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A FUNDAMENTAL STUDY OF LIQUID SPRAY EVAPORATION AT A HEATED SURFACE

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INTRODUCTION

In previous reports the heat transfer characteristics of a mist spray of water impinging on a heated surface under various pressures were described. The first Interim Report (February 28, 1979) described the heat transfer characteristics when the surface was a smooth horizontal one. The Second Interim Report (May 15, 1979) described the characteristics for a horizontal surface with grooves in it. Particular interest in the research reported was given to determination of the heated surface temperature and corresponding heat flux at which the dry-wall mode of evaporating heat transfer became flooded, with water accumulating at the surface. This flooding locus was determined experimentally for various pressures from atmospheric to just below the triple point of water.

In all the work reported previously, the water was supplied to the spray nozzle at approximately 20°C and the nozzle flow was continuous. The resulting flooding loci represented steady-state operation of the flash evaporation process.

The research reported herein was concerned with the influence of feedwater temperature and the influence of pulsing nozzle flow on the heat transfer characteristics in the spray evaporative cooling process.

FEEDWATER TEMPERATURE EFFECTS

To determine the influence of feedwater temperature on the heat transfer characteristics in the spray evaporative cooling process, a commercial water circulation heater was installed in the feedwater line between the supply reservoir and the nozzle. One pass through the heater would provide water at temperatures up to 50°C at the nozzle; higher temperatures could be obtained by multiple heater passes. A thermocouple installed in the water line just upstream of the nozzle provided a measure of the feedwater temperature.

To determine the influence of feedwater temperature, the tests to be run were the same as those reported previously. Initial tests were run with bell-jar exhaust orfice (#2) which provided a pressure in a range about 7 mm Hg abs. The feedwater temperature was heated to a temperature of 45°C.

When the system was operated in this fashion, the spray cone, which at 20°C was well-defined, became very large and poorly defined. It was also very difficult to control. An extra needle valve was installed in the flow system but it did not aid in controlling the spray cone expansion. During numerous trials, it was observed that as the temperature of the feedwater was increased above about 40°C, the water droplets leaving the nozzle "instantaneously" evaporated - flash evaporation - particularly in the interior of the spray. The resulting vapor plume forced the outer periphery of the spray cone to wide angles, and it became unstable. Vapor was formed almost immediately upon leaving the nozzle. As the temperature of the water increased above about 40°C the spray cone angle increased and greater amounts of vapor were observed to rise around the nozzle.

This flash evaporation of the heated water was so severe that it was not possible, in the limited space of the present experimental apparatus, to obtain a steady spray of water droplets on the heated surface. Hence, no data was obtained to report.

It can be concluded from the observations made that for a given system operating pressure, there is an upper limit on the feedwater temperature above which the spray will flash to vapor before hitting the surface to be cooled. The result would be a loss in effectiveness of the spray evaporation process for cooling the heated surface. From the observations made, it would appear that this feedwater temperature limit would be in the neighborhood of 40°C.

PULSING SPRAY EFFECTS

To study the influence of intermittant spraying - pulsing spray - on the heat transfer characteristics in the spray evaporative cooling process, an eletronic "switch" to open and close the spray nozzle was built and installed in the system, see Figure 1. The nozzle contained a solenoid valve.

The "on-time" was fixed at 200 msec and the on-off pulsing frequency was made variable between 0 and 4 hz, thus allowing the "duty cycle" of the spray to be varied.

Again, initial tests were run with bell-jar exhaust orfice (#2) which provided a pressure in the range about 7 mm hg abs. The smooth heated surfaced element was used. The results for steady state operation in this case were well correlated (Figure 11 in Iterim Report #1 and Figure 9 in Iterim #2).

Starting with a steady spray, an operating point on the flooding locus was established. This is point 1 on Figure 2. Pulsing of the spray was then started at a given frequency (duty cycle).

The heat flux-wall temperature condition moved into the dry-wall operating region and, with intermittant spraying, reached an essentially steady state condition at point 2 (Figure 2). This was dry-wall operation at reduced mass flow and hence reduced heat flux. The heated surface temperature was then lowered, as in steady state operation, by controlling (lowering) the base temperature in heated sample while keeping the heat flux constant.

In this manner, the system was brought back to the flooded condition. This new flood condition, point 3, was located on the original (steady-state), flooded locus line at the same heated surface temperature but at reduced heat flux. The measured ratio of Q_3/Q_1 was 0.85 for this duty cycle of 0.80.

The duty cycle was then decreased. The system moved and reached a pulsed steady state dry wall condition at point 4. Again bringing the system to the flooded state, it reached point 5. The ratio $Q_5/Q_1 = 0.64$ was measured for this duty cycle of 0.57.

The flooded mode operating points 1, 3, 5 established in this pulsing operation, shown in Figure 2, were within the scatter observed in obtaining the original flooded locus line.

Similar test were run at atmospheric pressure. Again it was found that the heat flux ratios at the various flooded-mode and pulsing steady state dry-wall modes followed the spray nozzle duty cycle quite closely. For initial steady state flooded operation at Q_1 = 98.6 KW/M^2, the following points were established;

duty cycle	=	0.80	0.57	0.40
Q = fraction of Q_1	=	0.84	0.62	0.45

Attempts were made to obtain similar data at pressures below the triple point of water. However, at these very low pressures, once pulsing of the nozzle started, water would accumulate on the nozzle. This accumulation of water would then shear off from the nozzle and drop directly onto the heated surface as a large droplet. These large droplets would then effectively cause flooding on the surface and disrupt the test sequence. Apparently this accumulation of water on the nozzle at these very low pressures is associated with the operation of the solenoid valve in the nozzle itself. This difficultly was not observed at pressures above the triple point nor for continuous duty operation.

The results obtained from these pulsing spray experiments suggest that spray evaporative cooling with continuous pulsing duty of the nozzle in no different from continuous steady state operation. The locus of the heat flux vs heated surface temperature at the flooding point is the same in either case. With intermittant spraying the flooding point - or any particular dry wall operating point-will establish the same as for steady flow operation but at a lower flux level as determined by the duty cycle of the pulsing spray.

This conclusion is not unexpected since, in steady state operation, the dry-wall and just-flooded modes of operation in spray evaporation at a heated surface are determined by mass flow rate. Continuous pulsed spray will reach an "effective" steady state but at a lower mass rate determined by the fraction of time the flow rate is "on" (the duty cycle of the nozzle).

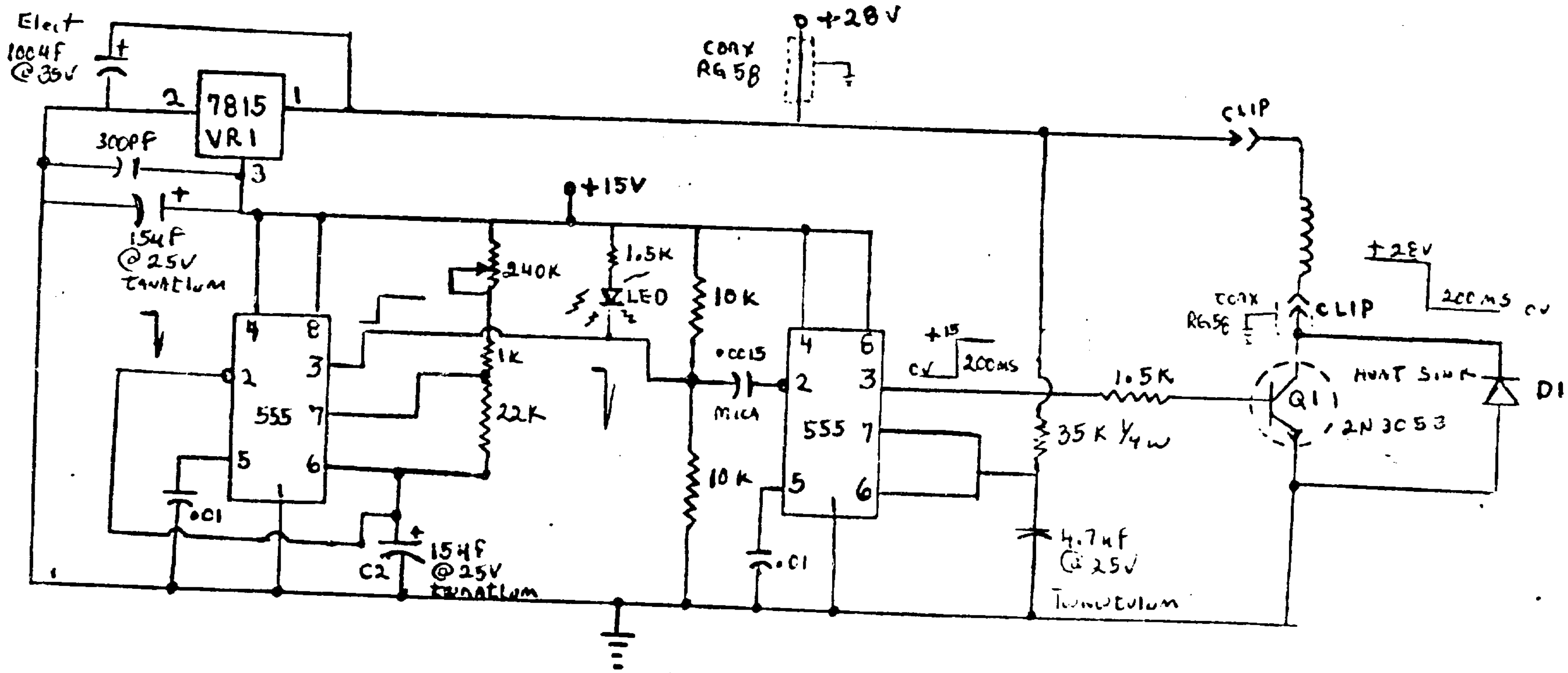
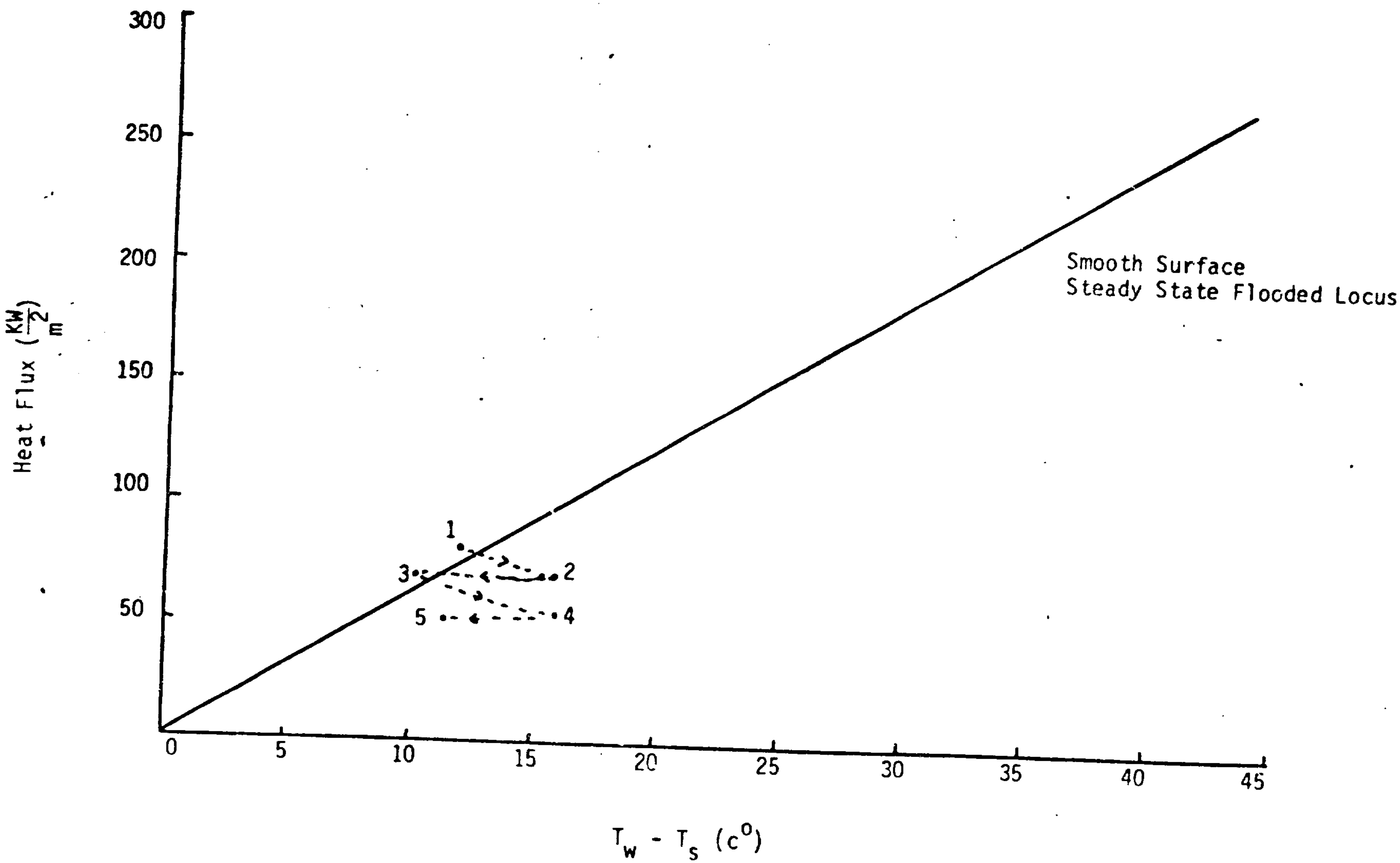


Figure 1. Pulsing "Switch" Circuit. On time 200 m sec, off time variable to obtain 0-4 Hz frequency.



<u>Figure 2</u>. Pulsed Spray Operation. $\bar{P}$ = 7.11 mm Hg.