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Woods Hole Oceanographic Institution

Cooling the Waters of the 17-Meter Flume at the Coastal Research Laboratory

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Robert J. Chapman and Richard E. Galat

December 1988

Technical Report

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Albert J. Williams 3rd, Chairman
Department of Ocean Engineering

COOLING THE WATERS OF THE 17-METER FLUME AT THE COASTAL RESEARCH LABORATORY

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Contents

1 INTRODUCTION

The 17-Meter Flume at Woods Hole Oceanographic Institution's Coastal Research Laboratory (CRL), described in Butman & Chapman (1989), is designed to develop a relatively wide range of flow regimes simulating steady flow environments in the coastal ocean (Trowbridge et al., 1989). The ability to control the temperature of the circulating water extends the experimental capacities and enhances the quality of the experiments that can be conducted in the 17-Meter Flume. In the absence of a temperature control unit, the water temperature varies depending upon the line temperature of the water supply used to fill the flume, the ambient room temperature and the amount of time that water has been circulated by the flume pump. It is possible to design experiments that adapt to the first two temperature constraints, but the variation of temperature over time is still a problem. This variation over time is due to the energy that enters the system as the centrifugal pump circulates the water, with an estimated 75% of the energy drawn by the pump converted into heat. This thermal drift can cause changes in viscosity and also may result in a deteriorating biological environment, as temperatures exceeding 30°C may occur if the flume is operated continuously over several days.

The cooling system described here (Fig. 1) acts as a balance for the heat input from the pump and permits the maintenance of a wide range of stable-temperature flows in the flume. Low-temperature conditions can be developed by running the cooling system at full capacity until the desired temperature is reached; then the cooling system will remove just enough heat to balance the heat input from the pump and the heat input from the ambient room conditions to maintain a constant temperature. High-temperature conditions can be developed by running the pump to heat up the water until the desired temperature is reached; the cooling system will then maintain a constant temperature.

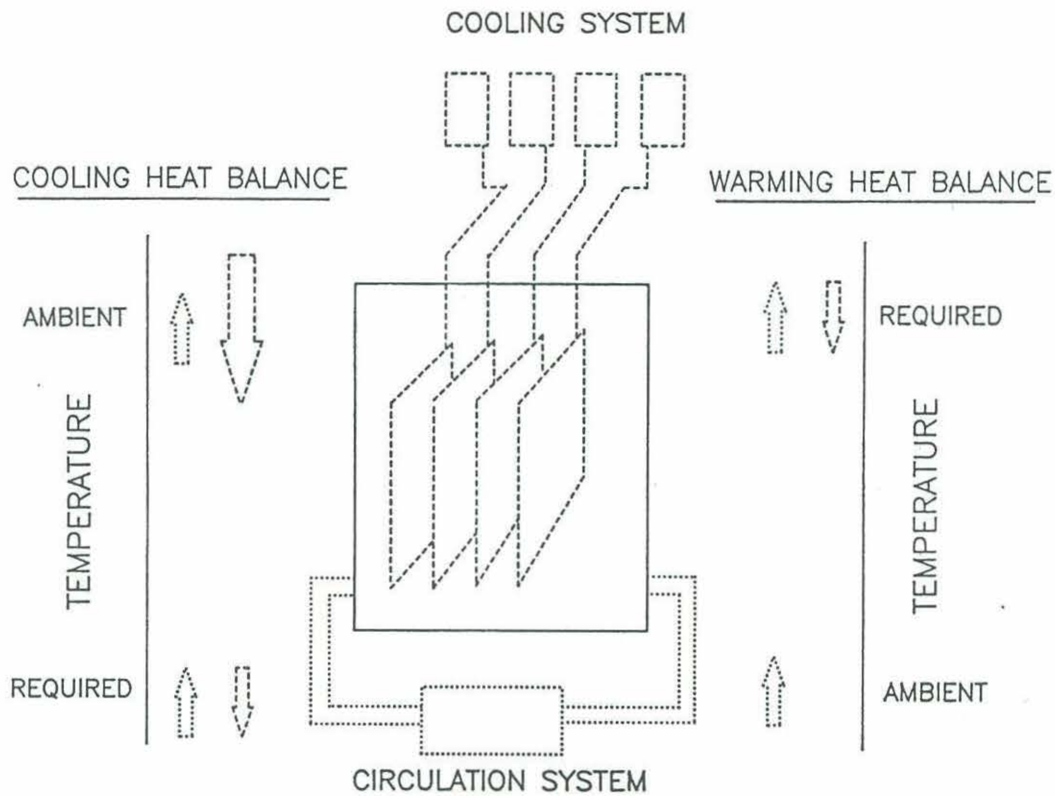

Figure 1: Schematic of the heat balance used to achieve constant temperature in the flume. The arrows represent the amount of energy contributed to the heat balance by the cooling and circulation systems; the dashed arrows show heat removed by the cooling system and the dotted arrows show heat input from the circulation system.

Due to the large water volume (~30,000 liters) required to operate the flume, a considerable period of time (on the order of 1 hour per °C) is required to reach the desired temperature; however, once this is accomplished, the chosen temperature can be maintained to ±0.5°C due to the stabilizing influence of the large water mass. The time required for the system to achieve the desired temperature is dependent upon the ambient and line temperatures.

This report reviews the design considerations that led to the final system configuration, and contains a detailed description of the system and the individual components. For operational information consult Butman & Chapman (1989).

2 DESIGN CONSIDERATIONS

The cooling system was designed to provide a temperature range (approximately 4-30°C) to simulate the range commonly occurring in coastal environments. Limited existing design information was available, however, for controlling water temperatures in such a large-volume, seawater flume. The U.S. Army Corp of Engineers' Cold Regions Research and Engineering Laboratory of Essex, New Hampshire, is one of the few local, large-volume temperature-controlled flumes, which can achieve temperatures within the range required in the 17-Meter Flume. The flume water temperature is controlled by direct contact between the water and refrigeration coils, and by simultaneously adjusting the laboratory room air temperature (down to an impressive 0°C) to match that of the flume water temperature. The latter eliminates any heat transfer from the flume surface areas exposed to the laboratory air and therefore assists in maintaining a constant temperature throughout the flume system. A system of this kind was beyond our financial and logistical range. The engineers at the lab were helpful, however, in providing assistance in the design of our system, which utilizes heat exchangers and extensive insulation.

The following explains the design constraints for choosing a cooling system for the 17-Meter Flume and describes the particular system selected.

2.1 Biological Constraints

Throughout the construction of the 17-Meter Flume, and subsequent modifications including the design and selection of materials for the various components of the cooling system, great care was taken to avoid the introduction of materials that may be toxic to marine organisms. All components which may be in contact with the water had to be non-toxic to organisms and non-reactive in seawater. The major component of the cooling system that is in contact with the water is the heat exchanger. Titanium was chosen over stainless steel due to it's superior behavior in a seawater environment (Dexter, 1972).

A refrigeration cycle using Freon was used to drive the system to eliminate the possibility of contamination due to system malfunctions. Cycles that utilize brine, ethylene gycol or other liquids could contaminate the circulating water in the event of a leak in the system. The advantage of using Freon is that it is a gas at room temperature so in the event of a leak, the Freon would evaporate instead of leaching into the water.

Another biological requirement was that the cooling system provide minimal surface area on which circulating larvae (the planktonic juvenile stages of invertebrates) and abiotic particles may collect. In addition to experimental considerations, settling out of larvae and sediment may also cause fouling within the system that could degrade the system's efficiency.

Certain types of heat exchangers, such as shell-and-tube or plated-and-frame heat exchangers, may provide low velocity areas on which biotic or abiotic particles may collect. A cooling system utilizing vertically oriented heat exchanger panels in the basin, however, minimizes the horizontal area for settlement.

Placement of the panels within the basin, rather than within the return pipe (see Fig. 1 in Butman & Chapman, 1989) also has the advantage of providing a gradual, uniform temperature change due to the large mass of water surrounding the panels. In-line, pass-through heat exchangers, on the other hand, have the potential of generating considerable temperature gradients because small masses of water are exposed to large temperature differentials. Organisms may react adversely to such conditions and thus, this type of heat exchanger was not ideal. By placing heat exchanger panels within the basin, these temperature gradients can be avoided, due to considerable mixing of water in the basin. The mixing is created by the centrifugal pump and the clockwise current generated by the flow entering the basin from the raceway and bypass.

2.2 Engineering Constraints

The engineering constraints were governed in part by the biological constraints, with some additional factors. The ability to install the system without altering the original flume set-up had two advantages: (1) heat exchangers that are located in the circulation piping would have required additional space and labor for installation, and (2) altering the circulation system would have also required re-calibration of the flume itself.

Since locating the heat exchangers within the circulation basin was optimal from both a biological and practical point-of view, panel-type heat exchangers oriented vertically were selected. The panels are two sheets of metal welded together to form a coolant path. Of the two types of metal, 316 stainless steel and titanium, that may best-suit our application, titanium was selected because of it's noted stability in seawater and because of a particular manufacturing process that makes titanium heat exchangers less expensive than those manufactured out of 316 stainless steel.

The refrigeration system consists of four individual units to increase the life of the system and to provide a fall-back system in the case of malfunction. One large unit would be problematic because it provides a constant output, so when the demand for cooling is low, the large unit would be providing too much cooling to the system. Thus, during the maintenance of a uniform flume temperature, the unit would cycle on and off as it reacted to the heat added to the system. This cycling greatly reduces the life of the unit. With four units, each rated at one quarter the maximum design load, all four units can be operating when the demand for cooling is high, and then controlled such that they would shut down individually as the demand for cooling decreased. This would allow one small unit to be running continuously instead of one large unit cycling on and off. In the event of failure with one unit, the other three units would still provide up to 75% of the maximum design cooling capacity.

Microprocessor temperature-controllers were the cost-effective solution for controlling the four individual cooling units. Utilizing thermocouples to sense the temperature of the water, the microprocessor controls the system to provide more or less cooling to maintain the desired temperature. Each controller controls two units.

In order to control temperature variations throughout the flume, all exposed surface areas were covered with insulation. Insulating the flume also proved to be a cost effective method of saving energy and equipment due to the reduction of heat transfer through the surfaces of the flume exposed to air.

2.3 Heat Balance Calculations

Table 1: System heat balance; calculations were made for ambient room temperature of 20°C and water temperature of 4°C.

System Component	Heat Gain without Insulation (BTU/HR)	Heat Gain with Insulation (BTU/HR)
Raceway - Fiberglass	111,600	530*
Raceway - Windows	37,600	120*
Raceway - Surface	18,500	18,500
Piping - PVC	35,800	900*
Piping - Epoxy	9,570	240*
Basin	12,700	12,700
Pump	45,000	45,000
TOTAL HEAT GAIN		77,990
TOTAL COOLING CAPACITY		78,000

* insulated components

To determine the necessary size of the cooling system, estimates were made of the power required of the system, as indicated by the heat balance. These calculations were made using the simplifying assumption that heat entered the system through only three means:

conduction, convection, and the pump heat generated by the pump. All the calculations were made with the assumption that the room temperature was 20°C and that the water temperature was 4°C. This is the maximum differential allowing indoor experiments (at room temperature) during the winter months, for ambient water temperature in the field. The results of the heat balance equations are presented in Table 1.

Conduction occurs when two materials of different temperature are in contact with each other. This included the entire surface area of the raceway, piping and settling basin. Potentially, heat could be absorbed from the ambient laboratory environment. For simplification, it was assumed that the circulating water and ambient air were at a constant temperature. The equation for the heat transferred through a material exposed to a temperature differential is:

$$Q = k\ A\ \frac{\Delta T}{\Delta l}$$

where

Q = heat transfer
k = conduction coefficient
A = surface area
ΔT = temperature differential
Δl = thickness of the material

The equation was first solved for all surface areas of the flume, and then revised to include the addition of insulation. This allowed estimates of the savings in energy losses required to make the installation of insulation cost-effective.

Convection is the transfer of heat from a material that is in motion. This calculation was made for the water surface in the raceway of the flume. The heat transfer equation for convection is:

$$Q = h\ A\ \Delta T$$

where,

Q = heat transfer
h = convection coefficient
A = surface area
ΔT = temperature differential

The convection coefficient h is dependent upon the velocity of the free surface. Heat transfer calculated using the extreme case of a surface velocity of 100 cm/s. The calculation yields a conservative estimate since the raceway is somewhat insulated with plywood covers and the temperature in the region between the water surface and the paneling would approach the temperature of the water.

The heat that enters the system from the pump is the greatest source of heat input with the insulation installed on the fiberglass, windows and pipes (Table 1). The pump is driven by a large electric motor. Assuming that the motor was roughly 90% efficient in converting electrical energy into mechanical energy, 90% of the 19 hp that the motor draws enters the centrifugal pump. Since the system is closed, the conservation of energy law dictates that all of the energy that the pump draws must enter the system. The energy is converted to a hydraulic head at the pump. Frictional losses within the system dissipate the energy in the form of heat as the water travels through the system.

3 SYSTEM DESCRIPTION

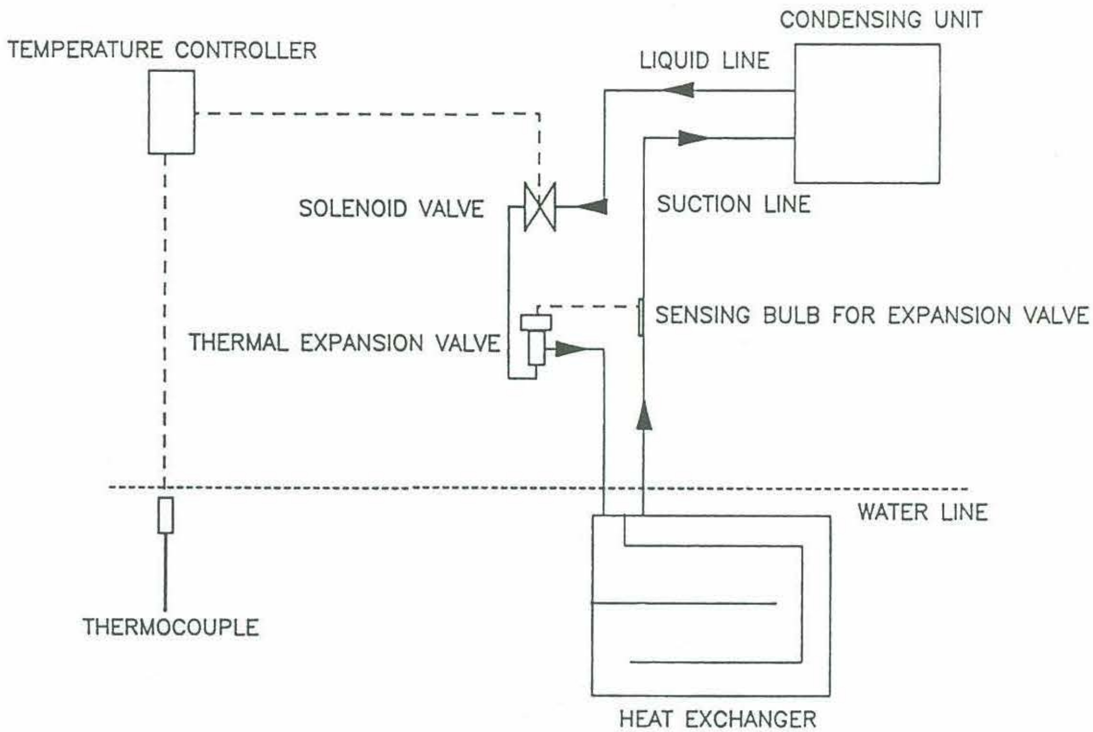

Figure 2: Refrigeration System

The system utilizes four individual refrigeration cycles. The refrigeration cycle, shown in Figure 2, is one of the basic thermodynamic cycles. The cooling media, gaseous Freon-12, enters the condensing unit, and is converted to a liquid at high pressure. This liquid then passes through an expansion valve which decreases the pressure of the liquid. The lower-pressure liquid then enters the heat exchanger. Since the pressure of the Freon has been lowered, the liquid is able to evaporate as it travels through the heat exchanger drawing heat away from the water in the basin. Finally the low-pressure vapor is drawn back into the condensing unit and the cycle repeats.

3.1 Condensing Units

The condensing units are commercially available units which are manufactured by Tecumseh. Each unit consists of a pump, that increases the pressure of the liquid, and a fan-cooled radiator, that liberates the heat from the media, allowing it to condense. The units are 2 hp air-cooled condensing units that run on 208 V, 3-phase current, and are capable of 19,500 BTU's of cooling at a -1°C expansion temperature. The condensing units are pressure controlled and are designed to switch on and off at the line pressures that correspond to the opening and closing of the solenoid valves. The condensing units are located outside the CRL on the north-facing side of the building. They are housed in a shed that protects them from the elements; a wooden baffle channels the cool air to the radiator and exhausts the warm air out the back. Locating the units outside has the advantage of alleviating potential noise problems and overheating the laboratory space with waste heat from the system. It is possible to pipe the warm air back inside during the winter months. This is presently not cost effective, however, since the flume is not used on a full-time basis.

3.2 Heat Exchangers

The titanium heat exchangers are manufactured by Tranter. The panels are made by welding together sheets of 0.58-mm-thick titanium. The welding occurs around the perimeter and also in a serpentine pattern on the panel to define the path of the coolant. The panels are then pressurized to spread the two sheets apart and create the coolant path. The inlet and outlet lines are at the top of the panel. The panels are 76-cm tall by 119-cm long with 30-cm-inlet and outlet titanium tubes. The four panels are housed in a fixture constructed of 76-cm-long fiberglass angle stock that is secured to the bottom of the settling basin. The panels are arranged in a vertical array with the panels 20 cm apart. The array is placed directly over the pump suction intake and aligned in the basin to provide a maximum amount of circulation around them. To assure the quality and integrity of the units, the factory pressure-tested the panels with halogen to detect potential leaks; the panels were then cleaned, dried and sealed for refrigeration service.

3.3 Controllers

The refrigeration cycle is controlled in two ways. The expansion valves regulate the flow of coolant through the heat exchangers to maintain maximum cooling and the temperature controllers operate the solenoid valves to regulate the amount of heat withdrawn from the basin. The expansion valves control the amount and pressure of the coolant that enters the heat exchangers to ensure that the Freon has completely vaporized before returning to the condensing units. This is accomplished via temperature regulation of an expansion valve. The temperature of the line leaving the heat exchanger causes an increase or decrease in the pressure in the capillary tube, which then controls the expansion valve, thus adjusting the coolant flow. The amount of heat that is withdrawn from the basin is controlled by the microprocessor-based temperature controller. The controllers sense the temperature of the water using thermocouples. The thermocouples are Copper-Constantan probes coated with

Teflon to protect them from the seawater and to prevent toxins from entering the system. The probes can be placed in either the raceway or the basin; they are presently located at the end of the raceway just in front of the weir (see Butman & Chapman, 1989). The temperature controllers are equipped with relays that open and close the solenoid valves to control the amount of heat withdrawn from the water. The solenoid valve, located in the main liquid Freon supply line, starts and stops the flow of Freon through the heat exchanger.

The temperature controllers display the water temperature using a L.E.D. display on the front of the unit. The display also allows the user to program the response cycle of the units. At present the units are programmed to work in unison. During the cool-down period, all four cooling cycles are operating until the desired temperature is reached. To maintain this temperature, two units will turn on if the temperature increases 0.5°C and all four will turn on if the temperature rises 1°C. Recent tests indicate that this set-up maintains the water temperature at $\pm$ 0.5°C for a water temperature of 7°C and an ambient air temperature of 20°C. With more extensive testing and reprogramming, greater accuracy could be achieved.

3.4 Insulation

The insulation was the most cost-effective component of the cooling system, as indicated by a comparison of the results of the heat transfer calculations for the components with and without insulation (Table 1). The raceway walls and bottom have been insulated with 5-cm-thick, foil-faced, extruded foam panels. These foam panels have an R-value of 14. The panels can be removed easily from the sections of the flume where there are windows to allow for observations and flow measurements. The circulation system piping has been wrapped with 2.5-cm-thick neoprene insulation with an R-value of 4. The neoprene was chosen over conventional foil-backed roll insulation due to its compatibility with seawater. The sump area is covered with 6 mil. reinforced plastic which reduces convective heat loss from the sump area as well as keeping dust out of the circulating water.

4 ACKNOWLEDGMENTS

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16. Abstract (Limit: 200 words)

A cooling system has been developed to control the operating water temperature of the 17-Meter Flume at WHOI's Coastal Research Laboratory. The system utilizes a microprocessor-controlled refrigeration cycle to maintain temperatures ranging from 4°C absolute to 10°C above the ambient room temperature. All components are non-toxic to marine organisms and do not create low flow areas for settlement of suspended particles. This report reviews design and other engineering considerations and describes in detail the system components.

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2. flume
3. engineering design

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