Dr. No. [illegible] RAF

177

SERI/TP-252-1969
UC Category: 62
DE83011962

CONF-830812--28

SERI/TP--252-1969

DE83 011962

Raft Thermocline Thermal Storage

Robert Copeland
James Green

May 1983

To be presented at the 18th Intersociety
Energy Conversion Engineering Conference
Orlando, Fla.
21-26 August 1983

Prepared under Task No. 1379.11
WPA No. 431

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

SERI/TP-1969

RAFT THERMOCLINE THERMAL STORAGE

Robert J. Copeland
and
James Green

Solar Energy Research Institute

ABSTRACT

A raft thermocline thermal-storage system consists of an insulated platform floating between the hot and cold regions of a liquid in a storage tank. Experiments were conducted to evaluate the raft's stability and effectiveness in delivering thermal energy. Water was employed as the storage fluid. The effects of inlet orientation (side, tangential, or vertical), flow rate, and raft insulation were measured and compared with a natural thermocline. The raft thermocline's effectiveness in achieving a thermal separation of the fluid was measured, and the critical Richardson number was found to be significantly different from that of natural thermoclines. The raft thermocline's effectiveness was equal to or better than that of a natural thermocline at all flow conditions.

INTRODUCTION

Future applications of solar thermal energy will require temperatures of 1100°C or higher. Advanced high-temperature molten salt solar thermal systems have the potential of supplying heat at these high temperatures (1). Several salts have melting points, transport properties, vapor pressures, and associated costs that make them attractive. Analyses have shown that hydrogen production costs and solar thermal electric power costs can be reduced (1,2) by means of a high-temperature molten salt system. The salts currently being studied include sodium-, potassium-, and other alkali or alkali-earth metal-compounds of carbonates, chlorides, hydroxides, and silicates. One of these salts could be used as the working fluid in both the receiver and the sensible-heat storage.

Figure 1 illustrates the thermal storage concept. The nature of the internal insulation, and users' demands for high-temperature energy from storage, make thermocline energy storage necessary; mixed-tank thermal storage produces unacceptably low temperatures during discharge. The concept shown in Figure 1 includes a raft—which separates the hot and cold fluid regimes and provides thermal insulation between the hot and cold regions of the liquid.

EXPERIMENTAL APPROACH

The stratification index, S, given by Cole and Bellinger (4) can be used to measure performance. In a perfectly stratified tank, the intergral I = 1, where

$$I = \frac{\int_0^{\tau} \dot{m}\, c_p\, (T_i - T_o)\, dt}{\int_0^{\infty} \dot{m}\, c_p\, (T_i - T_o)\, dt} \,. \qquad (1)$$

With a completely mixed tank, the outlet temperature decays exponentially; therefore, the integral I for a completely mixed tank is 0.632. The limits of I for a perfectly stratified and completely mixed tank allow S to be defined such that

$$S = \frac{I - 0.632}{0.368} \,. \qquad (2)$$

Values of S range from 0 for a completely mixed tank to 1 for a perfectly stratified tank. Note that S is difficult to measure accurately because (a) I and 0.632 are always nearly the same magnitude, (small differences in large numbers), and (b) 0.368 in the denominator effectively multiplies the errors by a factor of 3. Flow rates and temperature differences were measured and were repeatable to within 1%.

Overall, the accuracy of the integral I was estimated to be between 2% and 3%. Subtracting 0.632 from a number near unity and dividing by 0.368, the measurement accuracy of S may be estimated at ±10%.

The Richardson number has a strong influence on the performance of natural thermoclines, and by

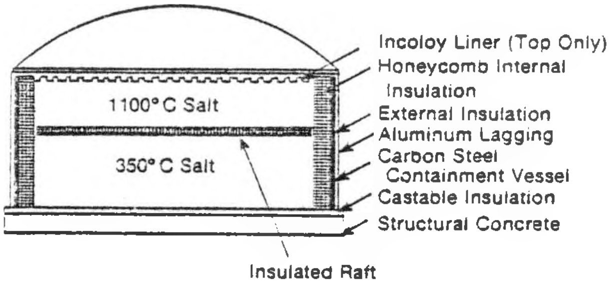


Figure 1. 1100°C Storage Tank Design

Table 1. Definition of Symbols

Symbol	Definition	Units	
		SI	English
θ	Tank outlet water temperature	^{o}C	^{o}F
θ_{in}	Inlet water temperature	^{o}C	^{o}F
θ_s	Tank water starting temperature	^{o}C	^{o}F
x	Elevation in the tank	m	ft
t	Time	s	s
τ	Ideal discharge time	s	s
g	Acceleration due to gravity	m/s^2	ft/s^2
β	Coefficient of volume expansion	$m^3/m^3\ ^{o}C$	$ft^3/ft^3\ ^{o}F$
ΔT	Temperature difference	^{o}C	^{o}F
L	Length of the tank	m	ft
v	Flow velocity	m/s	ft/h
k	Thermal conductivity of water	$W/m\text{-}^{o}C$	$Btu/ft\text{-}^{o}F\text{-}h$
ρ	Density of water	kg/m^3	lb/ft^3
c_p	Specific heat	$kJ/kg\ ^{o}C$	$Btu/lb\ ^{o}F$
$\dot{m}$	Mass flow rate	km/h	lb/h

implication should also have a strong influence on raft thermoclines. The Richardson number for the tank is

$$R = \frac{g\beta\Delta TL}{v^2} . \qquad (3)$$

The nondimensional Richardson number provides a means of extrapolating data taken with one fluid to another fluid and other geometric conditions. Water was selected as the fluid for the experiments because of its obvious advantages in cost, safety, and overall experimental convenience.

THE EXPERIMENTAL APPARATUS

Two experimental apparata were constructed to evaluate (a) the effects of raft stability and (b) the effectiveness of the raft in separating the hot and cold regions of the liquid. One apparatus consisted of a glass column 15.24 cm (6 in.) in diameter and 91 cm (3 ft) high. A wooden raft was placed inside the glass column and weighted to float on water but sink in corn oil. This oil/water equipment was employed to evaluate stability effects. Vertical, side, and tangential inlets were provided. Experiments were performed with water and corn oil (SP = 0.92) and water and air. Wooden rafts of varying densities and diameters were tested.

The second apparatus was a single-fluid thermocline. The system included an insulated plexiglass water tank, 44.45 cm (17.5 in.) in its internal diameter and 167.64 cm (66 in.) in column height. This apparatus is shown in Figure 2, which depicts the plexiglass tank with part of the insulation removed. The 3.8-cm (1.5-in.) foam raft floats between 57°C (135°F) hot water and 18°C (65°F) cold water. The flow control, temperature control, and metering equipment appear in the background.

Three experimental rafts were constructed and are shown in Figure 3. Each raft was significantly different from the others in thermal insulation effects, but they all had similar external geometries. The aluminum raft is on the right, the 3.8-cm (1.5-in.) foam raft is on the left, and the 7.6-cm (3.0-in.) foam raft is standing on its edge. By measuring the thermocline stratification index with different rafts, the importance of the raft's insulating value on its ability to separate the hot and cold regions of the liquid can be determined.

TEST RESULTS

The Oil/Water Apparatus

This apparatus, shown in Figure 4, was operated with and without oil. No substantial difference in the raft's behavior was observed when the oil was present. The raft was observed to operate in both stable and unstable conditions. Figure 4 shows the raft in an unstable condition. At high flow rates, the raft sank beneath the water/air (water/oil) interface. A short time after the water flow was terminated, the raft returned to the water/air or water/oil interface.

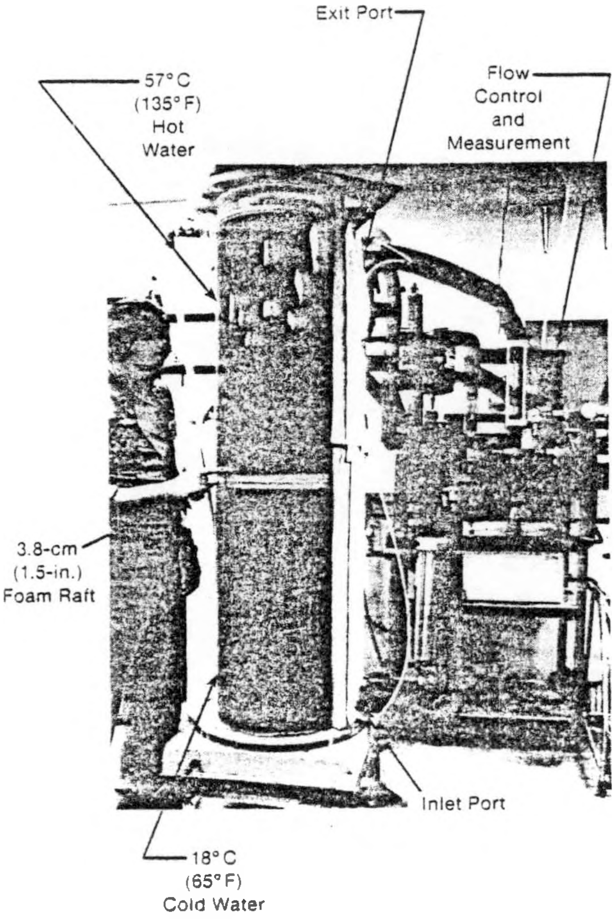


Figure 2. **Experimental Apparatus for Testing a Raft Thermocline**

At low water flow rates, the raft was observed to travel up the column at the interface. Measurements were made to determine the effects of several parameters on raft stability, and the results are summarized as follows:

(a) The raft's stability is essentially the same with either a water/air interface or a water/oil interface.

(b) If flow rates are sufficiently low, all rafts and inlet orientations will be stable.

(c) Side inlets and vertical inlets have nearly the same effect on stability; the side inlet is slightly preferred.

(d) A tangential inlet (i.e., swirling flow in the column) significantly reduces stability, compared with a side inlet.

(e) The density of the raft does not strongly affect stability. Changes of less than 20% were observed in the minimum stable water column height for even twofold changes in density differences (water density minus raft density).

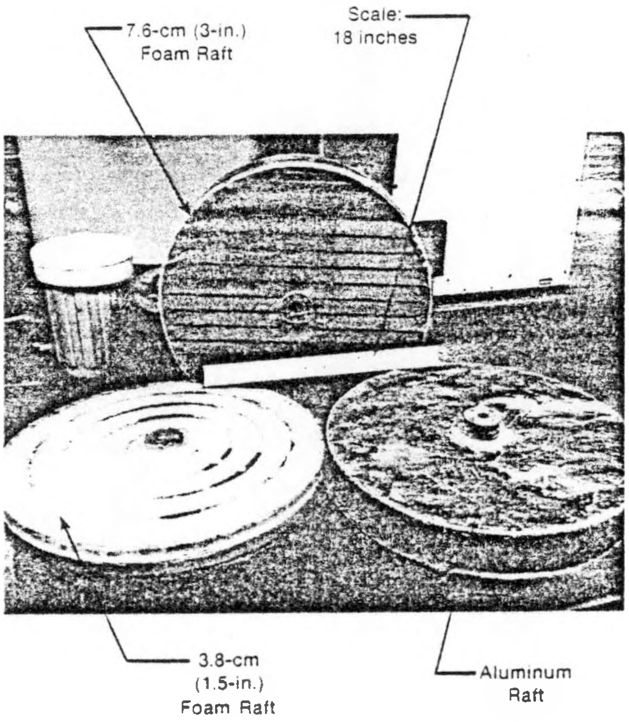


Figure 3. **Three Experimental Rafts**

(f) An oil/water interface without a raft is less stable than one with a raft.

(g) For vertical inlets, the critical Richardson number is strongly dependent on flow rate, and it is less than 0.015, according to our initial experiments.

(h) If the water column height is sufficiently great, all inlet conditions can be made stable.

Since water and oil are immiscible fluids, these data are indicative, but are not necessarily valid, for single-fluid thermoclines.

Single-Fluid Thermoclines

Tests of the system shown in Figure 2 are currently in progress. Results have been obtained for natural thermoclines and for the 3.8-cm (1.5-in.) foam raft. Figure 5 presents performance results for natural and raft thermoclines. The stratification index S is plotted as a function of Richardson number R. Note the log scale for this figure. Cole and Bellinger's work is included (4). They have indicated that a sharp drop in stratification occurs at the critical Richardson number of 0.25.

Our work with natural thermoclines shows the same critical Richardson number for natural thermoclines, but somewhat different stratification

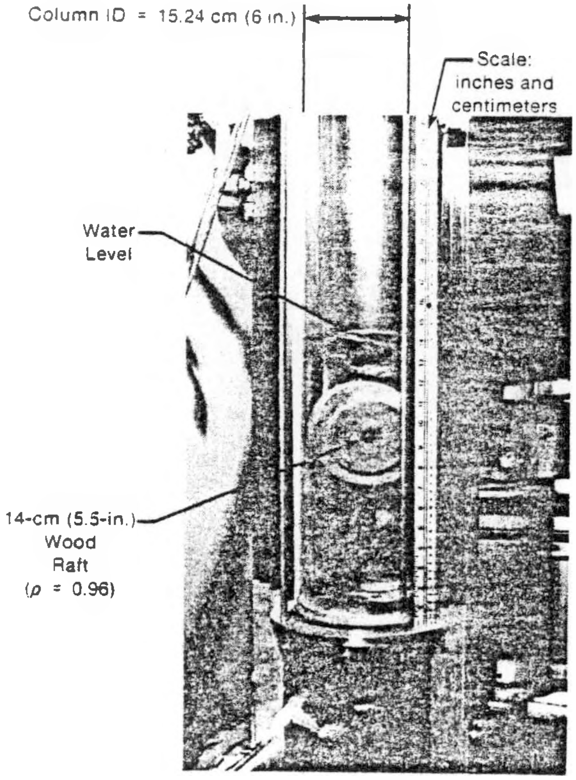


Figure 4. Raft Instability in the Oil/Water Apparatus

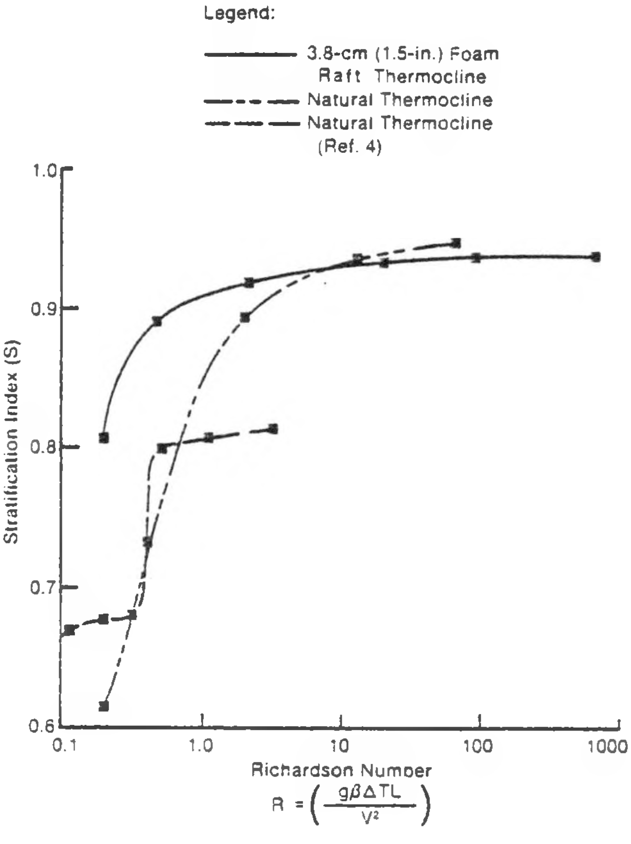
indexes than those of Cole and Bellinger. Our tank is plexiglass; it has a lower thermal conductivity than the steel tanks previously used. Because they are not as strong, the plexiglass walls must be thicker than the steel walls; consequently, they have a greater heat capacity. The difference in wall heat capacity and conduction may contribute to the difference in the measured stratification index for natural thermoclines, or the differences may be caused by different instrumentation. In either case, the measured stratification indices agree within experimental accuracy.

Raft thermoclines show essentially the same stratification as natural thermoclines at higher Richardson numbers. Since the same apparatus is employed for both the natural and raft thermoclines, the relative accuracy of these data is thus greater in comparing the two types. Clearly, raft thermoclines are more stable at low Richardson numbers (higher flow rates). This is also illustrated in the energy delivery profiles. Figure 6 presents the energy delivery for both a natural thermocline and a raft thermocline at the same conditions, R = 0.4. These data are taken at near the critical R for natural thermoclines. The delivered heat rate for the natural thermocline is significantly less than that of the raft as ideal discharge time (nondimensional elapsed time = 1.0) is approached. The thermal wave is clearly much sharper with the raft. This is illustrated in Figure 7: at the same Richardson number (1.6 in these data), the same flow rates, and almost identical conditions (inlet and initial temperatures are slightly different), the natural thermocline is not as sharp as the one with the raft.

CONCLUSIONS

This paper compares raft thermoclines with natural thermoclines. It was found that a raft improves the effectiveness as well as the stability of the thermocline and maintains greater levels of separation between hot and cold regions of a fluid that does a natural thermocline. The critical Richardson number for rafts is substantially lower than that for natural thermoclines.

Results from tests of the oil/water apparatus indicate that Richardson number is not the only factor determining raft stability, because variable raft density flow rate and column height do not correlate with Richardson number. Additional work



Note: All data are for side inlets and outlets.

Figure 5. Performance Results for Natural and Raft Thermoclines

on raft stability is needed, particularly in analytical models that will allow us to predict that stability more accurately.

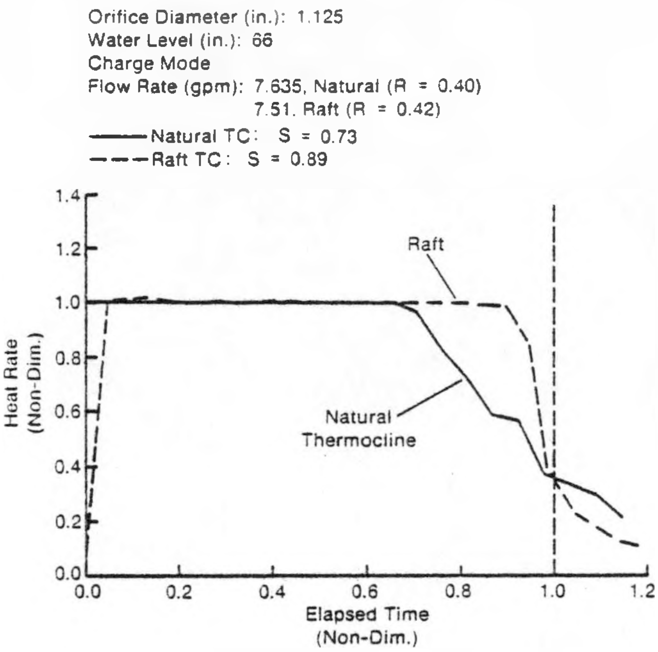


Figure 6. **Energy Delivery Profiles for Natural and Raft Thermoclines**

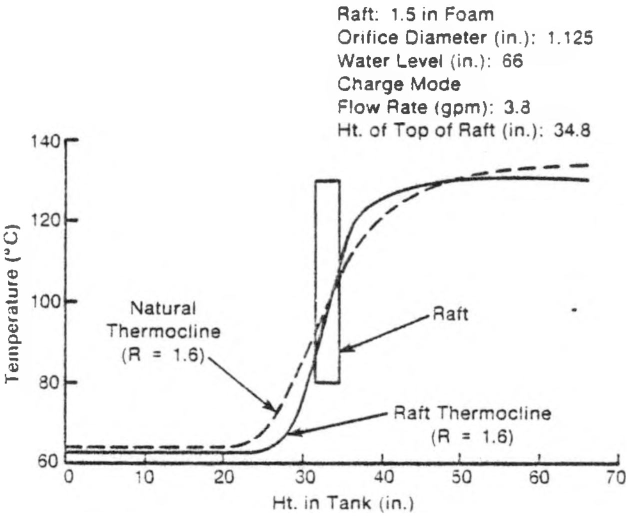


Figure 7. **Centerline Temperature Profiles for Natural and Raft Thermoclines**

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Eric Mott, Ray Kemna, and Harry Pohl for their assistance in the design, fabrication, and assembly of the experimental apparatus.

REFERENCES

1. Copeland, Robert J., James W. Leach, and Curtis Stern, "High Temperature Molten Salt Solar Thermal Systems," Paper No. 829337, presented at the 17th Intersociety Energy Conversion Engineering Conference, Westin Bonaventure Hotel, Los Angeles, California, August 1982; pp. 2032-2036.

2. Copeland, Robert J., Advanced, High-Temperature Molten Salt Storage, SERI/TP-252-1684, presented at the Energy Storage Contractors' Review Meeting, Washington, DC.; 23-26 August 1982.

3. Cole, Roger L., and Frank O. Bellinger, "Storing Solar Energy in Thermally Stratified Tanks," Paper No. 829344, presented at the 17th Intersociety Energy Conversion Engineering Conference, Westin Bonaventure Hotel, Los Angeles, California, August 1982; pp. 2024-2029.

4. Cole, Roger L., and Frank O. Bellinger, "Development of Natural Stratification Technology," in Proceedings of the Sixth Annual Thermal and Chemical Storage Contractors' Review Meeting, Washington, DC., 14-16 September 1981. Prepared for DOE by MCC Associates, Inc., DOE document no. Conf-810940; p. 224.