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REPORT TITLE

DETECTION OF NUCLEATE BOILING: REVIEW AND BIBLIOGRAPHY

AUTHOR

L. D. FeltenAI-67-MEMO 92(This Document Contains _____ Pages.
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TECHNICAL DATA RECORD		PAGE 1 OF 9	
AUTHOR <i>LDG</i> L. D. Felten		DEPT. & GROUP NO. 736-62	DATE 6/10/67
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TITLE Detection of Nucleate Boiling; Review and Bibliography		DRAWING 757-8094	TWR
		SECURITY CLASSIFICATION	
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		UNCL. ☒ AEC ☐ DOD ☐	RESTRICTED DATA ☐
		CONF. ☐	DEFENSE INFO. ☐
		SECRET ☐	
PROGRAM		SUBACCOUNT TITLE	
DISTRIBUTION		AUTHORIZED CLASSIFIER SIGNATURE <i>J. N. Kuehn</i> DATE 6-22-67	
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	ABSTRACT. A device to detect the onset of nucleate boiling during operation of a non-boiling type reactor, such as a sodium fast breeder reactor, could result in a lower hot channel factor and consequent operation at higher powers. A review of previous boiling noise detection work indicates that the sensitivity of the measurement for low frequency boiling noise and for system acoustic resonances which can be excited by boiling noise needs further investigation. The sodium loops at Santa Susana can be used for part of this work.		

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I. INTRODUCTION

A method of detecting the onset of nucleate boiling in a non-boiling type reactor is desirable for start-up and operational surveillance. It is of particular interest for the sodium fast breeder reactor, where such a detector could be used to experimentally reduce the hot channel factor in the reactor core. Measurements of both sonic noise and neutron flux noise have been made in an effort to obtain a characteristic signature of boiling in a system. Saxe²⁰ reviews various boiling detection methods which have been proposed for water moderated reactors.

II. BOILING DETECTION BY SONIC MEASUREMENTS

A majority of the acoustic measurements for boiling detection has been done in water systems. Recent work^{11, 12, 15, 18, 19} has included some measurements in sodium and potassium.

Goldman² summarized various boiling noises observed by investigators during heat transfer experiments. Audible frequencies were estimated and, in some cases, measured between 1000 and 2000 cps. Westwater³, et al, observed the increasing intensity of acoustic waves with increased boiling intensity. Schwartz and Siler¹³ observed the same effect and derived a correlation between sound intensity and ΔT for nucleate boiling. They found the sound spectrum approached white noise between 25 and 700 cps. The sound level at frequencies between 1000 and 3000 cps was negligible compared to the lower frequencies and no sounds were observed at frequencies greater than 3000 cps for either nucleate or film boiling.

Acoustic radiations from bubbles have been studied by Strasberg⁴, who determined that oscillation at the natural frequency of the bubble (simple volume pulsation) is the only mode of bubble oscillation which gives significant pressure waves. Strasberg also found that a bubble will pulsate at a frequency impressed on it by external pressure. However, the amplification of this pressure wave by the bubble will be greater than one only if the applied frequency is from 0.7 to 4.0 times the natural frequency. The natural frequency of oscillation for a bubble has been given by Minnaert¹. Figure 1 gives the natural frequency versus volume of helium bubbles in sodium. The figure shows that bubbles with diameter significantly greater than 1/4 inch oscillate at frequencies below 1000 cps.

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A second source of bubble noise considered by Strasberg is that caused by a bubble traveling around an obstacle and generating low frequency noise in the process. The frequency components of these generated pressure waves from a bubble entrained in a stream at velocity U , flowing over a cylinder of radius R , decrease in amplitude as the frequency U/R is approached. At this point the amplitude has fallen off by a decade. Thus, at a velocity of 20 ft/sec, a bubble would generate noise below 1950 cps when flowing over a 1/4 inch OD obstacle. Other irregular obstacles and constrictions could probably produce higher frequencies.

Bubble formation rate was studied with a stroboscopic light by Boyd²², who found that boiling bubbles formed at the rate of 25 to 50 per second, with the higher rates occurring at high heater powers. McFadden and Grassmann⁷ determined a relationship between bubble diameter and bubble frequency at a bubble formation site during nucleate pool boiling. Their data for several liquids was fit by the formulation, $fD^{1/2} = 17.5 \text{ cm}^{1/2} \text{ sec}$.

Nucleate boiling is also expected to produce some high frequency "cavitation like" noises from bubble collapse. DePrisco and associates^{6,9} have developed an ultrasonic instrument which detects the approach of nucleate boiling by measuring the power required by a vibrator to produce cavitation in the liquid under test. A 20 kc driving frequency was supplied and cavitation noises between 20 kc and 60 kc were detected. Application of this detection method to a liquid potassium system are being tried^{14,15}. The method only measures the approach to boiling of the liquid near the vibrator.

Preliminary boiling tests performed in a water system at Oak Ridge⁸ showed several peaks in the acoustic frequency spectrum between 600 cps and 3170 cps for boiling with a no flow condition. Several similar peaks between 30 cps and 2400 cps were observed in the same system for no boiling but with flow. After comparison of the two spectra with each other and with background, the investigators ascribed the peaks at 920 cps, 2070 cps, and 3170 cps to the boiling process. The amplitude of the peaks increased with increased boiling intensity.

James¹¹ reports similar results for boiling in water with amplitude peaks at 950 cps, 4500 cps, and 6000 cps. An increase in pressure of the system from one to three atmospheres moved the 950 cps peak to 1350 cps. Increased acoustic output was obtained for increased heat flux. This work also reports an acoustic spectrum for boiling noise in sodium. Peaks were obtained at 50 cps, 100 cps, 1050 cps, and 3000 cps.

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Frequency spectra of boiling in the two phase sodium loop at Santa Susana showed the largest peaks in the 1.5 kc to 3.0 kcps range ^{18,19}. In this case the boiling noise was observed to come in bursts which correlated with perturbations in the flowmeter signal.

Macleod¹⁷ compared acoustic spectra for boiling in different sized containers to emphasize the dependence of boiling frequency peaks on container size. He then further showed the similarity of the boiling frequency peaks to the resonant frequencies for the cavity size in which boiling was taking place. Macleod went on to show that the same frequency peaks could be obtained by observing the response of the system to a white noise source. A boiling test in a lake showed essentially no peaks in the kilocycle region. Macleod concluded that boiling noise is essentially broad band and that boiling spectra obtained by a particular environment are a property of that environment. This work also demonstrated the fact that swarms of bubbles attenuate sound generated in a system. Such an effect was noted during some acoustic noise measurements at SRE where a resonance signal on one accelerometer experienced a large attenuation when bubbles were introduced in large quantities.

From the above we conclude that:

1. Sounds of boiling bubbles forming give frequencies below 100 cps.
2. Natural frequency oscillations of the bubbles give frequencies in the kilocycle range (> 500 cps) for bubbles of less than $\frac{1}{2}$ inch diameter.
3. Acoustic frequency peaks in the kilocycle range are normally dominated by environmental resonances.

Thus, boiling could be detected in a particular system by:

1. The appearance of a low frequency signal (< 100 cps).
2. Increased intensity of a resonance peak.
3. Attenuation of a resonance peak.
4. Excitation of a new resonance.

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III. BOILING DETECTION BY NEUTRON FLUX MEASUREMENTS

Boyd's^{21,22} stroboscopic light experiment showed bubbles forming on a site at 25 to 60 per second. Boyd then inserted a boiling device into a reactor and observed the noise created on an ion chamber signal by the boiling phenomena. The boiling created broad band neutron noise, as detected by the ion chamber, in the 10 to 50 cps range. Boyd found that the boiling noise on the detector signal increased with increased heater power to the boiling device and, at the same time, the frequency band width increased in the upper direction. He concluded that nucleate boiling "can be detected by means of an ion chamber located in the vicinity of the boiling".

Colomb and Binford⁸ observed changes in the power spectral density of the Oak Ridge Research Reactor between the boiling and nonboiling case. They suggested further investigation of the effect for boiling detection. Fry, et al²⁴, followed up this suggestion by obtaining a detailed frequency spectrum of the reactor with one flow channel orificed to produce boiling conditions. At a reactor power slightly under that calculated to produce boiling they observed a resonance at 2 cps which they attributed to bulk boiling. Power spectral density measurements at lower reactor powers showed a peak at 11 cps and a magnitude increase "roughly as the square of reactor power at frequencies below 14 cps." Further investigation, however, showed these same phenomena under normal, nonboiling, operating conditions. The location of the 11 cps peak was shown to be dependent on coolant flow regardless of reactor power. The investigators concluded "that if nucleate boiling indeed occurred, its presence was not observable in any of the spectra obtained during the boiling test."

Measurements reported by Rajagopal²³ on the Saxton pressurized water reactor showed a resonance at 16 cps which he attributed to nucleate boiling. A second peak at 13 cps appeared in the runs with the higher average coolant temperatures. Coolant temperatures ranged from 526° to 531°F for the boiling tests.

Jordan²⁵ reports power spectral density measurements for boiling in the 3 Mw Ground Test Reactor. A coolant (water) flow channel was orificed to produce boiling conditions. Boiling was first indicated by thermocouple and ion chamber response at 2.35 Mw. It showed a repeatable hysteresis down to 1.62 Mw. The neutron noise showed resonances at 0.33 cps and multiples thereof up to 2.3 cps during the boiling.

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IV. CONCLUSIONS AND RECOMMENDATIONS

The dependence of acoustic frequency spectrum on environment indicates the possibility of correlating the boiling detection signal with boiling location for a particular system. Another area for examination is the acoustic frequency range below 100 cps. One would expect the amplitude at frequencies from 0 to 50 cps to increase with boiling and bubbles unless these phenomena were already swamped out by other low frequency noise. Measurements (kilocycle range) made at SRE showed large acoustic resonances already present in the system from pump noise, etc., without boiling. The determination of sensitivity of a method is vital to its use in a system. Boiling work in the sodium loop¹⁸ at Santa Susana should include the above investigations and should concentrate on method sensitivity in the presence of other flow noises.

Review of the neutron flux measurements indicates a need to determine the maximum distance from a void at which an ion chamber can detect the void and to correlate this distance with the size of the void. Further investigations are also required to define the fine spectra of the low frequency components of neutron noise in the presence of nucleate boiling. Correlation of amplitude of low frequency noise with boiling intensity should be more fully investigated.

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