walls. Each sidewall was a Pyrex glass heater evenly coated with a thin electrically conducting film for resistive heating. Each of the sidewall heaters was divided into three 8-in. vertical sections whose heating rate could be adjusted independently. Thermocouples measured the axial temperatures at six vertical positions in the center of the enclosure.

Heat losses from the system were held to a minimum by providing 4 in. of polyurethane foam insulation at the sides and bottom, by using double panes of glass for the front and rear walls, and by coating the free liquid surface with a surfactant film of stearic acid to retard vaporization.

Two experiments will be reported. In the first, the heat flux distribution in the three vertical segments was uniform (with ratios of heat flux in each segment of 1:1:1). In the second, the heat flux decreased with vertical distance up the plate (with ratios of heat flux in each segment of 1:2:3 in the order top:middle:bottom). The total rate of heat input to the system was the same (4,920 B.t.u./hr. at each sidewall) for both experiments. The experimental conditions corresponded to a fluid Prandtl number of 7 and a modified Grashof number

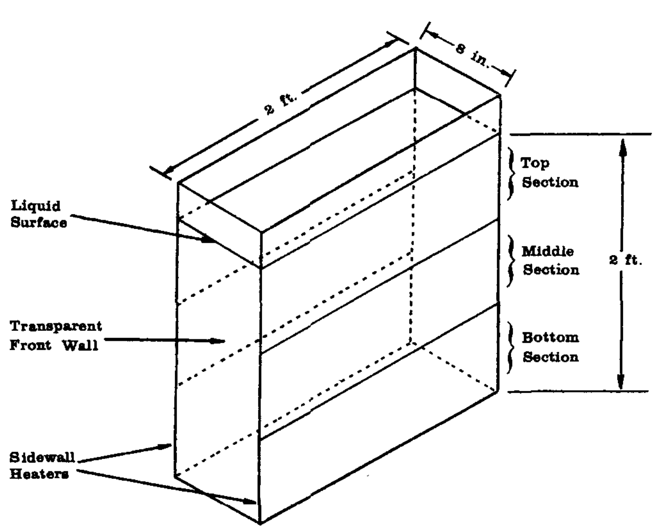

Fig. 1. Schematic diagram of experimental liquid enclosure.

E. S. Matulevicius is with Esso Research and Engineering Company, Linden, New Jersey.

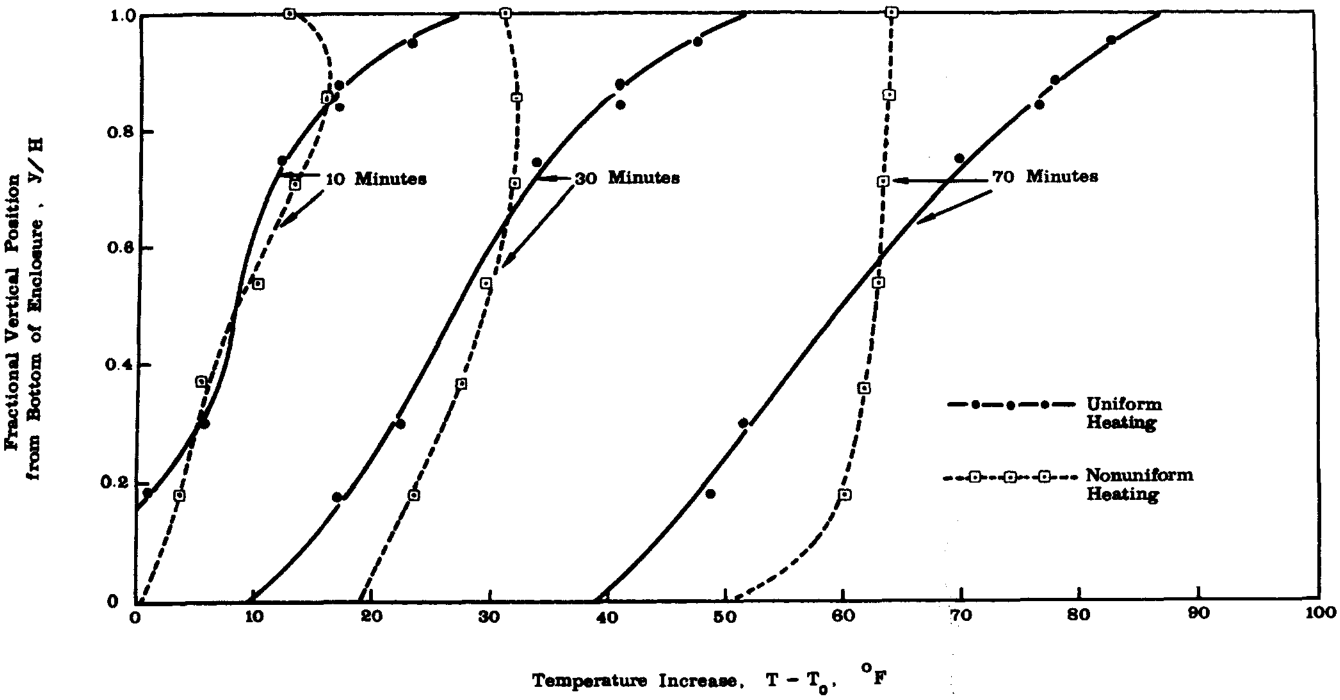

Fig. 2. Axial temperature profiles measured along centerline of enclosure at times of 10, 30, and 70 min. from start of heating from an initial uniform temperature T_0 of about 70°F.

of 10^{13}, based on total liquid depth as the characteristic length and mean heat flux over the entire heated surface.

RESULTS

The axial temperature profiles for each experiment are shown in Figure 2 at various times after the start of heating. The difference between the mixed-mean and surface temperatures of the fluid at equivalent times was decreased by an order of magnitude for the case of nonuniform heating! It is apparent that the severity of thermal stratification was drastically reduced when the total sidewall heat flux was redistributed to provide a greater percentage of heat input in the lower segments of the wall. The same results were achieved in numerous additional experiments conducted in this laboratory for cylindrical as well as rectangular enclosures.

The primary mechanism for reducing the thermal stratification appears to be closely related to separation of the natural convection boundary layer at the wall. The fluid rising in the boundary layer encounters an increase in core temperature and a decrease in the rate of heat input from the wall. Because the boundary layer fluid temperature does not increase as fast as the adjacent core fluid temperature, a portion of the boundary layer fluid looses buoyancy, decelerates, and is discharged into the core.

This boundary layer separation could reduce thermal stratification in two ways: First, by decreasing the boundary layer flow and hence the amount of energy carried to the top of the container, and second, by causing direct mixing between the core and boundary layer fluid. Qualitative dye tracer observations showed that the outer part of the boundary layer did appear to separate from the wall and mix with core fluid in the case of nonuniform wall heating.

The results reported here suggest that a practical method of reducing thermal stratification might be to vary the sidewall heat flux distribution. This could be accomplished, for example, by providing more external insulation near the top of a tank than at the bottom. The optimal variation in wall heat flux is not known, and research is continuing in this laboratory to determine quantitatively the conditions under which boundary layer separation can be expected and the effect of such separation upon the stratification phenomena.

ACKNOWLEDGMENT

This work was supported in part by the National Aeronautics and Space Administration under Grant NGL 22-009-019 (formerly NsG 496) to the M.I.T. Center for Space Research. The assistance of both C. L. Marx and T. Suraiya in performing some of the preliminary experiments is gratefully acknowledged.

LITERATURE CITED

1. Schwind, R. G., and G. C. Vliet, *Proc. Heat Transfer and Fluid Mech. Inst.*, 51-68 (1964).
2. Clark, J. A., "International Advances in Cryogenic Engineering," Vol. 10, pp. 259-283, Plenum Press (1965).
3. Barakat, H. Z., and J. A. Clark, *Proc. Third Intern. Heat Transfer Conf.*, **2**, 152-162 (1966).
4. Tatom, J. W., and W. O. Carlson, *Proc. Third Intern. Heat Transfer Conf.*, **2**, 163-171 (1966).
5. Evans, L. B., R. C. Reid, and E. M. Drake, *AIChE J.*, **14**, No. 2, 251-259 (1968).
6. Matulevicius, E. S., "Thermal Stratification in Enclosed Fluids due to Natural Convection," Sc.D. thesis, Massachusetts Inst. of Technology, Cambridge (1970).
7. Vliet, G. C., and J. J. Brogan, *Proc. Conf. Propellant Tank Pressurization and Stratification*, **2**, 61-87 (1965).
8. Neff, B. D., "Study of Cryogenic Propellants, Stratification Reduction," Final Report CR-65-33, Martin Company, Denver, Colorado (August, 1965).
9. Vliet, G. C., *J. Spacecraft and Rockets*, **3**, No. 7, 1142-1144 (1966).
10. Scott, R. B., "Cryogenic Engineering," pp. 242-243, D. Van Nostrand Co., Inc., Princeton, New Jersey (1967).
11. Pollard, R. B., and W. O. Carlson, "Progress in Heat and Mass Transfer," Vol. 2, pp. 23-40, Pergamon Press, Oxford (1969).