Light-Activated Switch Burnout Detection System

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Resistance-heated metallic test sections are often used to determine experimentally the thermal and flow characteristics of liquid-cooled nuclear reactor fuel elements. At the peak or critical heat flux, a boiling liquid undergoes either a relatively rapid transition from efficient nucleate boiling to high thermal resistance film boiling or a somewhat slower transition, as with annular flow bulk boiling, from a wetted-wall condition to one characterized by the appearance of dry patches. In an essentially constant heat input system, such as a nuclear reactor, rocket nozzle, or electrically heated test section, the heat flux is imposed independently of the thermal resistance of the coolant; and the rapid rise of wall temperature following the cessation of nucleate boiling can result in a fusion failure or burnout of the heating surface. For this reason, *burnout heat flux* is commonly used, as here, to denote the heat flux at the critical transition or wall dryout condition (*1*). When a large number of burnout tests are to be conducted, or when the test section is large and/or of complex geometry and expensive, it becomes economically desirable to employ an automatic system for detecting thermal burnout excursions and for interrupting the heating current before the test section is physically damaged so it can be reused.

In the past, burnout protection systems have been based most often on the use of thermocouple signals or on the unbalancing of a Wheatstone bridge connected to the test section at three axial locations. The thermocouple system, which acts to trip the power when the developed emf exceeds a preassigned limit of either level or rise rate, requires the use of a large number of thermocouple sensors in order to protect the entire surface and is not as suitable for d.c. heated test sections as for those heated by a.c. if the couples are directly attached to the surface. Radiant heating of an unattached thermopile may be used (*2*) but the decreased speed of response of the detection system limits this approach to moderate heat fluxes.

The bridge system [a modern version of which has been described by Salt and Wintle (*3*)] balances the electrical resistance of a portion of the test section against that of the remainder, and the bridge is suddenly unbalanced at the critical heat flux by an increase in the resistance of the monitored zone caused by the local temperature excursion. However, some metals such as the Inconels, Hastelloys, and Nichromes have such small temperature coefficients of electrical resistivity that the bridge method proves to be insufficiently sensitive when used with them. In addition, this system is relatively complicated and expensive if a.c. heating is utilized. In all the detection systems discussed, the signal generated by the sensor (thermocouple, bridge, or light-activated switch) is used to operate a relay and/or circuit breaker in order to interrupt the test section heating current.

The purpose of this note is to describe a new type of burnout detection system which appears to offer several advantages in comparison with other methods. The novel feature of the new system is the use of a solid state combination sensor/switch of the silicon PNPN type which is activated by incident thermal radiation emitted by the test section.

TABLE 1. APPROXIMATE OPERATING CHARACTERISTICS OF AVAILABLE *PNPN* SWITCHES

Maximum forward blocking voltage	— 200 v.
Current capability*	— 1.6 amp. d.c.
Maximum "open circuit" current†	— ~10 μamp.
Maximum junction temperature‡	— 300°F.
Typical response time	— 2 μsec.
Frequency capability**	— ~1 kc./sec.
Spectral response	— near IR through visible
Useful light levels¶	— 50 to 10^4 ft.-c.
Dissipation	— ~½ w.

* When the switch is mounted on a heat sink.
† At rated voltage and with zero effective irradiance.
‡ In applications where the device need not block forward voltage until after the junction temperature falls below ~200°F.
** In a d.c. circuit, the switch will continue to conduct until the current is externally removed.
¶ The light intensity required to trigger decreases with increasing anode voltage or junction temperature.

DESCRIPTION OF SWITCHES

The first type of light-activated unit investigated in this study was a GE- L7F subminiature,* which is 0.125-in. diameter by 0.300 in. long. This switch is no longer available, but is the type being used in an application which will be described. Later tests were made with a more sensitive GE-L9U unit, which is enclosed by a TO-5 transistor package with a 0.22-in. circular glass window in the top of the cap; the overall dimensions are 0.37-in. diameter by 0.25 in. high. Units soldered to a diamond-shaped heat-sink base are also available.

Since the characteristics of light-activated switches have been described in detail by Howell (*4*, *5*) and others (*6*), only the features which appear pertinent to the subject application will be considered. Approximate operating characteristics of the currently available PNPN type of light-sensitive switches are tabulated in Table 1.

The LAS (light-activated switch) is triggered into conduction when the radiant energy falling on it exceeds a certain level. The LAS responds typically within a wavelength interval of 0.4 to 1.2 μ, with a peak relative response (of unity) at ~1 μ in the near infrared spectral region. Since the relative response is typically one-half at wavelengths of ~0.8 and 1.1 μ, twice as much radiant flux is required for switching at these wavelengths as at 1 μ. Because effective energy is additive, a LAS that requires an effective triggering irradiance of 10 mw./sq. cm. will, if already supplied with 6 mw./sq. cm. at 1μ, require a minimum additional flux of 8 mw./sq. cm. at 0.8 or 1.1μ. Energy outside the response band does not contribute to the effective energy, and the closer the

* Companies other than General Electric supplying light-activated SCR's include Hoffman Electronics Corporation, Solid State Products, Inc., and Texas Instruments, Inc.

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Characterization and gain identification of time varying flow processes, Mellichamp, D. A., D. R. Coughanowr, and L. B. Koppel, **A.I.Ch.E. Journal, 12,** No. 1, p. 75 (January, 1966).

Key Words: A. Estimation-8, Gain-9, 8, Process-9, Flow-9, Sinusoidal Perturbation-10, Analog Computer-10, Adaptive Control-4, Control-8, Time Varying Process-9, Dynamics-8. B. Regulation-10, *p*H-9, Gain-8, Process-9.

Abstract: A method for continuously estimating the gain of a flow process, by sinusoidal perturbation, is presented. The resulting output perturbation is correlated with a second sinusoid to generate periodically an estimate of the process gain. A method of implementing such an identifier on a small analog computer is described.

The experimental testing of this identifier computer with both a real process (a *p*H regulating system) and with an analog computer simulation of the process is described. The results of identification tests with a nonstationary system are presented. From these results it is concluded that the identifier estimates the process gain satisfactorily, introducing a delay (equal to one-half the period of identification) and effective sampling or clamping of the gain estimate (over each period of identificaton).

Identification and adaptation in control loops with time varying gain, Mellichamp, D. A., D. R. Coughanowr, and L. B. Koppel, **A.I.Ch.E. Journal, 12,** No. 1, p. 83 (January, 1966).

Key Words: A. Estimation-8, Gain-9, 8, Process-9, Time Varying Process-9, Analog Computer-10, Digital Computer-10, Gain Varying Process-9, Adaptive Control-4. B. Gain-8, Process-9, Regulation-10, *p*H-9.

Abstract: A method is presented of applying the gain identification procedures, developed in a companion paper, to a control system. The method employs a small identification tank which follows the control tank; the identification tank is perturbed to estimate the gain of the process (controlled tank system). The effects of load changes on the identification system are minimized by this approach.

The results of analog and digital computer simulations of this adaptive process are given. Both a general system with linear change in gain and a *p*H control system with a step change in concentration of the buffer species are studied. Process gain changes up to 20:1 are introduced.

It is concluded that an adaptive control system of this type can be designed to maintain good control characteristics in a process experiencing wide gain variation. Criteria are presented to aid in the design of an adequate identifier.

Effect of ultrasonic waves on mass transfer rates of selected fluids, Fogler, H. Scott, and Klaus D. Timmerhaus, **A.I.Ch.E. Journal, 12,** No. 1, p. 90 (January, 1966).

Key Words: Ultrasonics-6, 8, Mass Transfer-7, 8, Liquid Phase-9, Benzene-9, Ethanol-9, Methanol-9, Carbon Tetrachloride-9, Acetone-9, Aromatic Hydrocarbons-9, Alcohols-9, Atomization-8, Diffusion-7.

Abstract: Ultrasonic waves were applied directly to the liquid phase to determine their effects on the rate of mass transfer. The rate of mass transfer was obtained by measuring the height of the gas-liquid interface as a function of time.

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spectral match between the radiant source and the LAS, the higher is the radiant efficiency. It should be emphasized that a LAS is a bistable high-speed power switch, characterized by latch or snap action between open and closed states, and is not a linear transducer of the photoresistive or photovoltaic types.

At the expense of restricting the view angle, various combinations of lenses and reflectors can be used to increase the irradiance at the switch, and neutral density filters could be used to attenuate the radiant flux (5). With the L9 unit, optional gate triggering inputs can be used which allow the use of an electrical signal to trigger the device or to provide a shuttering effect by decreasing the light sensitivity. Shuttering of this type would be useful in high-temperature systems (such as liquid metals) where the radiant emission is sufficiently high under normal operating conditions to trigger the switch at reasonable spacings. Fiber optics (7) can also be used for coupling a switch to a source if direct viewing is not feasible.

SENSITIVITY TESTS

The preliminary test arrangement consisted of a horizontal Inconel shroud tube 0.63-in. I.D. × 6-in. long concentrically enclosing an internal a.c. heated stainless steel tube of 0.0715-in. O.D. Two L7 prototype switches were mounted on the internal wall of the shroud tube at a nominal distance of 0.15 in. from the external surface of the heater tube. A Chromel/Alumel thermocouple was positioned inside the heater tube at an axial distance corresponding to the position of the switches. Slow, fast, and essentially instantaneous current rise rates were applied to the heater tube, and an ohmmeter connected to the switches indicated that they repeatedly latched into conduction when the heater temperature reached ~1,200°F. (corresponding visually to the appearance of first red heat).

The effect of ambient temperature variation on switch performance was investigated by spacing a single GE-L7F LAS mounted on the inside wall of a vertical Lavite shroud tube at a distance of 0.15 in. from an internal 75-mil O.D. A-nickel resistance heater and then exposing the switch to four heater temperature levels for durations of up to 2 hr.

The results showed that while the LAS trip temperature decreases with increase of ambient temperature, the effect is not large for the subject configuration until the internal heater temperature exceeds ~1,000°F. An increase of heater temperature from 500° to 1,100°F. reduced the temperature at which the switch ultimately became conducting by ~200°F.

The distance from a radiant source at which the LAS latched into conduction (herein designated the cut-on dis-

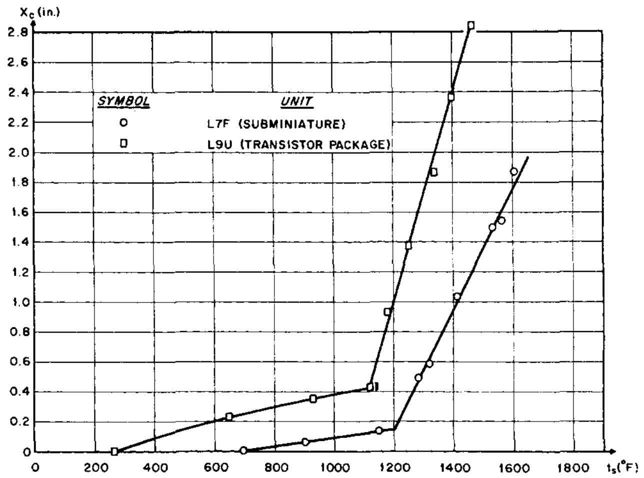

Fig. 1. Cut-on distance vs. source temperature for two light-activated switches.

tance x_c) was measured as a function of source temperature t_s up to t_s = 1,600°F. for each type of switch. These measurements were made with a horizontal Nichrome ribbon heat source radiating into a vertical chimney fabricated of synthetic mica. The switches were attached in a horizontal orientation to a vertical rack-and-pinion mechanism provided with a scale and slowly traversed downward within the chimney with the heater at a preset temperature until the switch closed. The results are shown for each unit in Figure 1. While not general, the variation shown should be typical of many heated metal sources.

Several simple tests of fiber-optic coupling were made with the GE-L9U switch in conjunction with readily available American Optical Co. fiber-optic light guides. The experimental arrangement consisted of a ⅛-in. O.D. A-nickel resistance heater enclosed concentrically by a vertical Lavite shroud tube identical to that used with the test sections of the two-phase heat transfer system. When the switch was positioned to view the internal heater through a hole in the Lavite shroud at a spacing of ¾ in., it became conductive at a heater temperature of 1,150°F. (± 21°F.).

When a straight ⅛-in. hexagon × 12 in. long image conduit was positioned so that one end was ⅛ in. from the heater* and the other end flush with the glass window of the L9 switch (aimed directly at the silicon pellet), the average switching temperature was 1,242°F. (± 45°F.). The same test conducted with a straight light-transmitting clad rod (⅛-in. round × 12 in. long) gave an average switching temperature of 1,265°F. (± 11°F.). With each light guide, therefore, it was possible to increase the spacing between the heater and switch by sixteenfold while incurring an increase in the heater temperature required for switching of only ~100°F.

A final test was conducted with a flexible fiber optic bundle (⅛-in. round × 12 in. long). When the bundle was fixed in a straight position, the switching temperature was 1,418°F. (± 16°F.), and when constrained to a 180-deg. *U* of 5-in. radius, 1,435°F. (± 32°F.). The effect of fiber bundle curvature was, as expected, insignificant, but the switching temperature was ~280°F. higher than for the switch alone at a spacing of ¾ in.

APPLICATIONS

LAS sensors may be used with a variety of test section configurations. In pool boiling tests conducted with horizontal tubes, two switches could be arranged to view the interior of the tube from each end. With vertical rod bundles, the switches could be used in a similar fashion if tubes were used as the test elements.

The LAS approach to burnout detection has been incorporated at the Oak Ridge National Laboratory into a two-phase boiling system designed for the determination of critical heat fluxes characterizing resistance-heated tubular test sections cooled internally by steam-water mixtures in swirl flow. Thirty-two L7F light-activated switches were mounted on the internal surface of an external concentric shroud tube fabricated of nonconductive Lavite. The switches were positioned so as to view the entire outside area of the test section and were wired in parallel so that the closing of any one would actuate a relay and circuit breaker to interrupt the test section heating current. The total response time of the complete detection system is ~80 msec. Small glow bulbs (14 v./0.08 amp.) were later wired in series with each switch to give an indication of the switch(s) triggered at incipient burnout and therefore an approximation of the site of overheating. A schematic of the essential circuitry is shown as Figure 2, where the provision made for testing the glow bulb indicators before and after each burnout run is also indicated.

Each of the fifty L7F switches acquired was tested before use to determine the source temperature of a Nichrome strip required to cause the switch to close when positioned 0.16 in. above the strip. The minimum, average, and maximum temperatures were 980°, 1,115°, and 1,215°F., respectively; 84% fell between 1,050° and 1,200°F.

This system has operated successfully at critical heat fluxes from 0.125 × 10^6 to 2.01 × 10^6 B.t.u./(hr.)(sq. ft.). At the latter flux, the adiabatic rise rate of the test section wall temperature is ~1,700°F./sec. With a high-speed circuit breaker, and because of the very fast response of the LAS, the system should operate equally well at much higher heat fluxes. The test sections have each experienced ~40 incipient burnouts without exhibiting any signs of excessive overheating, thermal expansion, or corrosion.

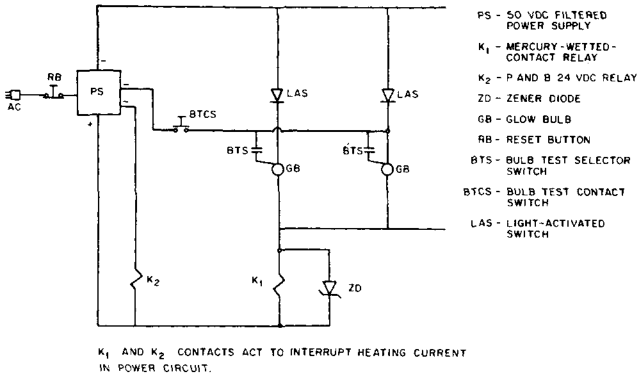

Fig. 2. Two-switch section of circuitry used with two-phase test section.

* The heater-to-rod spacing was ⅛ in. in all the light-guide tests.

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A generalized equation for computer calculation of liquid densities, Yen, Lewis C., and S. S. Woods, **A.I.Ch.E. Journal, 12,** No. 1, p. 95 (January, 1966).

Key Words: Predicting-8, Density-7, Liquid-5, Mixture-5, Pressure-6, Temperature-6, Computer-10.

Abstract: A generalized equation relating reduced density explicitly to reduced temperature and reduced pressure has been developed for calculating liquid densities on a digital computer. This equation correlates liquid densities of pure compounds to within 2%. With the aid of a pseudocritical method, it predicts liquid densities of mixtures to within 3%.

Column height required for continuous chromatographic separation: A probabilistic model, Sciance, C. T., and O. K. Crosser, **A.I.Ch.E. Journal, 12,** No. 1, p. 100 (January, 1966).

Key Words: A. Separating-8,4,9, Mixtures-1, Substances-1, Chromatography-9,10,8,4, Continuous-0, Moving-Bed-0, Adsorption-10, Columns-10,9, Height-6, Flow Rate-6, Rate-7, Extent-7, Mass Transfer-8. B. Evaluating-8,4, Predicting-8,4, Heights-9, Columns-9, Separating-4, Chromatography-4, Continuous-0, Moving Bed-0, Mixtures-1, Substances-1, Mathematical-0, Probabilistic-0, Model-10,8, Probability Theory-10,8.

Abstract: A probabilistic model is used to develop the mathematical theory of a continuous chromatographic column. Equations are developed relating column height, feed location, degree of separation, and flow rates. Necessary sorption data can be obtained from a fixed-bed chromatographic column.

The stability of Couette flow between rotating cylinders in the presence of a radial temperature gradient, Walowit, J. A., **A.I.Ch.E. Journal, 12,** No. 1, p. 104 (January, 1966).

Key Words: A. Variations-6, Density-9,6, Viscosity-9,6,7, Temperature-6, Stability-7,8, Couette Flow-9,8,4, Solving-8, Calculating-8, Stability Equations-9, Solutions-2, Taylor Number-2,7, Critical-0, Galerkin Method-10, Prandtl Number-6, Heat Transfer-8,4, Rotating Cylinders-9, Concentric-0.

Abstract: The effects of viscosity and density variations due to an imposed radial temperature gradient on the stability of Couette flow between rotating cylinders are investigated. The annular spacing between the cylinders is assumed to be small compared with the mean radius. The fluids considered are water and 50% aqueous glycerol. Approximate solutions to the stability equations are obtained by the Galerkin method. Computations are restricted to the case where the outer cylinder is at rest.

The influence of diffusivity on liquid phase mass transfer to the free interface in a stirred vessel, Kozinski, Allen A., and C. Judson King, **A.I.Ch.E. Journal, 12,** No. 1, p. 109 (January, 1966).

Key Words: A. Mass Transfer-8,9, Continuous-0, Liquid Phase-0, Helium-1,9, Argon-1,9, Oxygen-1,9, Carbon Dioxide-1,9, Water-5, Nitrogen-5, Absorption-10,8,9, Desorption-10,8,9, Calculating-8, Mass Transfer Coefficients-2,7, Concentrations-1, Diffusivity-6, Temperature-6, Eddy Diffusion-6, Surface Renewal-6, Agitation-6,9, Rates-6,7.

Abstract: Liquid phase mass transfer coefficients are measured in a continuous flow, stirred vessel containing a gas and a liquid phase. Helium, hydrogen, oxygen, argon, and carbon dioxide were desorbed from distilled water into nitrogen at seven different levels of agitation. The relationship of mass transfer coefficients to diffusivity is determined at low stirring speeds (at which the system is stratified) and at higher stirring speeds (at which the interface is broken). The results are interpreted in light of a general model considering eddy diffusion and surface renewal effects.

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Since the method described detects incipient burnout at temperature levels which correspond to substantial wall temperature rises with common combinations of coolant and imposed heat flux, the likelihood of premature burnout indications is greatly reduced. It should be noted, however, that in the slow burnout regime, which has been observed with two-phase water systems at high mass velocities and pressures, the critical transition is characterized by a relatively small wall temperature excursion to a new equilibrium level. In this regime of operation, the LAS system may be inadequate, since the irradiance at the sensor might be too small for triggering even after the dry-out transition has occurred. Similarly, if a low melting-point test section material like aluminum is used, it would be necessary to locate a sensitive LAS quite close to the surface to prevent fusion at the burnout flux. Finally, in very high heat flux tests, it is possible (*8*) to attain outside wall temperatures approaching the test section melting point while the heat flux is still below the critical value; in this instance, testing to destruction is the only recourse.

CONCLUSION

Detection of incipient thermal burnout with light-activated sensors is feasible, especially in the subcooled region. In addition to simplicity, fast response, and low cost, the subject method allows monitoring of the entire test section surface, can give an indication of the overheating site, and affords complete electrical isolation between the triggering source and output.

ACKNOWLEDGMENT

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