A multiprobe miniature thermistor system for the measurement of temperature profiles

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A new instrument for the determination of fine temperature profiles in hot, corrosive, electrically conductive, unsteady two-phase fluid systems under vacuum or pressure is described. It features simultaneous measurement of temperatures at close locations, by a column of miniature (0.25 mm diam) thermistors mounted at the tips of supporting hypodermic tubes, and streamlined design that minimizes hydrodynamic and thermal disturbances at the measured locations. Some of the techniques used in the construction, such as the welding, insulation, and handling of fine wires (0.025 mm diam), are of interest in many other applications. The instrument has been used to measure temperature distributions with an accuracy of ±0.02°C in a model of a flash-evaporator stage used for the desalination of saline water, and thus provided new and quantitatively significant data about the process.

I. INTRODUCTION

The measurement of the distribution of a physical variable (such as temperature) by means of a traversing probe is not always satisfactory for at least two reasons: (i) The distribution of the measured variable may change during the time required for the performance of a set of measurements with the traversing probe; and (ii) the placement of the traversing probe at different positions may impose changes in the measured medium.

Both of these problems may be alleviated by the use of a stationary multiprobe sensor instead of the traversing probe. The sensor enables a simultaneous measurement by its different probes and its influence on the measured medium is unchanging.

During the investigation of flash evaporation and the associated heat transfer in a flash evaporator stage of a research flash distillation system for the desalination of salt water (Lior[1]), it was necessary to measure the temperature distributions in the liquid and vapor phases, with particular attention to the interphase boundary. A free-surface stream of saline distilland enters the stage through an inlet aperture, which in this case was a sluice gate (see Fig. 1). The vapor space pressure in the stage is lower than the saturation pressure corresponding to the temperature of the incoming salt water. The salt water, therefore, evaporates with a corresponding decrease in its temperature and the vapor is condensed to form the product. The brine leaves the stage through a second aperture.

The energy necessary for evaporation is supplied to the evaporating interfaces by heat transfer from the warmer bulk liquid. Since the total interstage temperature difference associated with flash evaporation is usually of the order of 1°C and not more than 3°C, the temperature distributions associated with the transport of heat are small and difficult to measure to an acceptable accuracy; an accuracy of 1%, for example, would require an absolute measurement accuracy of the order of 0.01°C. This difficulty is compounded by the fact that it is practically impossible to maintain a given steady state of the process within those limits for a sufficient length of time, and by the nature of the measured medium, which is a hot (up to about 120°C), corrosive two-phase fluid, under both vacuum and pressure conditions.

A multiprobe sensor was developed, constructed, and used successfully to determine the temperature distributions in-

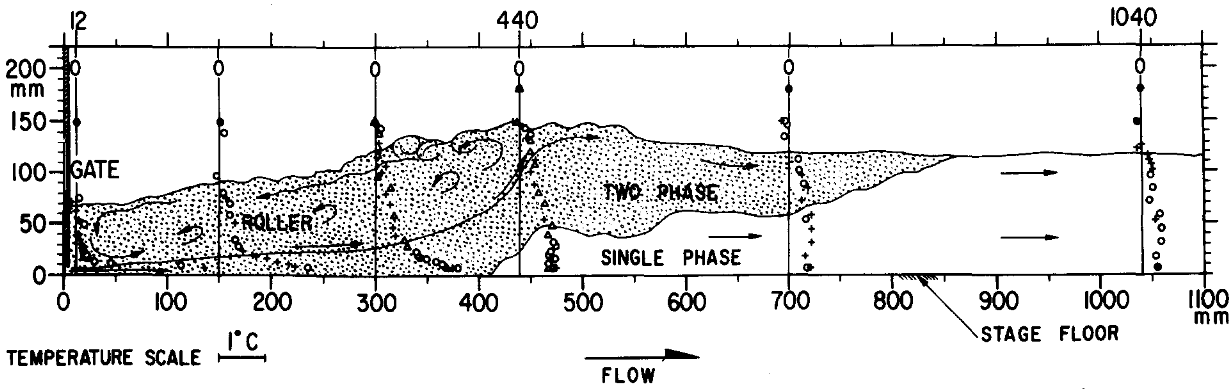

FIG. 1. Temperature distributions in flash stage, obtained with thermistor comb. At any one axial position, all symbols of the same type represent data obtained simultaneously and the horizontal displacements of all data points represent the temperature differences with respect to a reference (marked zero), situated at the highest elevation in the vapor space. Inlet stage temperature—99°C; Flow rate—1.9 kg/sec; Temperature flash-down—1.8°C; Average level—125 mm.

vestigated. It is suitable for a wider range of applications. The temperature-sensitive elements chosen are thermistors, mainly because of their high temperature sensitivity and availability in very small size. These advantages, as well as the significant improvements in their uniformity and stability, make their use increasingly widespread (e.g. Trolander *et al.*[2]). The particular units used were glass encapsulated, 0.25 mm diam bead thermistors with 0.025 mm, 90% platinum–10% iridium alloy leads. At 25°C, the nominal thermistor zero-power resistance is 100 kΩ and the temperature coefficient is −4.4% per °C.[3] The resistance at the highest experimental temperature used in this work is about 5 kΩ, still sufficient to render extension-lead effects on the temperature measurement negligible. These effects

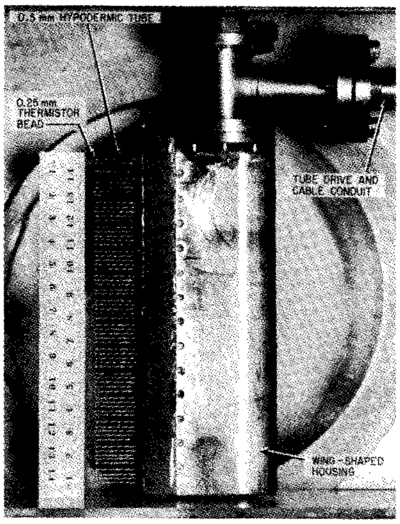

FIG. 2. Thermistor comb (in flash stage).

introduce measurement errors through asymmetry and variations of lead resistance (that are smaller than the total value of the lead resistance), which were evaluated to be <0.5Ω (or <0.01%) in resistance and <0.0025°C in temperature.

Each bead is mounted at the end of a 0.46 mm o.d. type 304 stainless steel hypodermic tube, which also serves as the conduit for the two thermistor wires. Sixty-eight such thermistor probes, spaced 1.75 mm apart on the average in the flash stage sensor, and thirty-six, spaced variously from 1.75 to 6.4 mm apart in the upstream (inlet) stage one, protruded 20 mm upstream from a streamlined, wing-shaped holder, as shown in Fig. 2. Due to some configurational similarity, the sensors were called "Thermistor Combs." This wing–hypodermic tube configuration minimizes the effects of the sensor assembly on the fluid at the thermistor beads.

All the thermistor lead wires were soldered to a terminal board secured inside the hollow wing. Gauge 22 Teflon-insulated extension wires were soldered to the same board and conducted through a 19 mm o.d. type 316 stainless steel tube, where their second end was soldered to a multipin hermetic connector. The tube served also to position the comb manually at any desired location along the stage. The tube slides in and out of the stage through a reciprocal-motion seal and bearing assembly, guided by a carriage running on four stainless steel bearings inside horizontal grooves machined in the walls of each stage (Fig. 3).

The sealed space formed by the hollow wing, the 19 mm stainless steel tube, and the cylinder mounting the hermetic connector was automatically maintained at a pressure about 0.05 bar above that of the ambient stage pressure. This deters fluid seepage into the comb through possible imperfections and helps to detect any leaks that might occur in this sealed space.

Since the techniques and materials involved in the construction of the comb resulted from careful and lengthy development and are generally applicable in the building of miniature instruments, a brief description of the major steps follows. The complete details are available elsewhere.[4]

II. MAJOR CONSTRUCTION FEATURES

The thermistor beads were supplied by the manufacturer with leads only 8 mm long. Extension wires of the same diameter and alloy as the thermistor lead wires were joined by lap welding with a stored-energy electric discharge welder. The extension wires were preannealed to eliminate their springiness and to improve weldability. Annealing was accomplished by the passage of a regulated direct current through the wire. The current was gradually increased to 0.36 A, maintained there for about 2 min, and then gradually decreased to zero.

The wires were welded with molybdenum-base electrodes, machined down to a tip diameter of approximately 0.6 mm. The force applied during welding was 10.8 N. To minimize the kinking of the wires at the weld, which would have substantially complicated their subsequent coating and threading through the tube, they were overlapped on the electrode as close to a straight line as possible. The brittleness of the resulting welds made reannealing necessary. The remaining wire stubs were trimmed off close to the weld. The joints produced by this method are strong and almost of the same

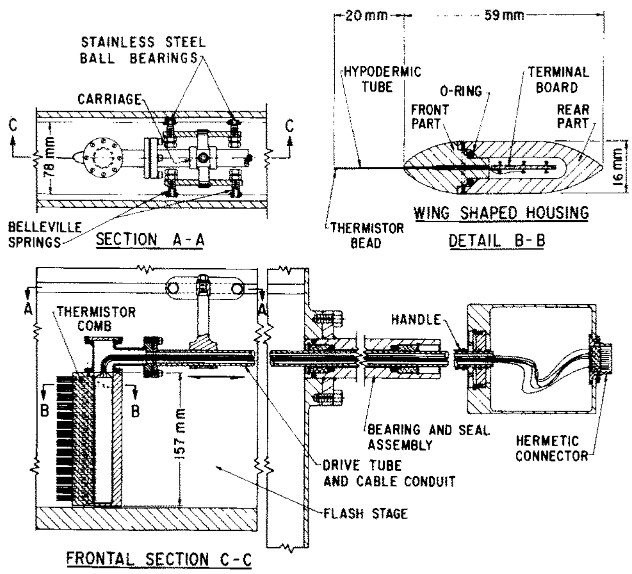

FIG. 3. The thermistor comb and carriage assembly.

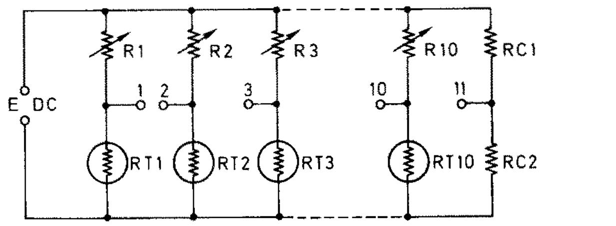

FIG. 4. System of bridges for absolute and differential measurements. R1–R10—Variable resistors; RT1–RT10—thermistors; RC1, RC2—fixed resistors (matched pair).

diameter as the wire. In practically all cases when the wire did break, the fracture was not at the joint.

The thermistor lead wires had to be electrically insulated from each other and from the hypodermic tube through which they passed. The insulation had to retain its properties when exposed to temperatures up to around 100°C even when exposed to brine (in case of brine seepage into the tubes), and had to be flexible.

The major difficulties in the development of the insulation process consisted of the handling of the thin and fragile wires, the occurrence of substantial beading of the insulating materials, and incomplete insulation, which left some wire areas bare.

The method developed that gave satisfactory results consisted of ultrasonic cleaning, followed by dip coating in Isonel 31 varnish (a modified polyester),[5] after the recommendations by Marg[6] and Fowlis.[7] The dipping was performed by gradual immersion and withdrawal at a rate of 1–2 cm/min by means of a simple water-float apparatus designed for that purpose.

About 15 such coats were needed. The varnish was overcoated with four layers of an epoxy[8] to improve resistance to water. The total insulation thus obtained has a uniform thickness of about 0.012–0.025 mm, and test samples had an electric resistance larger than $1.5\times10^{9}\ \Omega$ after immersion for one week in nearly boiling concentrated KCl solution.

A wire puller was made from a length of 0.2 mm o.d. hypodermic tubing, which passed through the thermistor support tube. The two wire ends were bonded into the prebeveled end of the wire puller with rapid curing cyanoacrylic adhesive, and finally threaded through the hypodermic tube by using the "wire-puller" as a guide.

The thermistor bead was bonded onto the end of the tube with an epoxy adhesive.[9] The electric resistance between the two wires and the tube was found to be above $1.5\times10^{10}\ \Omega$ after curing. Samples of the bonded probes retained a resistance greater than $10^{9}\ \Omega$ after immersion for about two months in a concentrated 90°C NaCl solution.

The other end of the thermistor tube was inserted into a tight fitting hole in the front part of the wing-shaped housing and bonded to it with the same adhesive. The thermistor comb was then assembled, dip coated with four coats of an epoxy varnish and mounted on the carriage (Figs. 2 and 3).

III. TEMPERATURE MEASUREMENTS

The resistance of the thermistors was determined by ten dc Wheatstone bridges. The output of each bridge was conditioned and recorded on a 12-channel oscillographic recorder. Thus, the temperature of any ten thermistors could be measured simultaneously. Each bridge could be connected to any thermistor by means of a patch cord system. Two groups of ten thermistors usually provided sufficient data on both sides of the liquid–vapor interface.

Essentially, the measuring circuit consisted on one reference and nine differential bridges (Fig. 4). The bridge output voltages 1–2, 1–3, $\cdots$, 1–10 were measured so that each of the nine thermistors (RT2–RT10) was balanced against one single thermistor (RT1). Any one of the thermistors in the system could be chosen as the reference. The reference thermistor itself was measured by bridges 1–11 and its temperature was thereby determined.

To maximize the bridge sensitivity at balance, and to minimize the load imbalance at the input of the signal conditioning amplifier, an equal-arms differential-bridge system was selected. Thus, RC1 = RC2 = [average thermistor resistance in experimental temperature range] and at balance R1 = RT1, R2 = RT2, etc. Note that all thermistors are of approximately the same resistance, also R1 $\approx$ R2 $\approx$ R3 $\approx \cdots$. To further reduce common mode and loading effects on the devoted amplifiers, which could be significant due to the relatively high resistance of the thermistors and their high temperature sensitivity, a differential amplifier with high input impedance, high common mode rejection, and low input bias current has been selected and further modified.[10] The frequency band width of the system was limited by the oscillographic galvanometer to 0–15 Hz (flat within $\pm5\%$). Since practically all of the noise in the system was 60 Hz, the galvanometer also acted as an effective noise filter, to obtain a terminal signal-to-noise ratio of better than ten at the operational accuracy level of ±0.02°C.

The dc excitation voltage E was experimentally determined to limit self heating in the thermistors to less than 0.01°C under the worst external conditions, obtained by immersion into vapor at the highest experimental temperature (lowest resistance) and vacuum ($\approx$0.03 bar). This voltage was found to be 0.38 V. The high sensitivity of the temperature measuring system allowed the maintenance of this voltage throughout the experimental range of temperatures.

All thermistors were preaged. The thermistor combs were individually calibrated *in situ* by their total immersion in constant-temperature nonflashing water circulating through the flash evaporator. Two secondary standard thermistor probes, one for each stage, were traversed vertically 2–3 mm upstream of the comb and served as the temperature

FIG. 5. The thermistor comb during measurement in the flash stage. Temperature of inflowing stream—78.6°C; flow rate—2.5 kg/sec; Temperature drop of stream in stage (flash-down)—0.3°C; average level—110 mm.

reference. These secondary standards were, in turn, calibrated in an oil bath (0.01°C) in which the reference was a platinum standard thermometer measured on a Mueller bridge.

The thermistor comb during measurement in flashing water is shown in Fig. 5. Three consequential facts indicated that the comb did not significantly alter the flashing process: (i) the distillate production rate of the stage did not vary with the position of the comb; (ii) the bow wave resulting from the wing-shaped housing of the comb always appeared downstream from the thermistor bead (in other words, the bead was outside the area influenced by the housing); and (iii) no change in bubble nucleation rate has been visually observed in liquid regions into which the comb was placed.

Temperature distributions during one of the runs, obtained with the thermistor comb at six axial locations in the flash stage, are shown in Fig. 1. Of particular significance is the fact that the differential measurement with the comb determines directly the thermal driving force for evaporation, namely, the difference between the temperatures of the liquid and the vapor. This difference also determines the local approach of the evaporating supersaturated liquid to equilibrium, and thus estimates the efficiency of the flash stage. The measurement also determines directly the temperature gradients in both phases and across the phase interface, which, in turn, are indicative of the rate of heat transport.

Supported by the experimental results, of which Figs. 1 and 5 are a part, and by research performed elsewhere (Gilbert *et al.*,[11] Catalytic Co.[12]), it has been concluded that the flow in the flash stage consists of two principal regions: submerged sluice gate flow with the associated hydraulic jump overlaid by a backflow roller, followed by open channel flow. The first regime consists of a two-phase mixture, with bubbles most prominent in the roller, and exhibits a large degree of turbulence. The superheated wall jet emerging from the interstage gate expands into the colder roller, until it meets the free surface. The liquid emerging downstream of the hydraulic jump, in the open channel region, is well mixed, contains few bubbles, and is essentially at a uniform bulk temperature. The liquid proceeds to evaporate mainly from the free surface with a corresponding steep temperature gradient at this interface.

The "thermistor comb" proved to be an excellent tool for the determination of temperature distributions in the liquid and vapor phases of evaporating fresh and saline water in a flash evaporator and, conceptually, could be very useful in other applications that have similar constraints, such as the measurement of thermal mixing (as in warm effluents, for example) and the investigations of natural convection. In the flash evaporation experiments described, the sensor has helped to shed new light on the process and to give quantitative support to some previous qualitative observations.

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