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To the Graduate Council:

I am submitting herewith a thesis written by David Arch Fugate entitled "An Electrocaloric Flowmetering System for Ultra-Low-Volume Sprayers." I recommend that it be accepted for nine quarter hours of credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

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AN ELECTROCALORIC FLOWMETERING SYSTEM FOR ULTRA-LOW-VOLUME SPRAYERS

A Thesis

Presented to

the Graduate Council of

The University of Tennessee

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

---

by

David Arch Fugate

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ABSTRACT

The purpose of this investigation was to develop a flowmetering system for use on ultra low volume (ULV) agricultural sprayers. The experimental data were to provide sufficient information to determine the feasibility of an electrocaloric flowmeter for this use.

A theoretical expression was derived from which flow rate through the electrocaloric metering system could be determined.

The data were obtained from a laboratory setup of the flowmetering system. Tests were conducted with distilled water, Malathion, and Panasol. The independent variables tested were flow rate and liquid temperature. The effect of four levels of each independent variable was measured from the effect it produced on the error percentage between the theoretical and measured flow rate.

Values of absolute viscosity and specific heat were determined for Panasol and Malathion.

It was found that accuracy of the system was affected by the flow rate, temperature, viscosity, and Reynolds Number of the metered liquid. The system performed satisfactorily with water, but produced considerable error with Malathion and Panasol at the lower flow rates tested.

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CHAPTER I

THE PROBLEM

I. INTRODUCTION

Recent research indicates that effective insect control can be obtained from applications of technical undiluted insecticides at rates as low as eight ounces per acre. These rates were first applied by aerial application, but at present several experimental and commercial ground driven sprayers capable of applying such rates of undiluted chemicals are available. Rates of application below 64 ounces per acre comprise what has become known as ultra-low-volume (hereafter referred to as ULV) spraying.

Definite advantages of ULV spraying include elimination of labor required for mixing and applying large quantities of diluted material; elimination of the need for diluents such as water and oils since air replaces these as the carrier; and lower cost of insecticides since less technical material is actually being used. Other advantages are better insect control than is obtained by conventional methods (11, 22) and longer residual effect resulting from deposition of finely atomized particles that adhere closely to plant surfaces (24, 29). Even though the feasibility of ground application of ULV rates has caused it to develop from an experimental to a commercial stage, several interrelated problems still need to be solved.

Since this type of spraying involves the use of highly concentrated and poisonous materials, there is a problem of safety. This

problem is more complex when the application rate is in the lower end of the ULV range because the fine mist from the nozzles is difficult to see and can be blown on the operator without his knowing it.

This drift of particles constitutes problems other than that of safety. The finely atomized spray particles have diameters as small as 33 microns (28), and a slight wind may displace them into an adjacent field or residence. Evidence that drift aids in distribution of spray particles in the target area has been shown (23, 28), but this advantage is overshadowed by its disadvantages. Several studies are reported which suggest ways to reduce drift, the most common being to increase the viscosity of the spray material by adding heavy oils to form emulsions (10, 15, 18). This serves to increase the particle size and density of the spray particles which reduces drift. It has the disadvantages, however, of increasing the amount of liquid applied and further complicating another problem; that of metering the rate of application.

The problem of metering the rate of flow of the material from the sprayer is one of a complex nature. This rate must be known so that the applied rate per acre of insecticide can be determined. The most common method for calibrating ULV sprayers is to catch the flow from a nozzle for a given time and multiply this rate by the number of nozzles to get the overall flow rate. This is then combined with swath width and ground speed to calculate the applied rate per acre. Since there are limitations on ground speed, and a certain rate per acre is usually desired, this process may need to be repeated several

times on a trial-and-error basis to arrive at the proper calibration. This procedure is costly in time required and material lost from the nozzles whose discharge is not being caught. Also, the person doing the calibration must come into direct contact with the sprayer discharge which is caustic to the skin and may be poisonous if inhaled or swallowed. This calibration process must be repeated for each insecticide formulation, since physical properties that affect flow rate are usually different for each formulation. Even more troublesome is the fact that flow rate is greatly affected by viscosity of the flowing liquid, which in turn changes with variations in liquid temperature. The temperature inside a sprayer tank may change as much as 40°F during a day's spraying; and with a constant operating pressure, the resulting viscosity change can cause output errors of 100 percent or more. In order to compensate for this, the sprayer must be recalibrated periodically during the day.

Even if a faster, more inexpensive method of calibration could be achieved, the operator would not know when he needed to recalibrate to compensate for viscosity change. The problem of nozzle stoppage could also occur at any time. These problems point to the need for a meter which would continuously indicate the sprayer output rate.

The following are several reasons such a meter has not been developed for ULV sprayers. Physical properties of technical insecticide formulations are not available to researchers. Several solvents could be used to dissolve a technical insecticide, which is usually of a solid nature, and these solvents largely determine the physical

properties of the formulation. Formulating and manufacturing plants guard information concerning solvents very closely, as their profit margin is closely related to the cost of the solvent used in a formulation (23). Given the knowledge of these physical properties, there is still the fact that the ULV meter must compensate for the changes in the temperature-dependent properties of the metered liquid that affect flow rate. Also, the elements of the meter exposed to the liquid must be able to withstand the extreme corrosiveness common to most ULV formulations. Metering ULV rates, which are as low as 0.02 gallons per minute, requires sensitivity that cannot be obtained with a large number of commercial flow meters.

It is evident from this brief discussion that considerable advantages could be expected from a ULV flow metering system which would eliminate:

1. Direct contact between the measuring elements and the metered liquid.
2. The need for extracting energy from the liquid to produce a mechanical signal.
3. False indications of flow rate resulting from viscosity changes of the liquid.

For this reason, the writer believes that electrocaloric principles can be utilized to develop a metering system that can be adapted to ULV sprayers.

II. OBJECTIVES OF THE STUDY

The principal objective of this investigation was to develop a flow metering system that could be adapted to ULV sprayers. It was anticipated that this study would provide a starting point for more specific testing and refining of the system.

The specific objectives follow:

1. To design, construct, and test an electrocaloric flow metering system for the ULV application range.
2. To conduct and compare flowmetering tests at different temperatures and flow rates using distilled water, a typical ULV solvent, and a typical ULV formulation.

CHAPTER II

REVIEW OF LITERATURE

Perhaps, the relative newness of the ultra low volume technique is one important reason why a reliable flow metering system for ULV sprayers has not yet been developed. Most of the work done with ULV spraying has been done within the past two years, with the bulk of the work directed toward the development and testing of application equipment and ULV formulations. No studies dealing exclusively with the problem of metering ULV insecticides have been reported. Burt et al. (3), Cleveland (5), Howitt (13), Mullins (23), Taft et al. (28), and Thomas (29) report studies that deal with development of ULV equipment; and each of these describes problems associated with calibration and metering. Much has been written about the theory of flowmeters and their application to general metering problems. Some of the more extensive reports of this nature are by Clark (4), Driskell (8), ASME (9), Katys (14), and McVeigh (20). Flow metering methods for low flow rates are discussed by Benseman (1), Bloom (2), Stoll (27), Walker (31), and Wingo (32).

I. METERING DEVICES USED WITH ULV SPRAYERS

A common ULV metering system consists of small diameter orifices fitted in the nozzle tips in conjunction with a pressure gage and regulating valve. The rated output of the orifices depends on their diameter and the operating pressure. The operating pressure is indicated

by the pressure gage and is regulated by the valve. A problem often encountered with this system is nozzle stoppage (3, 23, 29), and there is usually no indication by the pressure gage when the nozzles become clogged since they discharge such small quantities. As previously mentioned, physical properties that affect flow differ for most ULV formulations so that the orifices must be calibrated for each formulation. Also, large errors occur when the liquid temperature changes during operation due to the resulting change in viscosity (23).

A precision metering valve manufactured by Nuclear Products Company was used by Howitt (13) and Taft et al. (28). However, the valve gave erroneous output indications if it was not calibrated each time a different formulation was used (13). No mention was made of viscosity problems associated with this metering device, which is probably due to the fact that the tests in which it was used were conducted on small plots; and no prolonged periods of continuous spraying were necessary.

A constant pressure system for aerial ULV application maintained accurate calibration when chemicals of approximately the same viscosity were used (5). There was no problem with errors due to viscosity changes during application, because the formulation was dispensed from within the aircraft where fairly uniform temperatures existed.

II. FLOWMETERS FOR PRESSURIZED FLOW

All flowmeters may generally be classified into two functional groups (9). One group primarily measures the quantity discharged,

while the other measures the rate of flow. Moreover, all flow measuring systems consist of two distinct functional parts. One, called the primary element, is in contact with the fluid and causes an interaction with the fluid. The other, called the secondary element, senses the interaction and translates it into some type of readout.

Quantity Meters

Quantity meters (also known as positive displacement meters) measure isolated quantities of fluid through the primary element either by weight or volume. Usually, containers of known capacity are alternately filled and emptied resulting in essentially uninterrupted flow of the metered material. The flow passes through the primary element in isolated quantities, and the number of these quantities is counted and indicated in terms of volume by the secondary element or register.

Most quantity meters drive a counter directly to record the total flow; hence, rotating seals are necessary, and the operation of the counter places an additional frictional load on the meter. Since the energy to operate the meter must be extracted from the fluid, the frictional load must be minimized for accurate measurement of low flows. Some of the more common quantity meters are the nutating disk, gear or lobed impeller, Dethrige meter, reciprocating piston, and oscillating piston. Of these, only the reciprocating piston is recommended for flow rates below 0.02 GPM. It is also the most expensive and causes a relatively high pressure loss (12).

Rate Meters

Rate meters produce a readout from a continuous stream that moves through the primary element. Some type of interaction of the fluid with the primary element is monitored by a secondary element. This interaction of fluid and primary element depends on one or more physical properties of the fluid such as kinetic energy, specific heat, and inertia. The secondary element indicates changes in these properties which are related either theoretically or empirically to flow rate.

Differential head meters. Differential head meters are probably the most popular type of flow meter due to their versatility and low cost (12). They operate on the principle of converting fluid energy from one form to another. The principle involved is always the same regardless of the construction of the meter (9). The net cross-sectional area of the stream is reduced, causing an increase in kinetic energy. Since energy can neither be created nor destroyed, this increase in kinetic energy is obtained from a loss of pressure energy; so that pressure of the fluid is reduced. A fraction of the pressure reduction, called pressure differential, is measured which enables fluid velocity to be calculated. Two major disadvantages of differential head meters are large pressure drop and reduced accuracy if changes in density and viscosity occur. Some common types are the Venturi tube, pitot static tube, Dall flow tube, orifice, and flow nozzle. None of these meters are considered reliable below 0.2 GPM (12).

Variable area meters. Variable area meters operate by means of a differential pressure which remains constant, and a floating element which responds to flow rate changes. Area variation is produced by the rise and fall of the floating element; and in use, these meters must be in a vertical position to minimize frictional resistance. The relationship between the position of the floating element and flow rate is based on a calibration. In order for the calibration to apply directly, the specific weight of the fluid being metered must be the same as that with which the meter is calibrated. However, the calibration can be extended to cover any fluid by the use of the equation $q_b = q_a \left(\frac{W_a}{W_b}\right)^{1/2}$, where q_a and q_b are the volume rates of flow at the specific weights W_a and W_b, respectively (9).

The most common variable area meter is the rotameter in which the floating element is inside a tapered tube usually made of glass. The major variation in rotameter construction is in the construction of the floating element. Physical characteristics of the metered fluid determine the size, shape, and weight of this element. The element can be designed to be sensitive or relatively insensitive to viscosity. Some rotameters have two floating elements; one to indicate flow and the other viscosity.

Another type of variable area meter is the slotted-cylinder and piston meter. This meter is particularly suited for highly viscous liquids (9). In operation, the liquid enters the inlet port of a vertical cylinder with a loosely fitting piston. The piston is forced

upward by the incoming liquid until enough slots in the cylinder wall are exposed to let the liquid exit at approximately the same velocity as it entered. The primary element in this system is always the piston, but there are several variations of the secondary element. The simplest of these is a rod attached to the piston which moves inside a sight glass above the cylinder. Flow is indicated by the position of the rod on a scale beside the sight glass.

Instability of the floating element is the greatest disadvantage of variable area meters. When the meter is subjected to external vibrations, or if pulsations are caused in the fluid by the pump, fluctuations occur in the indicated flow rate.

Force-momentum meters. This type of flowmeter is commonly referred to as a mass flowmeter. Mass flowmeters are well suited for systems where an indication of the mass rate of flow is desired. Generally, this type of meter adds a known amount of energy to the fluid, and either measures the effect of the added energy, or measures the amount of energy required to produce a specific effect on the fluid.

The axial-flow, transverse-momentum mass flowmeter is a common type of mass flowmeter. It utilizes a turbine driven at a constant speed to induce a constant angular velocity to the fluid and a similar spring-retained turbine rotor to measure the force required to overcome the angular momentum of the fluid. The angular displacement of the retained rotor is directly related to the mass flow of the fluid (25).

Some other mass flowmeters are the radial (Coriolis) mass flowmeter, gyroscopic mass flowmeter, and massometer. The pressure loss is small in this type of meter and accuracy is good. However, since they require an external power source and precision rotating seals, their cost is relatively high.

Force-velocity meters. Force velocity meters are characterized by a rotating primary element that is kept in motion by the movement of flowing fluid. The primary element is usually in the form of a turbine or propeller. The major difference between the turbine and the propeller meters is the design of the rotor and blades. Normally, the propeller has a few large, sharply curved blades, while the turbine has many small and slightly curved blades. The operation of both meters is basically the same, but the turbine is better suited for high velocities. A discussion of the principles of operation of the turbine should suffice for both types.

Turbine type meters are used almost exclusively for liquids. The basic principle upon which they operate is the same as for hydraulic turbines. The liquid stream is directed through a passage in which the rotor is mounted. The rotor is caused to rotate by the reaction of the liquid against the blades, and the rate of flow is directly proportional to the speed at which the rotor turns. There are three general designs of rotors. In the first, the flow is radial to the rotor axis. In the second, the flow is axial to the rotor axis, and blades on the rotor are in the form of an elongated helix. The third design is a combination

of the first two, and the flow is partly radial and partly axial to the rotor (30).

Common variations of the turbine meter include the dual rotor turbine and the turbine compound. The dual rotor turbine meter has two rotors mounted on the same shaft but several inches apart. This design minimizes bearing friction, since the thrust loads of the rotors are in opposite directions (7). The turbine compound meter overcomes the loss of accuracy at low velocities common to turbine meters. An ordinary turbine meter is placed in parallel with a low capacity positive displacement meter through which the liquid passes at low flow rates. At high flow rates the liquid is directed through the turbine.

The force causing the rotor or propeller to turn in force-velocity meters is mainly dependent on velocity and specific weight of the metered fluid. Calibration is necessary for different liquids, but viscosity fluctuations during operation result in very small errors. If high accuracy and sensitivity is required of force-velocity meters, their cost is usually much higher. This is due primarily to the type of readout equipment necessary to sufficiently reduce operating friction in the meter.

Thermal Meters

As applied to the measurement of fluids, thermal meters are those in which the transfer of heat to or from the fluid stream is a basic part of the process. These meters are classified into two categories, depending upon the manner in which the heat transfer is utilized:

1. Thermo-anemometers are those in which the effect of a flowing fluid on a hot body is determined.
2. Caloric flowmeters are those in which the effect of a known quantity of heat on a flowing fluid is determined.

Thermo-anemometers may be further divided into two groups. The first group, of which the hot-wire anemometer is a common example, correlates the change in resistance of a small diameter wire with the velocity of the flowing medium to which it is exposed. This group is limited almost entirely to gas flow and is not considered very reliable for liquids (14).

The second group contains instruments in which the primary sensing element consists of a heated filament and a thermocouple or thermistor for measuring the temperature change of the filament. The rate of fluid flow is determined by measuring the variation in temperature of the filament for constant power input. Thermo-anemometers of this type are better suited for liquids than those previously mentioned, but they have two major limitations. The greatest limitation is the difficulty in maintaining a high element temperature. Heat is transferred from the filament by the liquid so fast that a very high power input is required to keep it at a substantially higher temperature than the liquid. The higher the temperature of the thermo-element, the more sensitive is the meter, and the less its readings are affected by ambient liquid temperature change (14). The second limitation is that readings are substantially affected by the ambient temperature of the metered liquid. A temperature compensating device described

by Deason (6) reduced error from 4 percent to 0.25 percent per °C change in liquid temperature. With this compensating device, full temperature compensation can be achieved at only one flow rate.

Caloric flowmeters are also known as electrocaloric flowmeters when electrical energy is used to heat the fluid. Use of this type of meter for liquids has the following requirements:

1. A knowledge of the specific heat of the flowing stream.
2. An efficient means of heating the liquid stream and of measuring the power input.
3. An accurate method of measuring the temperature increase of the heated portion of the stream.

Probably the most common flowmeter of this type is the boundary-layer flowmeter. In this meter the heater and temperature measuring elements are on the outside of the conduit, and the layer of fluid adjacent to the inner wall is heated (17). The amount of heat required to cause a given temperature differential across the boundary layer indicates the rate of heat transfer from the heated area of the conduit through the boundary layer. This rate of heat transfer is a measure of the mass flow rate of the fluid. Liquids can be metered through a wide range of flow rates with a reasonable expenditure of energy with this type of meter. Laub (17) used a proportioning system to reduce power input at high flow rates. Only a small fraction of the liquid was directed through the test section, and the heat required to produce a measurable temperature change was greatly reduced. The boundary layer flowmeter causes little or no pressure drop in the

stream, and none of the elements are directly exposed to the liquid. However, it is not independent of viscosity, and corrections must be made when flow changes from turbulent (Reynolds number greater than 2100) to laminar (Reynolds number less than 2100), as the boundary layer thickness is affected by these flow conditions (17).

Another type of electrocaloric flowmeter is similar to the boundary layer flowmeter in that heat is added to the flowing stream and a change in temperature is measured. Instead of heating only the film of fluid next to the conduit, the whole stream is heated. This method was originally devised by C. C. Thomas in 1911 and was used for measuring the mass flow of gases (19). Laub (16) found this type of flowmeter well suited for metering liquids at small flow rates.

The theoretical expression which applies to this meter for liquids is $M = Q/C\ (\Delta T)$ where M is flow rate (grams per second), Q is heat input (calories per second), C is specific heat (calories per gram per $^{\circ}C$), and ΔT is temperature change ($^{\circ}C$). From this expression it is seen that mass flow rate is proportional to heat input if specific heat remains constant. The specific heat of water varies only slightly between $0^{\circ}C$ and $100^{\circ}C$. However, for aviation gasoline, for instance; specific heat is 0.49 at $0^{\circ}C$ and varies proportionally to 0.55 at $50^{\circ}C$, or about 0.25 percent per $^{\circ}C$ (16).

In pipe flow the velocity distribution (velocity profile) of the stream is governed by the Reynolds Number which is inversely related to viscosity. When laminar flow exists, the stream velocity rises from zero at the pipe wall to a maximum at the center along a

parabolic distribution curve. For turbulent flow the velocity distribution curve rises much more sharply from zero at the wall to a maximum at the center. It follows that heat transfer from the wall to the liquid should occur at a faster rate when turbulent flow exists. To this extent the accuracy of this type of flowmeter is affected by the liquid temperature. This effect should be minimized if a good degree of turbulent mixing can be achieved in the heated portion of the pipe.

The response to flow changes is relatively slow for this type of flowmeter due to high thermal inertia. Response can be improved by using low mass resistance thermometers as temperature sensing elements and a good heat conductor, such as copper, in the test section where the heater and thermometers are located.

CHAPTER III

APPARATUS

I. THEORY OF THE TEST SECTION

A sketch of the test section of the electrocaloric metering system used in this study is shown in Figure 1. A known amount of electrical energy is added to the system by a constant voltage (E) which is dissipated as heat by the heater element. The change in temperature of the flowing fluid due to this addition of heat is indicated by the thermometers. The power dissipated by the heater can be calculated as

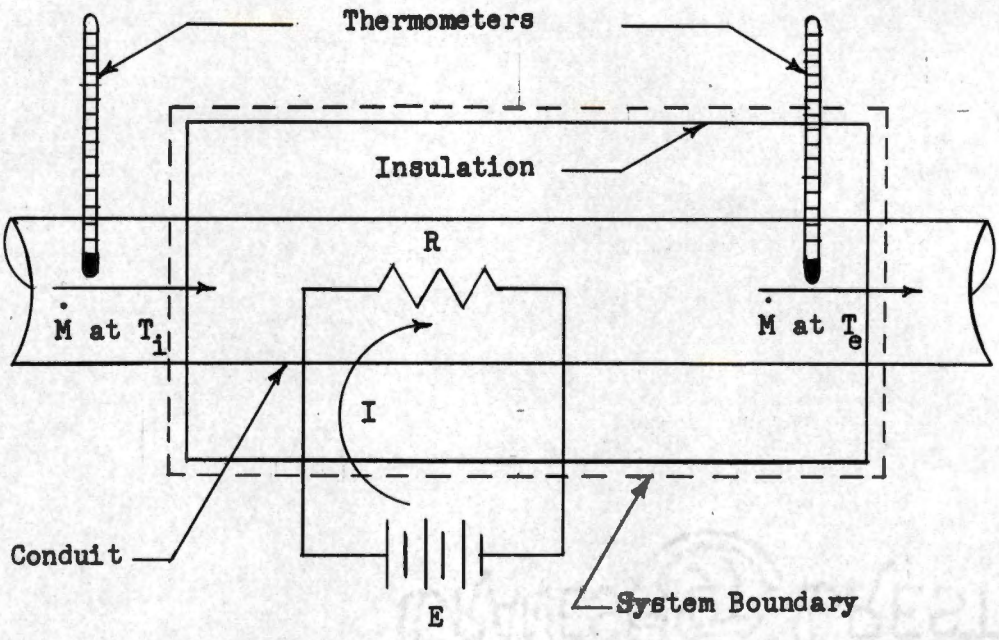
$$P = E^2/R \ , \tag{1}$$

where P is power dissipated (watts), E is heater voltage (volts), and R is heater resistance (ohms). Electrical power can be converted to heat units by introducing a conversion constant into Equation 1, which then becomes

$$\dot{Q} = KE^2/R \ , \tag{2}$$

where $\dot{Q}$ is heat dissipated by the heater (calories per minute), and K is the conversion constant which relates watts to calories per minute.

The system thus described can be treated as a steady-state, open system if the mass rate of flow into the system is equal to the mass rate of flow from the system; and if at any point within the system, conditions are unchanging with time. For the first condition to exist the fluid cannot expand or be compressed within the system;



$\dot{M}$ - mass rate of flow of liquid through the system
T_i - inlet liquid temperature
T_e - exit liquid temperature

Figure 1. Sketch of the test section.

its inlet velocity (V_i) must equal its exit velocity (V_e); and the cross-sectional area of the inlet must be the same as that of the exit. The second condition is obtained if the difference between exit fluid temperature (T_e) and inlet fluid temperature (T_i) is constant at the time of analysis. These conditions can easily be obtained with this system if it is used to meter incompressible fluids.

The first law of thermodynamics for a steady-state, open system is written in equation form as

$$Q = dh + d(KE) + d(PE) + W \ . \qquad (3)$$

Q is net energy crossing the system boundary, dh is the change in enthalpy of the system, d(KE) is change in kinetic energy of the system, d(PE) is change in potential energy of the system, and W is external work performed by the system. Since the distance is very short from inlet to exit and inside pipe surfaces can be made fairly smooth, change in fluid velocity, and hence change in kinetic energy within the system can be neglected in this study. Change in potential energy is zero if the inlet is at the same elevation as the exit. No mechanical work is performed inside the system boundary; therefore, Equation 3 reduces to

$$Q = dh \ . \qquad (4)$$

Since the fluids used for this study are virtually incompressible liquids, the change in enthalpy equals the change in internal energy (dU). This is derived from the following basic relationships for changes in enthalpy and internal energy:

$$dh = MC_p dT \tag{5}$$

$$dU = MC_v dT \ . \tag{6}$$

M is mass of the fluid, C_p is specific heat at constant pressure, C_v is specific heat at constant volume, and dT is change in temperature of the fluid. For incompressible fluids $C_p = C_v$, from which follows that dh= dU . Combining this with Equations 4 and 6 gives

$$Q = MCdT \ , \tag{7}$$

where C is the specific heat of the incompressible fluid. Equation 7 may also be written as a rate equation by considering a period of time dt during which the mass M passes through the system, and the heat q is transferred to the system. Then as dt approaches zero, the following rates are obtained:

$$\text{Heat Transfer Rate} = q/dt = \dot{Q} \ , \tag{8}$$

$$\text{Fluid Flow Rate} = M/dt = \dot{M} \ . \tag{9}$$

Equation 7 then becomes the rate equation

$$\dot{Q} = \dot{M}CdT \ , \tag{10}$$

or solving for mass flow rate,

$$\dot{M} = Q/CdT \ . \tag{11}$$

Equation 11 adequately describes the heat transfer of the system depicted in Figure 1, page 19, if heat lost to the surroundings by conduction and radiation is assumed negligible as compared to heat transferred from the heater to the fluid by convection. By carefully insulating the system from the surroundings and allowing sufficient time for equilibrium to take place, this assumption should result in very small error. From Equation 11 it follows that if heat transfer

rate ($\dot{Q}$) were kept constant and the temperature differential (dT) measured, the rate of flow ($\dot{M}$) would be inversely proportional to dT. In order for this relationship to be used, the specific heat (C) of the fluid must be known.

II. DESCRIPTION OF EQUIPMENT

Pump and Constant-Temperature Reservoir

An electrical, laboratory model, chemical metering pump (Figure 2) was used to pump the liquid through the system. The pump employed a synchronously rotating and reciprocating piston which completed one pressure and one suction stroke in each rotation. Flow rate could be altered at any time by changing the position of the flow rate indicator, which served to change the length of the piston stroke. Fine incremental flow rate control was made possible by a micrometer adjustment of the flow rate indicator.

The reservoir from which the liquid was pumped was constructed from a discarded glue melting pot with a capacity of 1-1/2 gallons (Figure 2). It had a 750-watt heating coil within the walls, and was thermally insulated with loosely packed fiberglass insulation. A thermally insulated lid was constructed that could be tightly clamped onto the reservoir. Both an inlet and an outlet were installed so that the liquid could be recirculated through the system. These were constructed from 3/8-inch copper tubing inserted through holes in the lid and soldered to the lid to eliminate air leaks. The portion of the tubing that extended below the lid was bent on both the inlet and

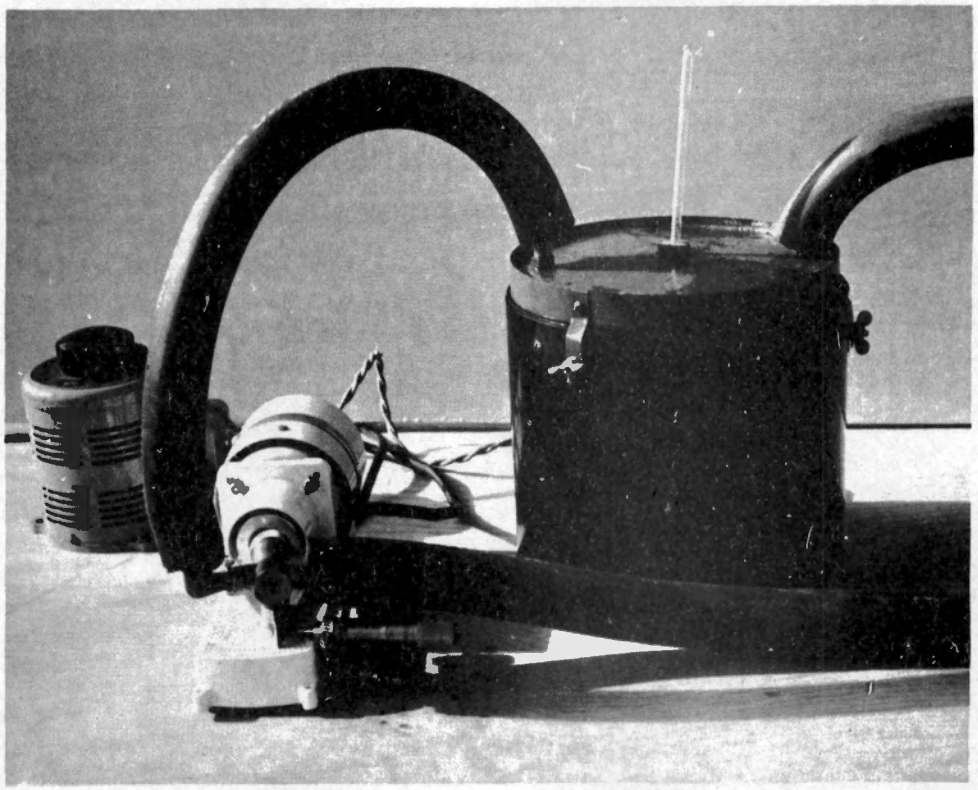


Figure 2. Pump and constant-temperature reservoir.

outlet in a manner that caused the liquid to be stirred during recirculation. Hose barbs soldered to the copper tubing extended through the top of the lid. A mercury thermometer for determining the liquid temperature was inserted into a cork stopper which was inserted into a hole in the lid. This hole was large enough to allow the liquid to be added to the reservoir without removing the entire lid. A variable resistor connected in series with the heater coil was used to regulate the input voltage.

The Test Section

The test section consisted of a 60-watt heating unit and a resistance thermometer (Figure 3). The heating unit was constructed from a section of thin copper conduit with three small heater buttons mounted inside thin brass sleeves. The sleeves were machined to 0.032 inches wall thickness and inserted into 1/8-inch brass plates. A boss was machined on the outside of the closed end of the sleeves and tapped for a #2 machine screw which was used to mount the heater buttons. A layer of heat sink compound was applied to the mounting surface before installation of the heaters. The brass plates and sleeves were inserted into the ends of the copper conduit, and all joints were sealed with silver solder. Pipe fittings were soldered onto the brass plates to form the liquid inlet and outlet. Details and discussions of the heating unit are included in Figure 4. The heater buttons had a 20-watt heating capacity at a maximum of 28 volts. They were connected in parallel to give a total heating capacity of 60

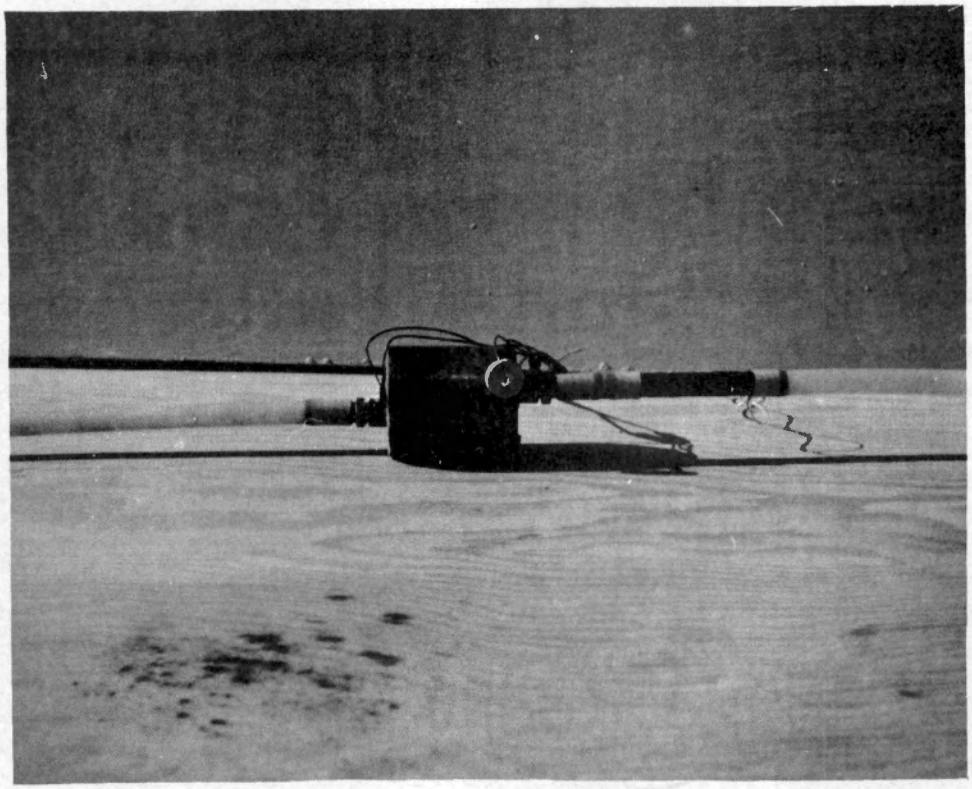


Figure 3. Test section with heater button exposed.

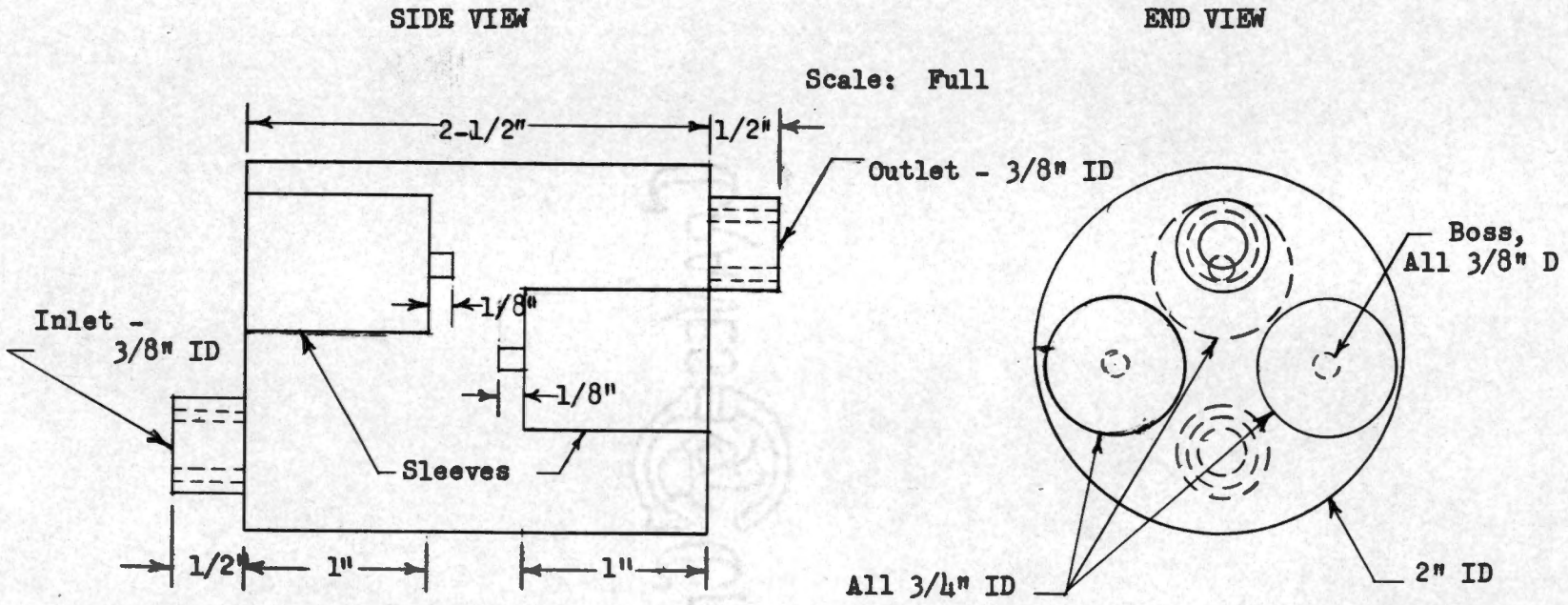


Figure 4. Test-section heater.

watts at the maximum input voltage. The input voltage was supplied by a general-purpose, voltage and current regulated, d-c power supply unit (Figure 5). The power supply had a variable voltage output from 0 to 40 volts d-c and a maximum current of three amperes. A voltmeter and an ammeter, both rated at 2 percent accuracy, were built into the power supply.

The resistance thermometer had a non-inductive, nickel-iron alloy element with a resistance of 676 $\pm$ 0.5 percent ohms at 25°C. The element was two inches in length and 0.375 inches wide. It was mounted onto the outside wall of a 3-1/2-inch section of beryllium-copper tubing with a wall thickness of 0.064 inches. Hose barbs were machined on the ends of the tubing to eliminate the need for pipe fittings, and hence reduce the mass of the temperature sensing unit. One layer of plastic tape was tightly wound over the thermometer element to hold it in close contact with the tubing. Resistance measurements were made with a standard bridge ohmmeter (Figure 5), which had a rated accuracy for resistance measurements of plus or minus 1 percent plus one digit. Maximum voltage across the measured resistance was 40 volts d-c.

Careful consideration was given to thermal insulation in the design of the test section. The two basic requirements of the insulation were to prevent heat transfer from the system to the surroundings and to prevent heat transfer from the heater to the resistance thermometer, except that heat which was transferred from the heating unit by the liquid. To help meet the first requirement, the heater buttons were essentially surrounded by the flowing liquid inside the copper

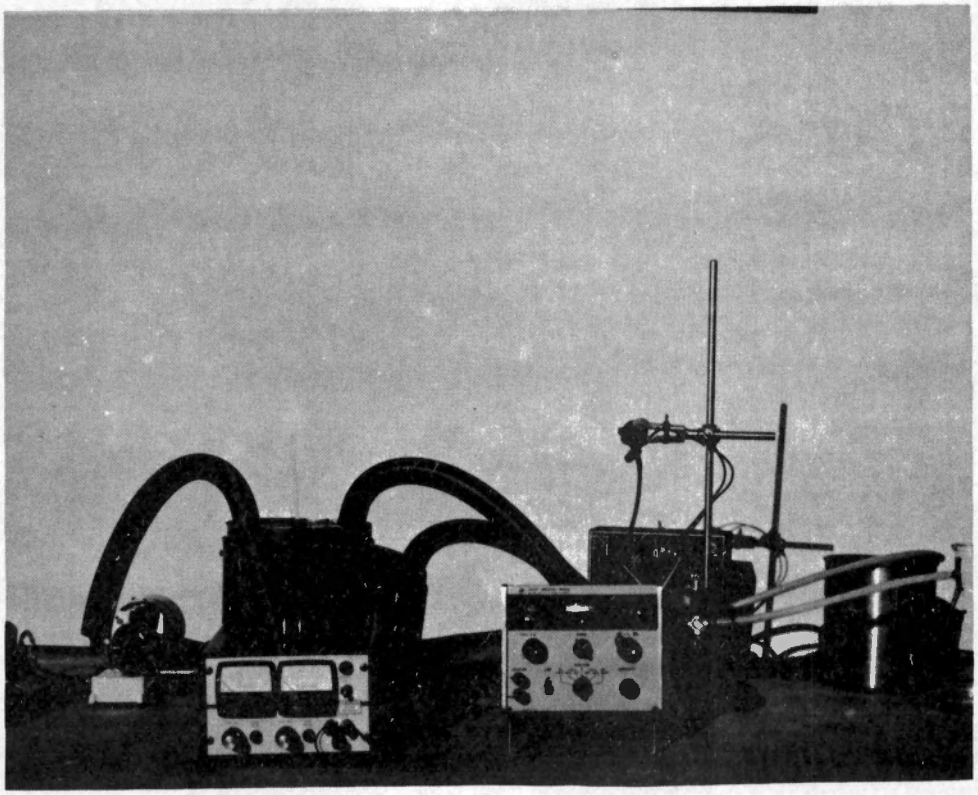


Figure 5. The electrocaloric flowmetering system.

conduit. The open ends of the sleeves in which the heaters were mounted were filled with rubber thermal insulating tape, and the whole heating unit was then covered with a layer of this tape. All of the liquid line in the recirculating system was insulated with rubber insulating tubing which had a three-inch inside diameter, and a 1/2-inch wall thickness. The test section was further insulated with a section of the same type of tubing which had a two-inch inside diameter. Both layers were necessary to prevent heat loss to the surroundings and still keep the outside surface of the resistance thermometer insulated from the heater. To prevent conduction of heat along the walls of the conduit from the heater to the resistance thermometer, a short piece of 3/8-inch nylon tubing, which is a poor heat conductor, was used for the liquid line between the heater and the thermometer. Nylon tubing was also used as the liquid line for the rest of the flowmetering system.

The Calibration and Recirculation System

In order to ascertain the accuracy of the electrocaloric metering system at several flow rates, a quick and accurate method for determining the actual flow rate was necessary. Also, since the liquid was to be metered at temperatures other than room temperature, it was necessary to recirculate the liquid to obtain uniform temperatures throughout the system prior to a test. Both of these needs were met through the use of two three-way, electric solenoid valves and an automatic laboratory timer (Figure 6). The solenoid valves were installed

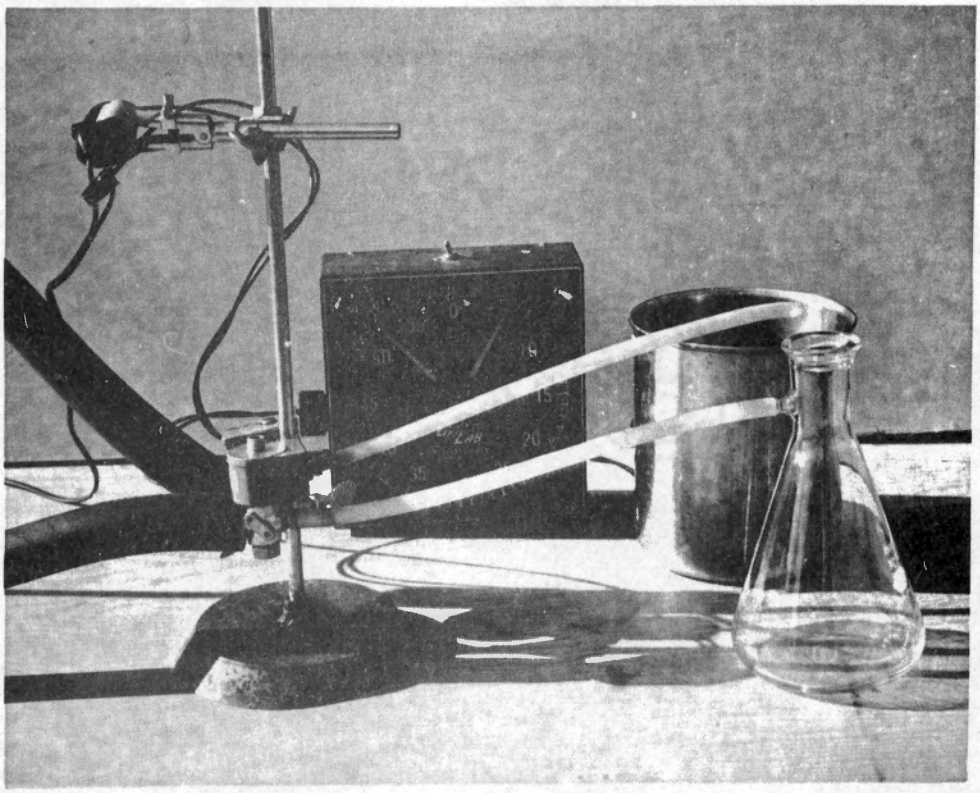


Figure 6. The calibration and recirculation system.

in the liquid line downstream from the test section. In the de-energized position, the first solenoid let the flow pass on to the second solenoid which, in the de-energized position, let the flow return to the constant-temperature reservoir. The laboratory timer energized the first solenoid for a predetermined period of time which caused the flow to be diverted into a calibration beaker. The flow rate could be determined by measuring the amount caught in the beaker during the known time interval. While the heating unit in the test section was in operation the second solenoid was energized, thus directing the flow into a catching container to prevent the heated liquid from returning to the constant-temperature reservoir. This arrangement made possible the calibration of the system at any time during a test.

CHAPTER IV

PROCEDURE

I. PRELIMINARY INVESTIGATION

A simplified version of the electrocaloric metering system was constructed to verify the theory of the flowmetering technique and to aid in the final design of the system. Only one of the 20-watt heater buttons was mounted in the heating unit, and all of the preliminary tests were conducted with distilled water at room temperature. In these tests resistance thermometers were installed in the test section at various distances downstream from the heater. The heat input produced the largest temperature change in the thermometer closest to the heater, and in the final design the centroid of the resistance thermometer was located two inches downstream from the heating unit.

Some difficulty was experienced in the temperature calibration of the resistance thermometers. Of the four resistance thermometers on hand, no two produced equal resistance readings at any given temperature. For all of the thermometers, the resistance corresponding to any given temperature deviated from the value reported in the manufacturer's data. However, the change in resistance for a given temperature change was found to closely agree with the rated change as reported by the manufacturer. To eliminate the error which would be produced by inconsistent temperature-resistance characteristics between the upstream and downstream thermometers, only one thermometer was included in the final

design of the system. Initial temperature of the liquid was read on the downstream thermometer just prior to turning on the heater, and the final temperature was read on the same thermometer when equilibrium occurred. Since it was necessary to know only the change in liquid temperature produced by the heater, the change in resistance per degree change in temperature was the only calibration that was needed. However, the elimination of the upstream thermometer made it imperative that the temperature of the incoming liquid remain constant during the time between the initial and final thermometer readings.

A slow response to flow rate changes was observed in the preliminary tests. In the final design, efforts were made to reduce the mass of the elements in the test section, and thereby reduce the thermal inertia of the system. Some fluid leakage occurred at the pipe fittings in the preliminary tests, but this problem was eliminated through the use of teflon tape to seal the fittings. Close agreement with theory in the preliminary tests made more extensive testing of the flow-metering technique with a refined system appear justifiable.

The preliminary tests showed that power input to the test-section heater could be calculated from the heater voltage and the heater current with very little error. When the power supply was operating on the constant voltage mode, the current fluctuations were too small to register on the ammeter scale which meant that power input was very nearly constant at system equilibrium.

II. EXPERIMENTAL DESIGN

After the electrocaloric metering system was redesigned, four sets of tests were conducted. Three liquids were investigated at four flow rates and at four liquid temperatures. The liquids were distilled water; Panasol, a petroleum-base solvent used in ULV application; and Malathion (O, O-dimethyl phosphorodithioate of diethyl mercaptosuccinate), a ULV insecticide formulation. The flow rate levels were 50, 200, 350, and 500 cubic centimeters per minute. The temperature levels were 70, 85, 100, and 115 degrees Fahrenheit. The four rate levels cover the range of discharge rates for an eight-row sprayer at a ground speed of five miles per hour and operating within the ULV range of application of below 64 ounces per acre. The four temperature levels cover the range of temperatures found inside a sprayer tank on a normal summer day in the Midsouth (23).

The levels of the two variables were arranged in a split-plot arrangement of treatments with rate treated as the main variable (26). Each level of both variables was combined, which resulted in 16 individual combinations or tests to be conducted. To reduce the experimental error, and at the same time provide a means of estimating it, each test was repeated three times. Therefore, 48 tests were made for each liquid.

It was realized that operation of the system with the liquid temperature different from room temperature might introduce error resulting from heat transfer through the system insulation. To help

determine the magnitude of this error a separate set of tests was conducted with distilled water at room temperature. In this set 10 tests were conducted at each of the previously defined flow rates, which resulted in a total of 40 tests.

III. METHOD OF CONDUCTING TESTS

Treatment combinations of rate and temperature levels were not completely randomized because of the amount of time required to obtain the desired liquid temperature in the constant-temperature reservoir. In each replication of tests the rate levels were randomized at each temperature level, and the tests were conducted in order of magnitude from the lowest to the highest temperature level, as it was easier to raise the liquid temperature than to lower it. The liquid was heated in the constant-temperature reservoir until the desired temperature plus or minus one degree was indicated by the mercury thermometer. During this heating period the liquid was recirculated by the pump to maintain uniform temperature in the reservoir. After the desired temperature was indicated by the mercury thermometer, the recirculation was continued until the element of the resistance thermometer produced constant resistance readings on the ohmmeter for one minute. When this equilibrium occurred the flow rate indicator on the pump was set to produce the desired flow rate, and the test-section heater voltage was applied. At the time the heater voltage was applied, the second solenoid was energized preventing the heated liquid from returning to the reservoir. While the test section was being heated, the

exact flow rate was determined by energizing the first solenoid with the automatic timer and catching the flow in a graduated cylinder for a known period of time. When the flow rate was not on or near the desired rate, it was adjusted before the data were recorded. Final thermometer resistance was measured when the system reached equilibrium which was considered to occur when the thermometer resistance remained constant for one minute. The data recorded for each test were initial and final resistance of the thermometer, heater wattage, and flow rate.

The first set of tests was conducted with distilled water, and a brief analysis of the data indicated that accuracy of the system decreased with flow rate. Since a much greater change in liquid temperature was produced by the heater at the lower rates, the decreased accuracy could possibly be attributed to heat loss through the insulation at the lower flow rates. For this reason the heater input voltage was set in subsequent tests to produce approximately the same temperature increase at each flow rate.

Panasol and Malathion were found to cause the buna-n rubber valve seats and O-ring gaskets to swell and render the solenoid valves inoperable. Heating the rubber accessories in an oven for several hours caused them to return to their original size and become reusable. To have one solenoid valve operable at all times, the system calibration procedure was performed prior to turning on the test-section heater, and thereby the need for one of the solenoid valves was eliminated.

The theoretical volume rate of flow was calculated from the following equation which is equivalent to Equation 11, page 21,

$$q = \frac{EIK}{\rho CdT} \tag{12}$$

where q is volume rate of flow (cubic centimeters per minute); E is heater input voltage (volts); I is heater input current (amperes); K is a conversion constant that relates volt-amperes (watts) to calories per minute; ρ is liquid density (grams per cubic centimeter); C is liquid specific heat (calories per gram per ^{o}C); and dT is change in liquid temperature (^{o}C). The accuracy of the meter was calculated by dividing the difference between the calculated flow rate and calibrated flow rate by the calibrated flow rate.

CHAPTER V

RESULTS

The results of the tests conducted as described in Chapter IV provided a basis for evaluating the accuracy of the flowmetering system and for determining the separate and combined effects of the test variables on the flowmeter accuracy. The data were statistically analyzed to determine the level of accuracy that could be expected from the system, and other statistical tests were conducted to determine the degree of significance of the effects of the test variables on flowmeter accuracy. Further tests were used to separate the treatment means that were significant at the 95 percent level of probability.

I. SPECIFIC HEAT DETERMINATIONS

The data were first analyzed using a calculated specific heat as the response variable. It was calculated from the measured parameters of each test and Equation 12, page 37. A considerable variation was observed in the specific heat values thus calculated for both Panasol and Malathion. This pointed to the need for the true specific heat values of these liquids which would make possible a better measurement of the experimental variation.

A small water calorimeter and a technique known as the "method of mixtures" were used to determine the specific heat values for Malathion and Panasol. The calorimeter was checked for accuracy using a heated brass slug, whose temperature and heat capacity were known,

to measure the specific heat of distilled water. At, or near, room temperature it produced specific heat values very near to the true value of one calorie per gram per ^{o}C for distilled water. However, at temperatures above or below room temperature, considerable error was produced by heat transfer to or from the surroundings. Attempts made to adequately correct for this error proved unsuccessful; and as a result, reliable specific heat values could only be obtained at liquid temperatures close to the ambient room temperature. The highest room temperature that could be maintained was between 85 and $90^{o}F$, which is close to the midrange temperature ($92.5^{o}F$) of the temperature treatment levels. Since specific heat of many liquids varies only slightly with temperature (0.14 percent ^{o}F for aviation gasoline is typical), the value obtained in this temperature range can be used in the calculations for each of the temperature levels without introducing a large error into the calculated flow rate. The average specific heat values obtained for Malathion and Panasol in the temperature range between 85 and $95^{o}F$ were 0.309 and 0.421 calories per gram per ^{o}C, respectively.

With the specific heat values thus obtained, the theoretical flow rate for each of the tests and the corresponding percent error between the theoretical and measured flow rate were calculated as described in Chapter IV. The error percentages were subsequently used as the response variable in the statistical analyses.

II. DATA ANALYSIS

A split-plot analysis of variance (25) was performed with the data obtained for each liquid to obtain a measure of the separate and combined effects of liquid flow rate upon flowmeter accuracy. The analysis of variance tables for the split-plot arrangement of distilled water (hereafter referred to as Water-48 to distinguish it from the set of 40 tests conducted with water which will accordingly be referred to as Water-40), Malathion, and Panasol are presented as Tables I, II, and III, respectively.

Liquid Temperature

Liquid temperature was shown to have a significant effect on flowmeter accuracy at the 95 percent level of probability for each of the liquids tested. As can be seen from the calculated F values (Tables I, II, and III), liquid temperature had the greatest effect with Malathion, followed by Panasol; and it had the least effect with water.

A Duncan's Multiple Range Test (21) was performed on the temperature means for each of the liquids to determine which ones were significantly different from the others. These tests for all three liquids are included in Table IV. This test showed that significantly better flowmeter accuracy was obtained at liquid temperatures of 70, 85, and 100°F with water and Malathion; but for Panasol, means at 100°F were not significantly better than those obtained at 115°F.

TABLE I

ANALYSIS OF VARIANCE FOR SPLIT-PLOT ARRANGEMENT OF TREATMENTS OF WATER-48

Source	Degrees of Freedom	Sum of Squares	Variance	F
Main Plot				
Flow Rate	3	588.0	196.01	5.10*
Replications	2	3.3	1.65	0.04
Main Plot Error	6	230.6	38.43	
Sub Plots				
Liquid Temperature	3	238.5	79.48	5.19*
Flow Rate x Liquid Temperature	9	405.7	45.08	2.94*
Sub Plot Error	24	367.8	15.32	

*Denotes significance at the 95 percent probability level or greater.

TABLE II

ANALYSIS OF VARIANCE FOR SPLIT-PLOT ARRANGEMENT OF TREATMENTS OF MALATHION

Source	Degrees of Freedom	Sum of Squares	Variance	F
Main Plot				
Flow Rate	3	9339.5	3119.80	199.73**
Replications	2	14.8	7.40	0.47
Main Plot Error	6	93.7	15.62	
Sub Plots				
Liquid Temperature	3	1958.7	652.90	24.01**
Flow Rate x Liquid Temperature	9	7558.0	839.78	30.89**
Sub Plot Error	24	625.5	27.19	

**Denotes significance at the 99 percent probability level or greater.

TABLE III

ANALYSIS OF VARIANCE FOR SPLIT-PLOT ARRANGEMENT OF TREATMENTS OF PANASOL

Source	Degrees of Freedom	Sum of Squares	Variance	F
Main Plot				
Flow Rate	3	3589.20	1196.39	13.51**
Replications	2	39.70	19.85	0.22
Main Plot Error	6	531.40	88.57	
Sub Plots				
Liquid Temperature	3	2315.50	771.82	8.89**
Flow Rate x Liquid Temperature	9	5551.7	616.86	7.10**
Sub Plot Error	24	2084.4	86.85	

**Denotes significance at the 99 percent probability level or greater.

TABLE IV

EFFECT OF LIQUID TEMPERATURE ON FLOWMETER ACCURACY FOR WATER-48, MALATHION, AND PANASOL

Liquid and Temperature	Percent Error Means	Significance[a]
Water - 48		
70°F	6.55	a
85°F	6.58	a
100°F	9.26	a
115°F	11.94	b
Malathion		
85°F	18.20	a
100°F	18.81	a
70°F	20.16	a
115°F	33.72	b
Panasol		
70°F	4.39	a
85°F	6.58	a
100°F	16.58	b
115°F	21.22	b

[a]Means followed by the same letter are not significantly different at the 95 percent level of probability.

There are several possible reasons for the significant effect of liquid temperature on flowmeter accuracy. In this study liquid temperature was usually different from room temperature which resulted in some heat transfer between the test section and the surroundings. Ambient room temperature was between 75 and 85°F during testing which caused a larger temperature gradient at the higher liquid temperatures. Analysis of Equation 12, page 37, shows an inverse relationship between change in liquid temperature (dT) and flow rate (q). The heat transfer from the test section to the surroundings, which occurred when liquid temperature was higher than ambient room temperature, would cause the measured dT to be too low. The result would be a calculated value of q which is higher than the actual or calibrated value. This, in fact, was the case with both Water-48 and Panasol as can be seen by Table V. The percent error means for Malathion do not agree with this hypothesis, which indicates that some other temperature-related parameter must account for some of the effect of temperature on accuracy.

The theory upon which this electrocaloric flowmetering system was based includes no consideration of liquid viscosity. It was assumed that the viscosity of the liquid does not appreciably affect the heat transfer from the heater to the liquid. This assumption is better for flow where a high degree of turbulence about the heater exists than for the case where flow is laminar. The nature of the flow is governed by the Reynolds Number of the flowing liquid which is inversely related to the liquid viscosity and hence to the liquid temperature. From this

TABLE V

PERCENT ERROR MEANS AS A RESULT OF EACH TEST CONDITION FOR WATER-48, MALATHION, PANASOL, AND WATER-40

Test Condition[a]	Water-48	Malathion	Panasol	Water-40[b]
A_1B_1	+ 8.5[c]	+22.6	- 5.1	
A_1B_2	+ 9.3	+23.1	+ 6.6	
A_1B_3	+16.6	-37.0	+31.3	
A_1B_4	+22.5	+89.2	+65.3	
A_2B_1	+ 5.9	- 9.1	+ 4.9	
A_2B_2	+ 5.9	-12.2	-11.5	
A_2B_3	+10.1	- 5.0	+ 7.6	
A_2B_4	+13.3	-10.6	+ 9.9	
A_3B_1	+ 3.5	-30.0	- 4.5	
A_3B_2	+ 3.4	-29.1	+ 5.2	
A_3B_3	+ 8.1	-29.2	+10.1	
A_3B_4	+ 7.9	-27.4	+ 8.1	
A_4B_1	+ 8.3	-20.9	+ 3.0	
A_4B_2	+ 7.6	- 8.4	+ 3.0	
A_4B_3	+ 2.2	- 4.1	-17.3	
A_4B_4	+ 4.1	- 7.7	+ 1.5	
A_1				-6.2
A_2				+5.0
A_3				+4.6
A_4				-3.8

[a] A signifies liquid flow rate level, and B signifies liquid temperature level. Subscripts on A signify the following: 1, 50cc/min; 2, 200 cc/min; 3, 350 cc/min; and 4, 500 cc/min. Subscripts on B signify the following: 1, 70°F; 2, 85°F; 3, 100°F; and 4, 115°F.

[b] Liquid temperature held constant at 75°F (ambient room temperature).

[c] Means preceded by a + are those for which the average calculated flow rate was greater than the average calibrated flow rate. Means preceded by a - are those for which the reverse was true.

it follows that the significance of the effect of temperature on accuracy could be due in part to viscosity changes of the liquid.

In order to calculate Reynolds Number at each test level, it was necessary to know the corresponding viscosities of the three liquids being tested. The viscosity of water was available, but the viscosity of Malathion and Panasol had to be measured. A MacMichael viscosimeter with an uncertified 32 gauge wire was used to make these measurements. The wire was calibrated through the use of a water standard at a viscosity of 1.00 centipoises, a disc plunger, and a 185 milliliter sample cup. The viscosimeter thus equipped gave a high degree of precision in the viscosity determinations. The measured absolute viscosities of Malathion at 70, 85, 100, and 115°F were 41.03, 32.43, 25.43, and 20.20 centipoises, respectively. The corresponding values for Panasol were 15.57, 14.10, 12.67, and 11.40 centipoises, respectively.

The velocity of the liquid was calculated at the inlet to the test section heater for each of the flow rates, and Reynolds Numbers were calculated for each test condition. The IBM 7040 digital computer was used to perform linear correlations of liquid viscosity, velocity, and Reynolds Number to percent error for each set of tests and all the tests combined. The correlation coefficients for each separate correlation are listed in Table VI.

There was not a significant correlation of liquid viscosity to percent error at the 95 percent probability level for any of the individual tests. This indicates that for a given liquid and flow rate

TABLE VI

CORRELATION COEFFICIENTS BETWEEN PERCENT ERROR MEANS AND LIQUID VISCOSITY, VELOCITY, AND REYNOLDS NUMBER FOR WATER-48, MALATHION, PANASOL, WATER-40, AND COMBINED TESTS

Parameters Correlated to Percent Error Means	Tests from Which Means Taken				
	Water-48	Malathion	Panasol	Water-40	Combined
Viscosity	-0.3906	-0.1992	-0.2103	0.0000	0.3094*
Velocity	-0.6409*	-0.4411	-0.4659	-0.9812*	-0.3830**
Reynolds Number	-0.5777*	-0.4169	-0.4274	-0.9811*	-0.3071*

*Denotes significance at the 95 percent level of probability or greater.

**Denotes significance at the 99 percent level of probability or greater.

level, differences in viscosity resulting from the different temperature levels had less effect on experimental error than did some other facter, such as might be the differences in heat transfer at the different temperature levels. This is especially notable since the correlation coefficients are negative which means that percent error tended to be lower (accuracy was higher) at the higher viscosities (lower temperatures). However, a positive correlation coefficient was calculated for the combined tests that was significant at the 95 percent level of probability. The positive correlation means that for the viscosity range within the combined test (0.599 centipoises for water at 115°F to 41.03 centipoises for Malathion at 70°F) percent error increases significantly with liquid viscosity.

Reynolds Number, a function of liquid viscosity and thereby liquid temperature, was found to have a significant negative correlation with percent error in both of the water tests and in the combined tests. The ranges of Reynolds Numbers for Malathion, Panasol, and water were 3.3 to 67.7; 6.9 to 93.7; and 113.4 to 1856.8, respectively. From this it is seen that Reynolds Number produced a significant effect on percent error in the tests where a wide range of Reynolds Number existed. It is difficult to predict the Reynolds Number above which flow became turbulent about the test-section heater due to its irregular design. However, it is probable that it was less than the value of 2100 required to produce turbulence in regular pipe flow (16), and that turbulent flow existed in some of the tests in this study.

Liquid Flow Rate

Liquid flow rate had a significant effect on flowmeter accuracy at the 95 percent level of probability in each split-plot arrangement of treatments. However, it did not show significance for Water-40.

The Duncan's Multiple Range Test (Table VII) showed that for each of the tests in which flow rate was significant, significantly better flowmeter accuracy was obtained at flow rates of 500, 350, and 200 cubic centimeters per minute (cc/min) than at 50cc/min. For the Water-48 and the Panasol, the three higher rate levels were not significantly different from each other, but accuracy tended to increase with flow rate. In the Malathion tests, however, significantly better accuracy was obtained at flow rates of 200 and 500 cc/min than at 350 cc/min.

The correlation coefficients of liquid velocity to percent error for Water-48 and Water-40 were significant at the 95 percent probability level, and the same correlation for the combined test was significant at the 99 percent probability level (Table VI, page 48). Since liquid velocity was directly proportional to volume flow rate in all the tests, this correlation applies in the same way to volume flow rate. The negative correlation indicates that for a given volume flow rate, flowmeter accuracy can be improved by reducing the cross-sectional area of the conduit and increasing the liquid velocity.

Flow Rate x Liquid Temperature

The analyses of variance also showed a significant two-way interaction between flow rate and liquid temperature in each of the split-plot

TABLE VII

EFFECT OF LIQUID FLOW RATE ON FLOWMETER ACCURACY FOR WATER-48, MALATHION, AND PANASOL

Liquid and Flow Rate	Percent Error Means	Significance[a]
Water - 48		
500 cc/min	5.57	a
350 cc/min	5.75	a
200 cc/min	8.79	a
50 cc/min	14.22	b
Malathion		
200 cc/min	9.21	a
500 cc/min	10.28	a
350 cc/min	28.42	b
50 cc/min	42.98	c
Panasol		
500 cc/min	6.19	a
350 cc/min	6.98	a
200 cc/min	8.50	a
50 cc/min	27.10	b

[a]Means followed by the same letter are not significantly different at the 95 percent level of probability.

treatment arrangements. This significance points out that the different levels of each treatment did not respond in the same manner to the different levels of the other treatments. In general, beneficial interpretations of significant interactions are difficult to make (26). The problem is further complicated here because of the separate effects of liquid temperature on heat transfer with the system surroundings and of temperature on liquid viscosity.

System Accuracy and Variability

Standard deviations and overall mean percent errors between theoretical and calibrated flow rate were determined for each set of tests and all the tests combined. The overall means provide a measure of the accuracy of the electrocaloric flowmeter, and the standard deviations provide a measure of the variability of the treatment means from the overall means. These values of the overall means and the standard deviations are as follows:

	Water-48	Malathion	Panasol	Water-40	Combined
Overall Means	8.58%	22.85%	12.18%	4.90%	13.80%
Standard Deviation	5.23%	20.50%	15.38%	1.00%	15.73%

A comparison of the overall means and standard deviations for the two sets of tests conducted with distilled water indicates that operation of the system with liquid temperature different from room temperature may introduce considerable error and variation into the flow rate determination.

The system tested in this study performed satisfactorily for Malathion and Panasol at the rate of 500 cc/min and for Panasol at 350 and 200 cc/min as well. However, the magnitude of the errors obtained at the other flow rates showed that this system should probably not be used for Malathion, Panasol, or similar liquids at low rates in the 50 to 200 cc/min range. It is possible that a reduced cross-sectional area of the conduit with an increased liquid velocity, as previously suggested, might prove this flowmetering system feasible for these liquids at the volume flow rates tested.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Studies have shown that effective insect control can be obtained from applications of highly concentrated insecticides in the ultra-low-volume range of below 64 ounces per acre. One of the problems related to the ultra-low-volume application of insecticides is that of metering the rate of flow of the material from the sprayer.

An electrocaloric flowmetering system was designed, and a simplified version was constructed and tested. Close agreement with theory in the preliminary tests led to the redesign and construction of a refined electrocaloric flowmeter with which more extensive tests were conducted.

The tests were conducted with distilled water, Malathion, and Panasol at four levels of liquid temperature and at four flow rates. The levels of the two variables were arranged in a split-plot arrangement of treatments with flow rate treated as the main plot variable. A separate set of tests was conducted with distilled water to determine the magnitude of the error resulting from undesirable heat transfer through the system. The dependent variable used to measure the effects of the test variables was the error percentage between theoretical flow rate and calibrated flow rate.

Based on the data obtained from the testing of the electrocaloric flowmetering system the following conclusions were drawn:

1. The accuracy of the electrocaloric flowmetering system improves with increased liquid volume flow rate between the flow rates of 50 and 500 cubic centimeters per minute.
2. The accuracy of the system is adversely affected by increasing temperature differentials between the metered liquid and the system surroundings.
3. An inverse relationship exists between accuracy of the system and liquid viscosity for the range of viscosities from 0.599 to 41.03 centipoises.
4. Better flowmeter accuracy may generally be obtained with higher Reynolds Numbers of the metered liquid for the range of Reynolds Numbers investigated.

Further study and testing is necessary to determine the feasibility and practicality of the flowmetering system for ultra-low-volume sprayers. The writer recommends that other studies be conducted to determine more precisely the effect of liquid velocity, viscosity, and Reynolds Numbers on the accuracy of electrocaloric flowmeters.

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