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A SYSTEM FOR THE EXPERIMENTAL STUDY OF FLASH EVAPORATION

NOAM LIOR AND RALPH GREIF

University of Pennsylvania, Philadelphia, Pennsylvania 19104, and
University of California, Berkeley, California 94720

SUMMARY

The performance of meaningful experiments on heat, mass and momentum transport phenomena during flash evaporation in water desalination Multi-Stage Flash units requires careful design and construction of the experimental apparatus due to the very small thermodynamic driving potentials and the generally hostile nature of the fluid. The paper describes the design philosophy and considerations utilized in the construction of a two-stage scaled-down model of a flash evaporator, and the instrumentation and techniques developed or adapted for the measurement of temperature, pressure, flow, level and salinity, and for the visualization of the flow.

INTRODUCTION

To perform meaningful measurements of heat transfer, mass transfer and fluid mechanics phenomena in systems typical to multi-stage flash desalination equipment, careful consideration needs to be given to the process characteristics which have an important interaction with the measurement technique and instruments.

The major of these characteristics are the small driving thermodynamics potentials (such as small gradients of temperature, pressure and concentration) implemented due to economic considerations, and which are hard both to maintain constant and to measure; the mode of evaporation, which includes surface evaporation and bulk nucleation and which is influenced by the placement of measuring probes, by noncondensables and by surfactants; the existence of two phases (vapor and liquid) in a turbulent flow, which complicates measurements significantly; the heat and mass transfer in the bulk, between the liquid and the many evaporating interfaces, typified by sharp temperature and salt gradients in very thin layers near these interfaces, and by rather nonuniform temperature and concentration profiles; the local and overall dynamics of the process, namely, fluctuations of the same order of magnitude as the parameter's average magnitude, as well as overall instabilities due to the two-phase, free-surface nature of the flow which is highly sensitive to condenser temperature, noncondensables and effect of immersed instruments; transport in the vapor space from the flashing liquid to the condenser, which includes convection and diffusion of vapor and noncondensables and the effect of obstacles on their flow; the fairly hostile environment composed of brine and distilled water and which is corrosive, scaling and fouling; and the need to sustain both vacuum and pressure in the operating temperature range of MSF units, requiring a well-sealed vessel to prevent infiltration of air and exfiltration of vapor and noncondensables.

The experimental apparatus which was designed and built based on the above considerations, and which was used successfully in extensive experiments (1), is described below.

GENERAL DESCRIPTION OF THE EXPERIMENTAL EQUIPMENT

The experimental research system consists of a scaled-down model of one stage of a horizontal flash evaporator with nonflashing inlet stage (Figs. 1, 2). The stages are channels of rectangular cross section, 78 mm wide and are separated by an adjustable sluice gate which forms a full width rectangular flow orifice between them. The flash stage is connected by means of a full-width-and-length 75° elbow to a full-length condenser. This arrangement provides a uniform and direct path for the evolving vapor so that visual as well as experimental examination of the vapor-liquid interface may be carried out.

The whole flash evaporator assembly is mounted on a steel stand which is supported on a bearing block at one end and can thus be tilted to provide various flow-slopes for the evaporator. The piping connected to the evaporator is flexible in the region near the fulcrum so that the slope can be readily changed. The flexible joints in all piping connected to the flash evaporator are also designed to prevent the transmission of vibrations which would have interfered with the sensitive measurements performed in the system.

The flow system (Fig. 3) is a closed loop with an independently cooled condenser. The flashing liquid is circulated by the main pump and is heated to a constant temperature by the vertical, steam-heated heat exchanger. It then enters the inlet stage and flashes in the flash-stage before returning to the circulation pump. The flashed-off vapor condenses in the main condenser* and the resulting distillate

*The condenser consists of nine 5/8" O.D. U-tubes in a shell (all 70-30 copper-nickel alloy), 4 ft long. The total heat exchange area is 11 ft^2.

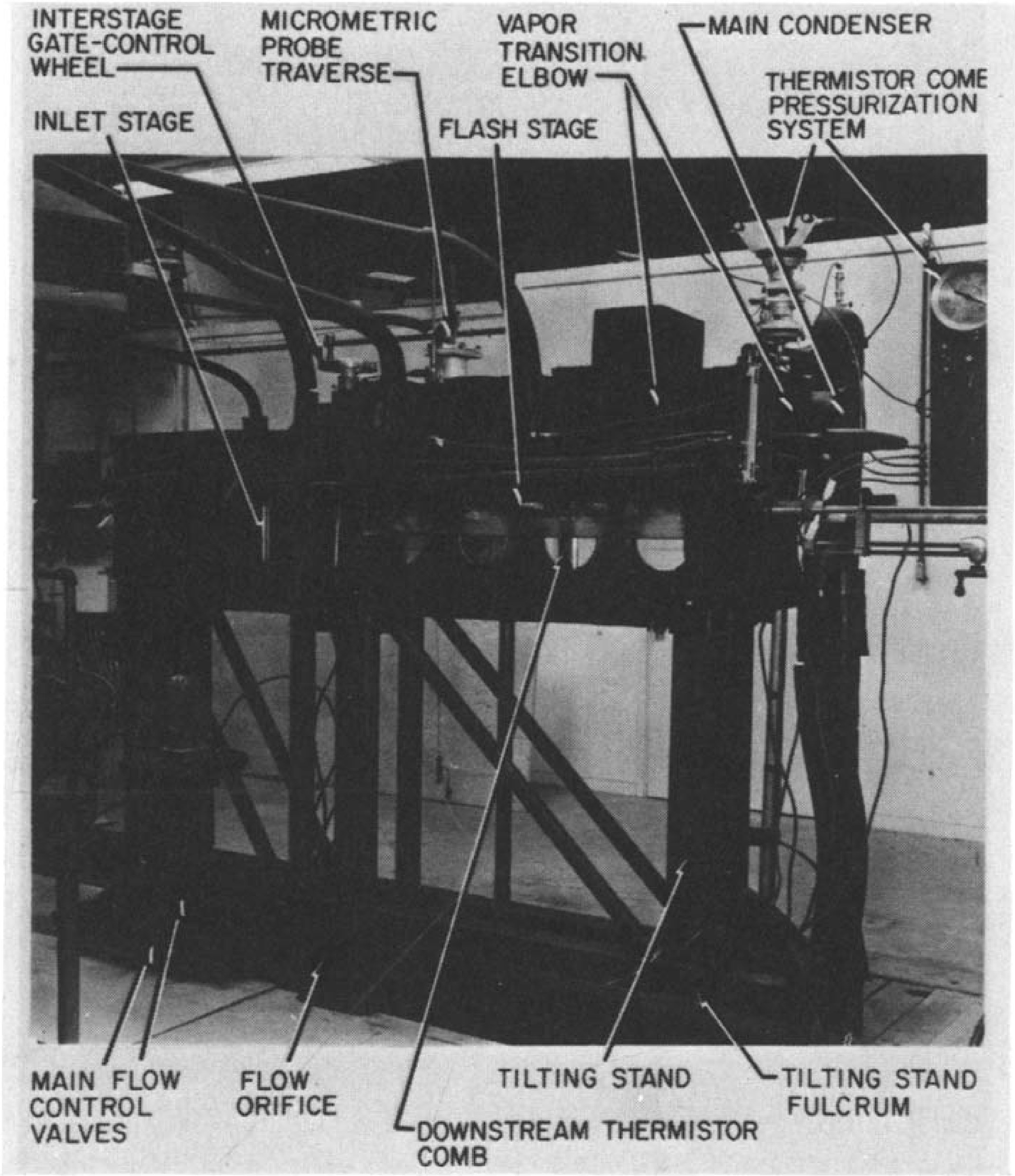

Fig. 1. The flash evaporator

flows by gravity to a distillate collection and measurement system. It is then pumped back to the suction side of the main circulation pump. The main condenser is cooled by city water, the coolant loop incorporating a cooling tower which is available when larger quantities of coolant are needed. The whole flow-system is thermally insulated.

Large and numerous glass windows enable good visual observation of the process. In addition, temperatures, pressures, flow rates and salinities are measured at multiple locations throughout the system. These are noted in the flow diagram (Fig. 3) and are described below in more detail.

In particular, each evaporator stage is equipped with a wing-shaped sensor containing closely spaced miniature hypodermic needle thermistor thermometers. Due to some configurational simililarity, these sensors are referred to as "thermistor

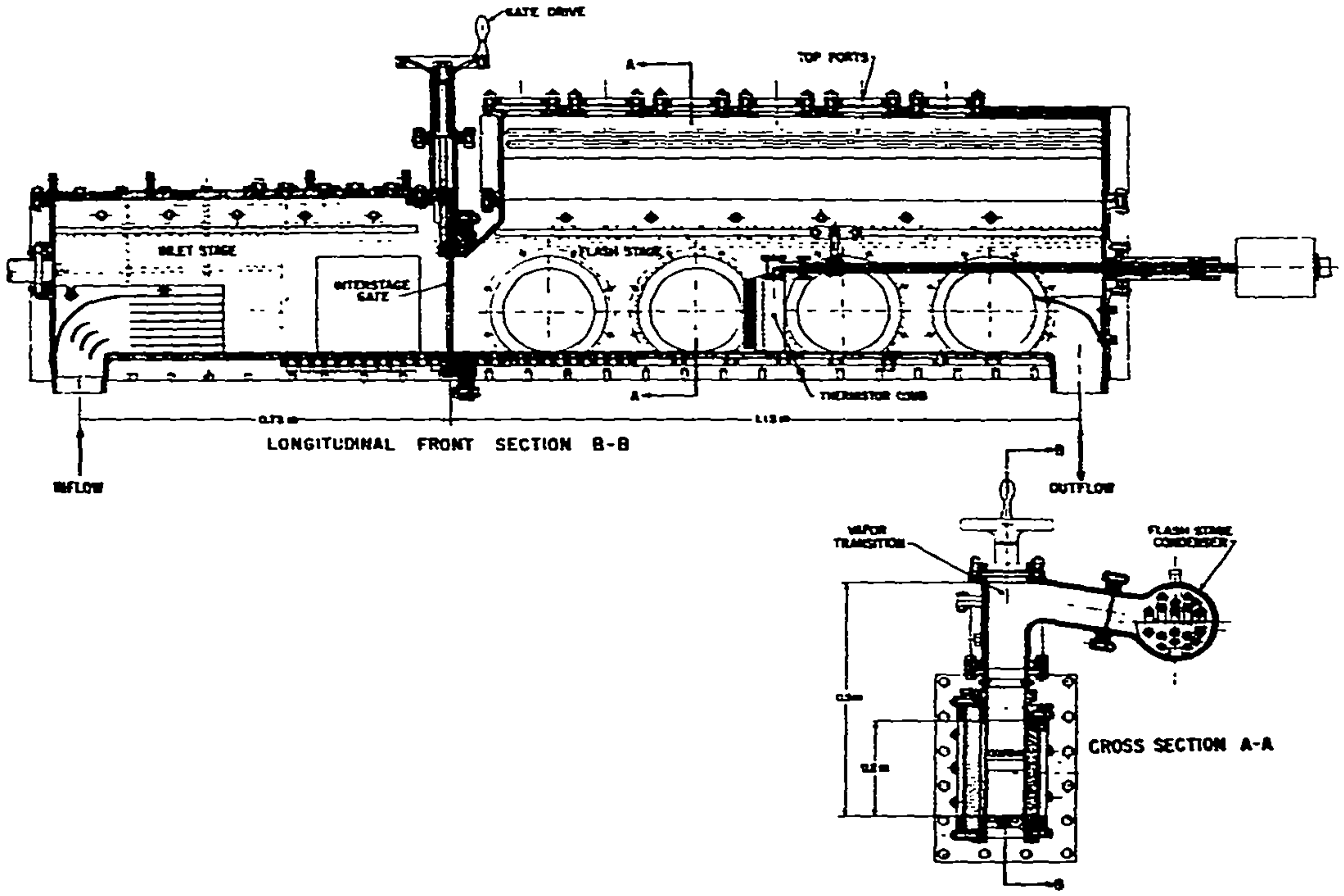

Fig. 2. Cross-sectional views of the flash evaporator

combs". They provide temperature measurements of high accuracy along a line vertical to the stage floor, in both the liquid and vapor regions. They can be moved in the axial direction along each stage.

Practically all demountable seals in the system are groove-confined O-Rings from ethylene-propylene elastomer. All seals for reciprocal motion (such as in traversing instrument probes) are elastomer O-Ring loaded Teflon rings.

The flash evaporator system has been designed to operate from 0 to about 2 Bars, which enables flashing from about ambient temperature to 120°C. The flow rate through the evaporator can be varied and precisely measured from about 0.063 to 6.3 liters/second (1 to 100 gpm). The system has been designed for operation with flashing liquid levels up to about 100 mm, but levels of us to 200 mm can be accommodated. The level is changed by adding or withdrawing liquid from and to a holding tank.

The vertical heater has sufficient area to supply the heat required for all practical flashing rates at all the flow and temperature conditions described above. Its effective heat transfer area can be varied by adjustment of the condensate level in the shell.

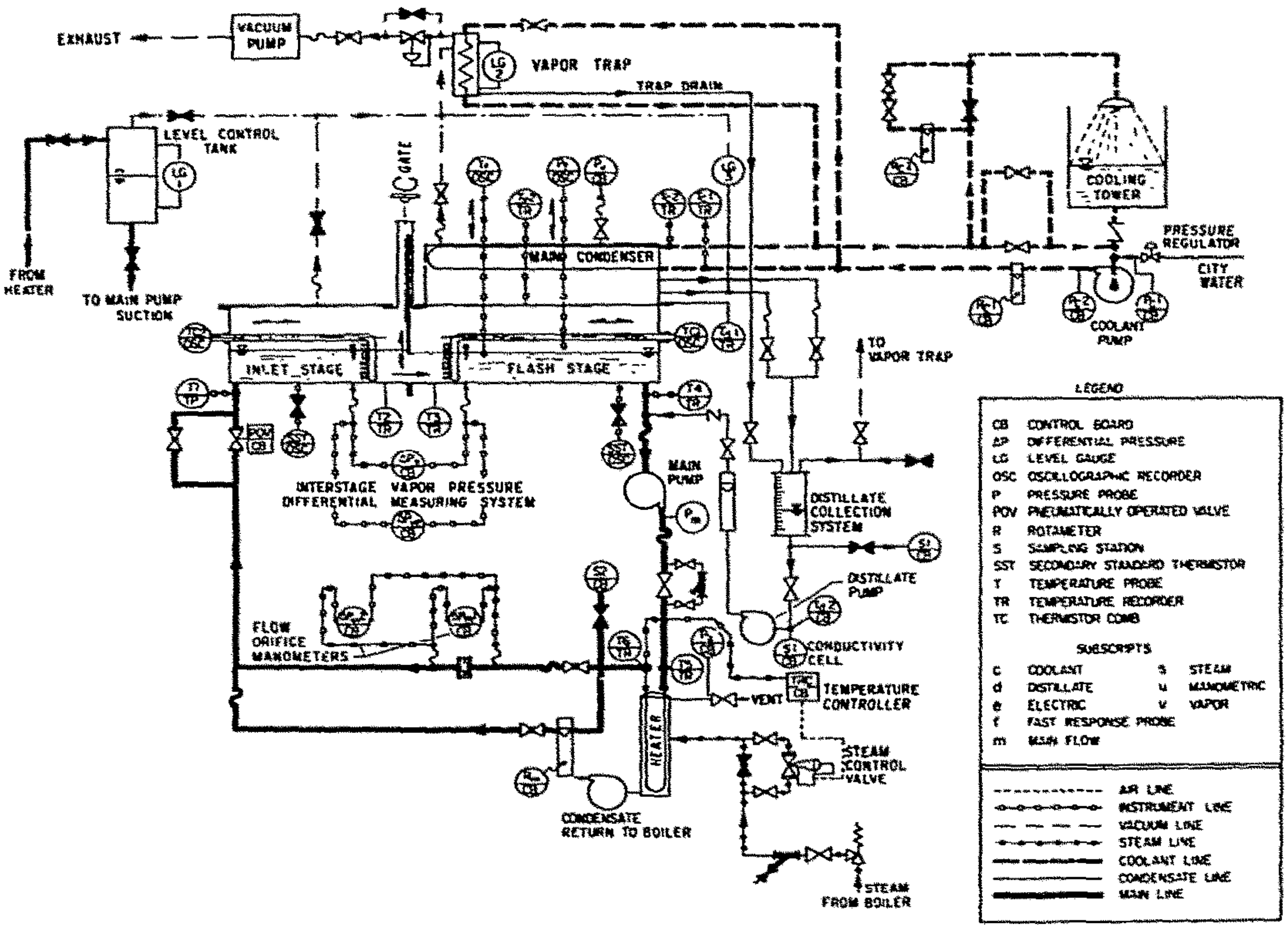

Fig. 3. Flow diagram

Throughout the design and construction, care was taken to make the system corrosion resistant so as to avoid contamination of the fluid as well as damage to instrumention.

The controls are essentially concentrated on one board (Fig. 4)) thus enabling one person to operate and monitor the whole apparatus. Most of the precise electronic measuring components are assembled on a single, wheel mounted cabinet.

THE FLASH EVAPORATOR

Both stages and the vapor-transition elbow were cast from 70-30 copper-nickel alloy. The condenser and most of the piping were fabricated and welded from the same allcy. The castings were arc-welded with a 70-30 copper-nickel rod. The castings, particularly in the areas in the vicinity of the welds, were quite porous and had to be impregnated. Remaining porosity has been locally sealed with silicone

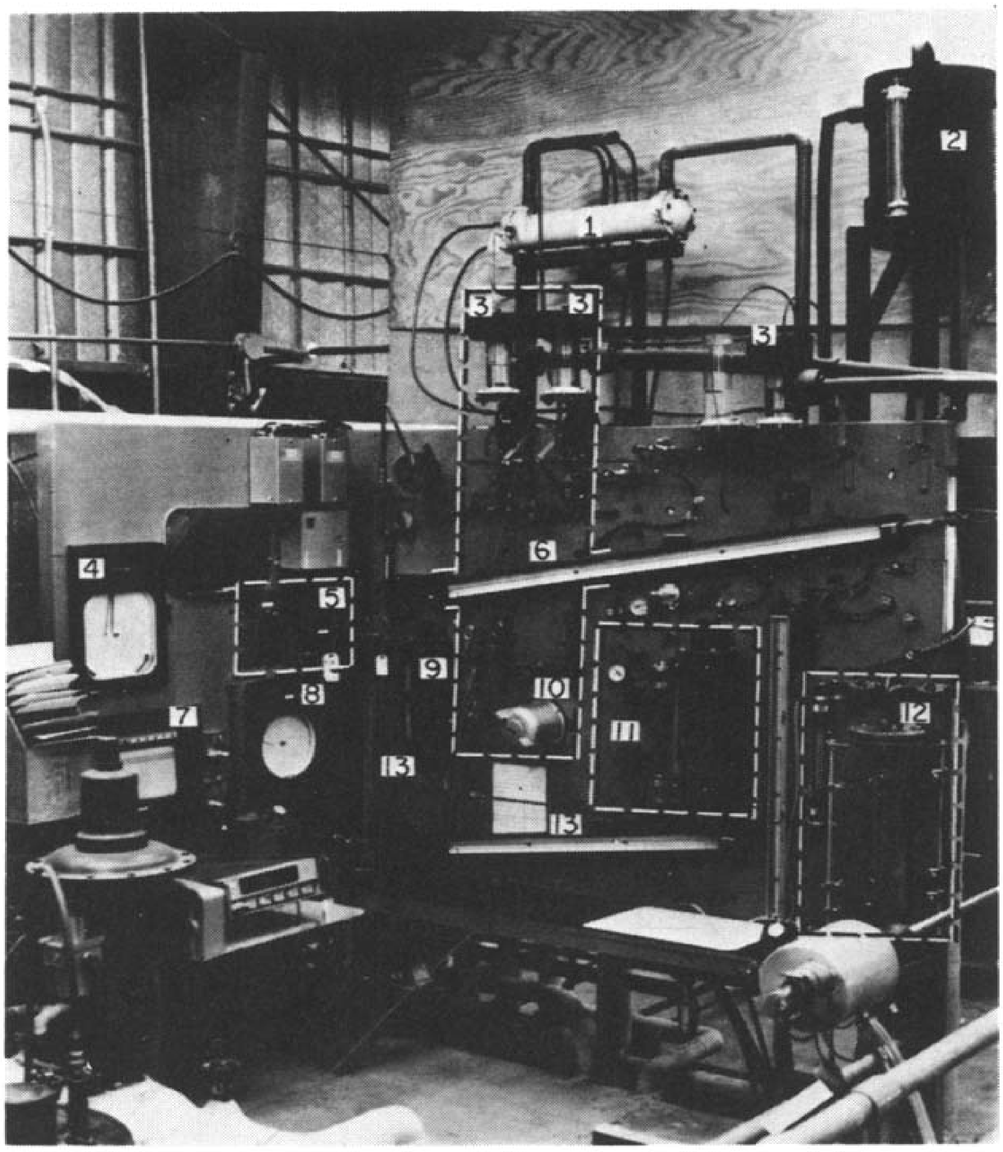

Fig. 4. The control board

(1) vacuum pump vapor trap (2) holding tank for level control (3) vapor manometer condensate pots (4) temperature controller/recorder (5) conductivity measurement and alarm (6) interstage vapor ΔP manometer (7) ΔP & ΔT recorder (8) 12 pt. thermocouple temperature recorder (9) low range, main flow rotameter (10) interstage ΔP electronic transmitter (11) condenser coolant measurement and control (12) distillate collection system (13) main flow orifice manometers.

rubber adhesive/sealants until leaks under full vacuum were reduced to about 2 cmHg per 12 hours for the whole system. Parts fabricated and welded from rolled copper-nickel plates have shown no porosity.

The length of the inlet stage is 0.730 m. This was determined to provide, in combination with flow straightening vanes (at this stage's inlet) sufficiently uniform flow at the inlet to the flash-stage. The length of the flash stage is 1.129 m. This length is made up of the estimated stage length necessary for flashing under extreme conditions, and has been determined by Richardsons-Westgarth & Co. (2) formula to be about 0.4 m, plus about 10 hydraulic diameters to reduce the effects of the stage discharge configuration on the flow in the flashing region. A flow-directing vane at the stage exit guides the liquid out.

The evaporator was thermally insulated and the measured heat loss to the surroundings (by means of a heat flux meter) never exceeded 3% of the total evaporative heat transfer.

Both stages are equipped with large glass* windows on both sides and top. The glass in the sides of the stages has been mounted so that the sides form a continuous surface, without steps (Fig. 2). This has been achieved by having the round glass windows beveled and by bonding a rectangular glass insert onto the inner side of the rectangular windows, thus filling-in the cavity created by the metal frame supporting the window.

To obtain both adequate thermal insulation and continous visual access, plexiglass plates are mounted at some distance in front of the windows. The circumference of the plexiglass plates is pressed against the plastic foam (which insulates the rest of the evaporator) and the resulting sealed air layer provides the necessary thermal insulation. The plexiglass plates serve also as safety shields for the possibility of window breakage. None of the windows broke throughout the experiments.

The continuously adjustable gate separating the stages creates a vapor seal between them by means of an elastomer O-ring backed Teflon seal along its two sides and the top. Numerous instrument access ports are available in the flash evaporator assembly and in the process line.

PROCESS DESCRIPTION (FIG. 3)

Main loop

Upon discharge from the main circulation pump, the main liquid stream is bypassed, either partially or fully, through a filter with 5μ elements, and then enters the steam-heated main heat exchanger. The temperature of the liquid at the exit is controlled by an automatic temperature controller which pneumatically operates the positioner of the steam control valve. The liquid capacity of the oversized heater provides the system with satisfactory control dynamics, and the constancy of the controlled system temperature had been observed to be within ±0.25°C of the set point (and usually better), this being within the performance limits of the controller itself. The flow rate is controlled manually with a parallel combination of a larger, remotely operated, valve (POV) and a smaller valve.

Product (distillate) loop

The distillate forming in the main condenser flows by gravity to a collection-and-

*All windows were made from HERCULITE Brand (Pittsburgh Plate Glass Co., One Gateway Center, Pittsburgh, PA 15222) tempered plate glass. The rectangular windows are 1-1/4" thick, the 4 in. diameter windows at the top are 1/2" thick, and the 8 in. diameter windows in one side are 1 in. thick.

measurement graduated glass vessel, the vapor space of which is connected to the vapor space of the condenser. The distillate collection rate is measured in that vessel with a stop watch. The overall accuracy is ±1% of the measured flow rate. The vessel is equipped with a sampling system for the distillate. The conductivity and the temperature of the distillate are continously measured at the exit from the vessel. The level of liquid in the collection vessel is maintained within specified limits by a photoelectrically activated controller which turns the distillate pump on and off. For more detail see (3).

The coolant system

The temperature and flow rate of coolant through the main condenser are the major factors that determine the vapor pressure in the flash stage, and thereby, the amount of flash-down. This explains the need to control these variables precisely, a fact which has been amply confirmed during the actual experiments.

Due to economic reasons, the control system was essentially manual. City water was piped through a water-pressure regulator to the suction side of the coolant pump. It was then pumped through a rotameter (R_c1) through the condenser. Most of the coolant was recirculated by the pump and the rest measured with a rotameter (R_c2) and either dumped or circulated through a cooling tower from which it was returned to the system.

The fact that small quanitites of ambient-temperature coolant are mixed with much larger quantities of hotter, recirculating, coolant provides sensitive condenser control. The coolant recirculation loop is thermally insulated. The pump discharge rate obtained is constant and so, essentially, is the city water temperature. Consequently, once the valves are set, both coolant temperature and flow rate attain stable state.

The vacuum system

The vacuum system evacuates the noncondensable gases from four vessels: the inlet stage, flash stage condenser, level control tank and distillate collection vessel. This is performed with a mechanical vacuum pump which maintains, by means of a vacuum regulator, a constant vacuum in the vapor trap installed between it and the system. The four vessels are connected separately to the vapor trap with needle valves. All vacuum lines are monotonically graded to insure condensate drainage and prevent liquid locks. The trap drains the condensate by gravity into the distillate collection vessel, thus insuring that all distillate is measured.

FLOW INSTRUMENTATION

Main flow

Flow rates greater than 0.82 liter/second (13 GPM) are measured with a squareedge ASME (4) flow orifice with an opening diameter of 32.84 mm, a β_0 ratio of 0.395 and Vena Contracta taps. The pressure differential across the orifice is measured with two mercury-filled manometers ($\Delta P_m 1$ and $\Delta P_m 2$) connected in parallel: a 6"-range inclined manometer with divisions of 0.01" and a 24" U-tube manometer with 0.1" divisions. This pressure differential measuring system yields an error less than ±0.26% of the measured flow.

The orifice has been calibrated in-situ, using city water at ambient temperature, once before and once after the completion of the experiments. No significant difference between the two calibrations has been observed. The calibrated values were compared with those obtained from the ASME formula (4).

Flow rates below 0.82 liter/second are measured by bypassing the flow through a 0.82 liter/second (13 GPM) romameter ($R_m 1$). The rotameter has been calibrated in-situ at three temperatures: ambient, 50°C and 82°C and correction curves were obtained. The estimated measurement error (after correction) is ±0.25% of the flow.

Coolant flow

The flow rate of the coolant through the condenser is measured by a 50 gpm rotameter ($R_c 1$). The portion of coolant that is dumped (or circulated through the cooling tower) is measured on a separate, 0.5 gpm rotameter ($T_c 2$). Both rotameters were calibrated in-situ, obtaining an accuracy of ±0.5% of the measured rate.

PRESSURE

The vapor pressure in the flash stage and the pressure differential between the vapor space of the inlet stage and that of the flash stage are measured at fixed location taps by manometers. Pressure fluctuations in the liquid or vapor of the flash stage are measured with a piezoelectric pressure gauge* which can be positioned at several locations along the flow axis and also traversed in the vertical direction by means of a micrometer.

There exist many difficulties in measuring vapor pressure with a glass-tube type manometer, including condensation of vapor in the glass tubes, and rapid spurious pressure fluctuations. It was therefore decided to use condensate pots above the manometers (Fig. 4). The pots are automatically replenished by condensation from the vapor space connected to them. The connection to the vapor spaces is by means of 3/4" copper tubing which is termally insulated. The tubing is monotonically graded from the condensate pots down to the measured vapor space, to provide adequate condensate drainage and avoid liquid locks. The level in the pots is therefore self-regulating, when the condensate level rises about the vapor inlet, it drains back into the

*F.S. Range: 10 psia; Sensitivity: 100 mV/psi; Model 201A1, Kistler Instrument Co., Overlake Industrial Park, Redmond, WA 98052.

respective evaporator stage.

The interstage vapor pressure differential was measured simultaneously by two instruments connected in parallel: a 250 mm inclined mercury-in-glass manometer with 0.01" (0.25 mm) divisions and an electronic differential pressure transmitter* with an adjustable full-scale range of 37 mm Hg to 370 mm Hg. The electronic transmitter output is recorded on a potentiometric recorder, after appropriate signal conditioning. The transmitter has been calibrated by comparing its output signal to the pressure measured simultaneously on the inclined manometer. The estimated accuracy of both systems is ±0.13 mm Hg

TEMPERATURE MEASUREMENT

To experimentally obtain accurate temperature profiles in the flash evaporator, several complementing temperature measuring systems have been designed and utilized. The "thermistor comb", that is, a vertical sensor incorporating closely space miniature thermistors, enables a simultaneous measurement of absolute and differential temperatures in the liquid and vapor phases along a line perpendicular to the stage floor. This method provides the necessary accuracy in the measurement of the small temperature differentials associated with flash evaporation, provides directly the thermal driving force for evaporation (from the measured temperature differential between the liquid and the vapor)and determines the temperature gradients in both phases and across the phase interface, which are indicative of the rate of heat transport. In addition, the influence of the sensor on the measured medium is fixed in contrast to the more commonly used vertically traversing probe which may introduce extraneous effects at different positions. One such sensor is located in the flash stage and one in the inlet stage. Thermistors were chosen to measure temperature mainly because of their high temperature sensitivity and their availability in very small size.

The basic measuring element is a 0.010" (0.25 mm) diameter bead thermistor encapsulated in glass**. Its nominal resistance at 25°C is 100,000 ohm, and it is mounted at the end of a 0.46 mm diameter type 304 stainless steel hypodermic tube, which also serves as the conduit for the two thermistor wires. Sixty-eight such thermistor probes are present in the flash-stage comb, thirty-six in the inlet-stage comb. They are mounted into a streamlined, wing-shaped holder whose disassembled front part is shown in Fig. 5.

*F.S. Range: adjustable from 0-20 to 0-200 inch water; Model 10B2491EK, Fisher-Porter Co., Warminster, PA 18974.

**Part No. G51A59, Victory Engineering Corp., Spring Ave, Springfield, NJ 07081.

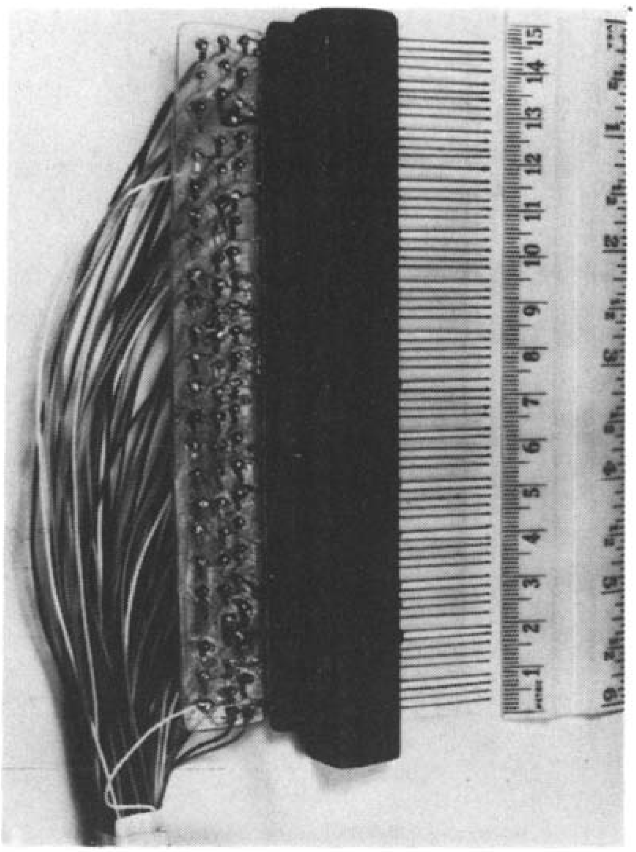

Fig. 5. Front part (disassembled) of the thermistor comb

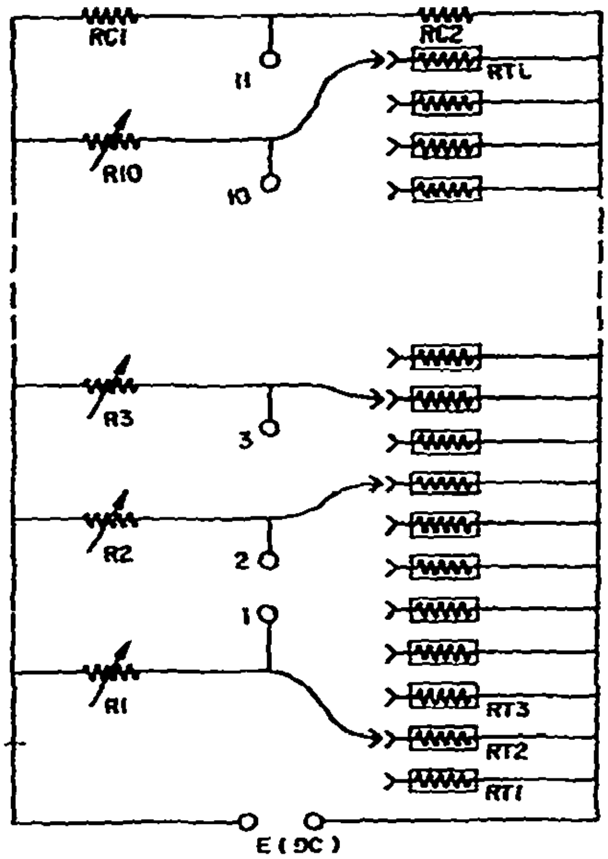

Fig. 6. Differential Bridge System with "absolute" reference

Two miniature thermistors were mounted in the end of 1/8 in. O.D. stainless steel tubes and served as secondary temperature standards (SST) for the calibration of the thermistor combs as well as providing temperature measurements in both evaporator stages.

The resistance of the thermistors was determined by ten DC Wheatstone Bridges. The output of each bridge was amplified, conditioned and recorded on a 12-channel oscillographic recorder and thus, the temperatures of any ten thermistors could be measured simultaneously. Each bridge could be connected to any thermistor by means of a patch-cord system. Essentially, the resistance measuring circuit consisted of one reference and nine differential bridges (Fig. 6). Any one of the thermistors in the system could be chosen as the reference.

All bridge components, as well as all other components in the electronic circuits, were selected for their stability and accuracy, and were assembled into a temperature stabilized (±1°C) cabinet, so as to achieve a resistance measurement of the order of 0.01% of the measured value.

The thermistor combs were 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 reference. In the calibration procedure, this reference probe was placed upstream of <u>each</u> thermistor in the comb and was always connected to the reference bridge. The comb thermistor being calibrated was connected to the adjacent differential bridge, the output signals of both bridges were balanced on the oscillograph, and the values of the balancing resistors R1 and R2 of each of the two bridges (Fig. 6) were recorded. The value of R1 determined the local calibration temperature (by the below-described calculation), while R2 is the resistance of the calibrated thermistor at that temperature.

The secondary standard thermistor references were, in turn, calibrated in an oil bath maintained at constant (±0.01°C) temperature by means of a temperature-controlled circulation bath. The temperature reference was a platinum standard thermometer measured on a Mueller Bridge with a high-sensitivity mirror-galvanometer.

To translate the bridge measurements to temperature, the relationship between the resistance of the thermistors and their temperature (the R-T curve) was determined during calibration. From the R-T curve and the circuit equations, a relation was derived between the reference and differential temperatures of the thermistors and the actually recorded values of resistance and oscillographic galvanometer deflection. These relations were programmed for a digital computer to yield the appropriate reference and differential temperature distributions both in tabular and graphical form. The overall accuracy of the Thermistor Comb system for measuring temperatures was ±0.02°C. Other details on the Thermistor Comb and its measuring circuits are descirbed in (5).

In addition to the thermistors, twelve thermocouples at fixed locations of the entire flow loops were used mainly for process monitoring. Also, a 5μs response thin film platinum resistance thermometer (T_f) was mounted on a micrometric vertical traverse drive. This was used to measure temperature profiles across the evaporating liquid-vapor interface, and could detect high-frequency temperature fluctuations.

PHOTOGRAPHY

Still photographs of the flashing process were taken during each experimental run and a 16 mm movie was taken during one run. Most of the still pictures were taken on Polaroid film with a Speed-Graphic camera. Photography of the process is made difficult by the reflections coming from the glass windows and by the turbulent two-phase fluid. Reasonably good results were obtained by using polarizing filters mounted on both the camera lens and the light source (an electronic flash bounced to the subject by a silver-colored reflection screen). The flash duration was about 1 millisecond, except for some pictures that were taken with an ultra-fast 10μs strobe. The filters and the lighting technique has eliminated most of the glare, while the fast speed of the flash helped reduce the blur emating from the motion of the fluid.

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