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Summary: Boiling of water at 1 to 15 bar flowing upward within a narrow duct and a round test section was observed using both neutron radiography and infrared (IR) thermography. The IR readings of the test section outer wall temperatures show the effects of both fluid temperature and wall heat transfer coefficient variations, producing a difference between liquid and two phase regions. The IR images, in fact, appear very similar to the neutron images; both show clear indications of spatial and temporal variations in the internal fluid conditions during the boiling process.

Numerous investigators have reported using neutron radiography to observe air bubbles rising through water (1-5) and boiling of water (6). The high cross section of water makes this technique uniquely capable of observing two component and two phase processes taking place within opaque components. We report here on the simultaneous use of a complementary video technique, Infrared Thermography. IR Thermography makes use of recent advances in the design of IR videocameras making them capable of high resolution and wide dynamic range, with automatic real-time color coding of temperature patterns on displayed images. Some of these cameras are also capable of remote operation using a PC-style keyboard, making it possible to locate the camera itself near a neutron beam, while allowing control and adjustment of the image to be done from a remote area. These experiments were carried out at the Pennsylvania State University 1 MW TRIGA reactor facility using a Precise Optics neutron radiography camera and a FSI IQ-325 infrared camera.

The test setup consisted of a pumped flow loop which could be fitted with electrically heated test sections of various designs. Controlled direct current up to 1500A flowing through the metal walls of the test sections can produce boiling inside the test sections.

At atmospheric pressure, a narrow duct test section, with a uniform channel thickness was used. This test section was positioned face-on to the neutron camera. The IR camera was positioned at an angle behind the neutron camera with the neutron camera moved back to allow an unrestricted IR view. The IR camera viewed the entire 0.7 m length of the test section; the neutron camera viewed about 0.15 m near the top. A typical result is shown in Figure 1.

The liquid was pumped into the bottom of the test section at a constant rate and at a temperature below the boiling temperature. After leaving the test section, the fluid was cooled and returned to the pump. The neutron image showed the familiar chaotic boiling process which, at low pressures, is characterized by alternating periods of all liquid followed by periods of mostly steam.

The IR image shows a continuous increase in temperature at a constant rate in the bottom (nonboiling) part of the test section. Then, at the point where boiling starts, as seen from the neutron radiography video, the IR camera reveals a temperature drop of 10°C to 20°C, and any movements of the boiling interface can be followed as they occur. When steam is seen forming in the neutron image, the IR image shows the boiling point moving downward, and vice versa. This is clearly evident in the video recordings of the tests.

Similar tests were run using 11 mm inside diameter round test sections at 7 and 14 bar with very similar results. The boiling process at these higher pressures is more steady, so the sequence of an increasing temperature profile in the lower part of the test section, followed by an abrupt drop in temperature at the boiling point, followed by a constant temperature, could be seen clearly.

The reason why temperatures in the non-boiling region can become higher than those in the boiling region is that a thin region of liquid at the wall can become superheated (raised to above the boiling temperature) without boiling if there is no suitable nearby nucleation site. Since water has a very low thermal conductivity, this temperature rise at the wall can be 20°C or more, as was observed. (The stored thermal energy in this superheated liquid is what causes the abrupt "explosions" when boiling starts.) Note that at the heat fluxes used (approximately 100 kW/m^2), the temperature drop through the wall was 5°C or less. In boiling regions, the nearby steam surface furnishes an efficient nucleation site so the liquid temperatures do not normally rise much above the boiling temperature.

Test sections with three different wall thicknesses were used, and differences in the response times were seen. The thicknesses ranged from 0.45 mm to 1.23 mm. The response time for thermal diffusion can be characterized by the time required for diffusion to a given depth, taken as the wall thickness;

$$\tau = t^2 / \alpha,$$

where: α = thermal diffusivity, $k / \rho C_p$, and
t = wall thickness.

For the stainless steel material used, these time constants ranged from 0.14 s to 0.45 s. While no quantitative measurement of the frequency spectrum of the fluctuations was made, the qualitative appearance confirms that filtering of the processes consistent with these characteristics was taking place; moving interfaces were definitely less distinct when using the thicker test sections.

Split screen videotapes have been assembled showing the processes described above. The combination of real-time neutron radiography and IR thermography has provided a new measuring technique for studying the behavior of boiling phenomena in a heated duct. It has helped to significantly improve our understanding of the heat transfer processes under these test conditions.

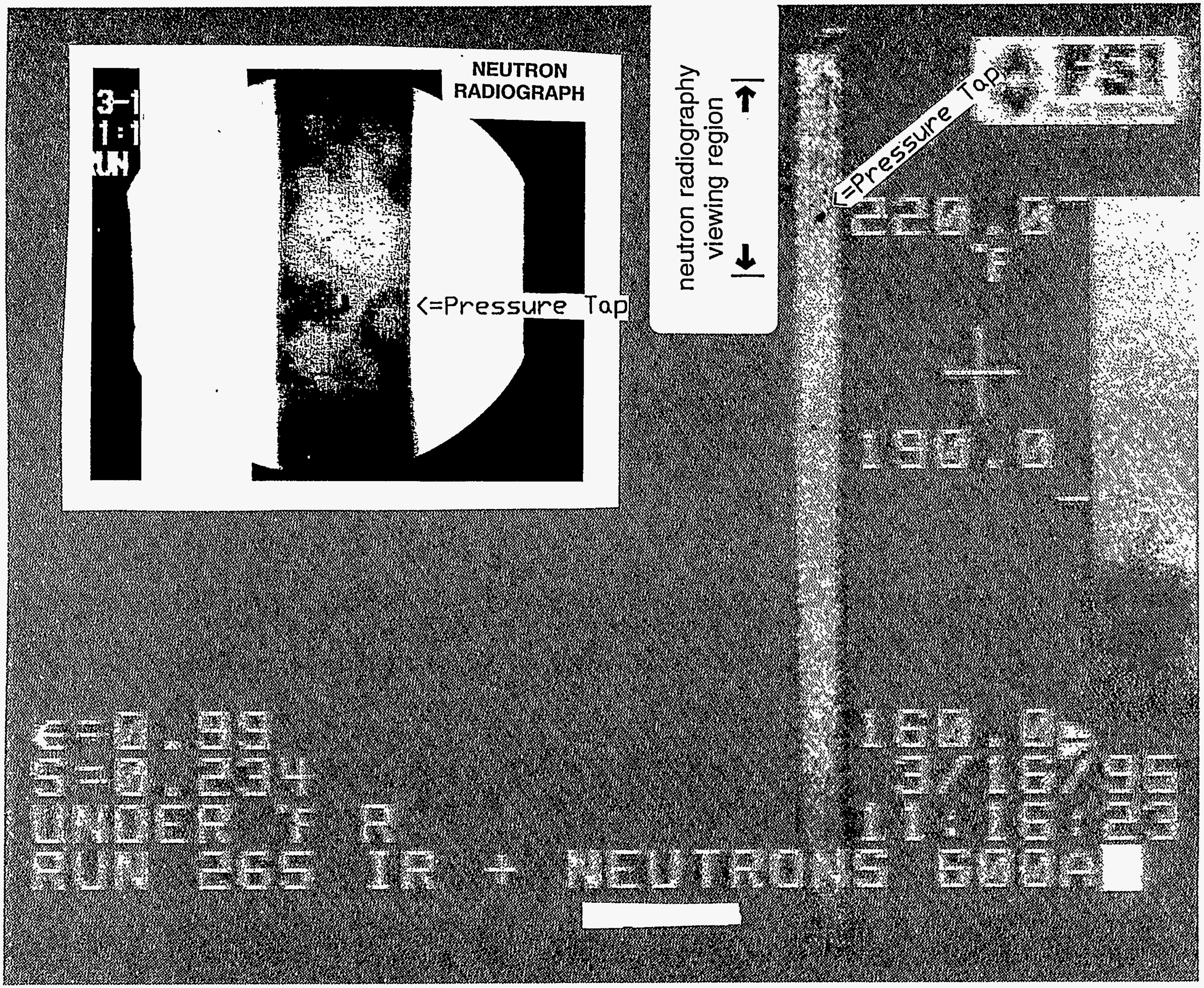

FIGURE 1: SELECTED FRAMES FROM VIDEO RECORDING OF REAL-TIME NEUTRON RADIOGRAPHY DATA

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