Simulation of Water/Steam into Sodium Leak Behavior for an Acoustic Noise Generation Mechanism Study

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Abstract

This simulation first allows us to define a transition zone from a bubble to jet mode of the argon out-flow and hereinafter to define a similar area for water-steam leak in the KALIMER SG (Korea Advanced Liquid Metal Reactor Steam Generator) using a water mock-up system, taking into account the KALIMER leak classification and tube bundle design, as a simulation of a real water-steam into sodium leak. In accordance with leak conditions in the KALIMER SG, the transition from bubbling to jetting is studied by means of turbulence regime simulation for argon out-flow through a very small orifice, which has the equivalent diameter of about 0.253 mm. Finally the noise generation mechanism is explained from the existing experimental data. We also confirmed the possibility of micro-leak detection from the information of the bubbling mode through simulations and the experiment in this study.

Key Words : acoustic leak detection, steam generator, hydrogen and argon bubble, noise generation, sodium-water reaction, KALIMER

1. Introduction

The simulation of a water steam into liquid sodium leak behavior by means of a gas jet into water injection is widely applied for developing an acoustic leak detection system using in an industrial SG as a more accessible, more secure and cheaper approach for the substantiation of the adopted design solutions, and testing of the designed devices for both equipment and the

advancing of a developed system as a whole.

Unconditionally, this simulation does not fully mirror the actual process of a water steam into sodium leak in the SG because of the absence of simulation procedures for background noise, which is always present in an SG, and because of the absence of chemical reaction noise, which is always present during a water steam into sodium leak.

The imperfection of this simulation approach

can be compensated for in the future by means of a background noise investigation on an industrial SG in operation and measurement of the acoustic noise of a water steam into sodium leak in an experimental test facility during the subsequent development stages of the KALIMER acoustic leak detection system (KALDS).

Experimentally it has been established that the water steam in sodium leak in an SG represents a long-lived multi-stage intrinsic process by the concrete design of a tube bundle of an SG, structure material of the heat-transfer tube of an SG, place of leak originating and thermal parameters of water steam and sodium. Nevertheless, outgoing from the capability of a leak detection system and avoidance of secondary leaks, the classification of a water steam into sodium leak for a large (The flow rate is more than 1 kg/sec.), intermediate (The flow rate is in the range of 1 g/sec ~ 1 kg/sec.) and small leak (The flow rate is less than 1 g/sec.) is generally accepted.

From the point of view of thermodynamics and acoustics such classification does not mirror the entity of a water steam into sodium flow out process. Actually, in a range of increase for the water steam leak from 0.01g/sec up to 1kg/sec there exists at first the bubble, and then jet mode of the water steam into sodium leak. Finally, from the point of view of hydraulic gas dynamics, the bubble and jet modes of a leak can be successfully modeled by means of the controlled injection of gas into water. This simulation allows us to define a transition zone from bubble to jet mode of argon flow out and hereinafter to define a similar area for a water steam leak in the KALIMER SG. These outcomes are essential for acoustic measurement of a water steam into sodium leak both for the sodium test facility and in conditions of an industrial SG

The subject of this study is first the determination of the transition from bubbling to jetting for argon gas into water injection, taking into account the KALIMER leak classification [1] and tube bundle design, as a simulation of a real water steam into sodium leak. In accordance with leak conditions in the KALIMER SG, the transition from bubbling to jetting is studied by means of turbulence regime simulation for argon   outflow through a very small orifice, which has the equivalent diameter about 0.4 mm. Finally the noise generation mechanism is explained from existing experimental data.

2. Equipments and Experiment

The experimental equipment of the water mock-up is shown in Fig. 1. The container for the acoustic leak experiment was constructed with stainless steel 304, and its sizes are height 2000mm, diameter 500mm and thickness 10mm. The water pump is installed to be able to circulate the water inside the container, which is for making the moving condition of water like the circulation condition of the SG, which is the upstream flow direction of water. The gas injection system consists of a low-pressure bomb that is for low flow supply, and a high-pressure bomb that is for a high flow rate with high-pressure condition. It is possible to supply the pressure up to 120kg/cm^2. In this equipment it is possible to measure the temperature of water inside the container, which is for determining the situations of acoustic noise generation in acoustic system.

The surface outside the container was installed with a wave-guide with a length of 300mm and diameter of 5mm, and three acoustic sensors were installed at the top of the wave-guide at intervals of 500mm. The acoustic sensor was used with model SE1000-H of which can be installed or detached from the sensor adapter of the DECI as shown in (A) of Fig. 1. The power adapter was

installed like as pre-amplifier between the acoustic sensor and data acquisition board (Model; GAGE CS-512).

The signal analyzer was programmed with the LabVIEW of the National Instrument, of which analysis is possible by inputting the 4-channel signals, and by saving the signal data in a Pentium personal computer. The sampling was 1024byte(1 word) which is possible to save with a raw signal and the results of the Fast Fourier Transform (FFT) to be filtered by the hamming window.

The injector was made so that the diameter of the hole is 0.253mm as shown (B) in Fig. 1. The hole was made with a hole length of 5mm using the electrical charge method, feeding by 0.33, 0.63, 1.42, 1.83 cm^3/sec of argon gas at 1kg/cm^2 into water, and another experiment was for changing the pressure, 10kg/cm^2 and 20

kg/cm^2, which is to be controlled with the high flow rate. The flow rates are 247cm^3/sec at 10kg/cm^2, and 499cm^3/sec at 20kg/cm^2. The results of the experiment were obtained from the acoustic sensor installed at the highest position of the three of acoustic sensors.

3. KALIMER SG in the Jet Regime

The simulation of a water steam into sodium leak by means of argon into water injection should be implemented pursuant to the requirements of the KALIMER project both for the economizer (sub-cooled part), and for the super-heater part of the SG.

It is important to note, from these figures, that the KALIMER tube bundle arrangement designed preliminarily, as shown in Fig.2 and Fig.3, allows
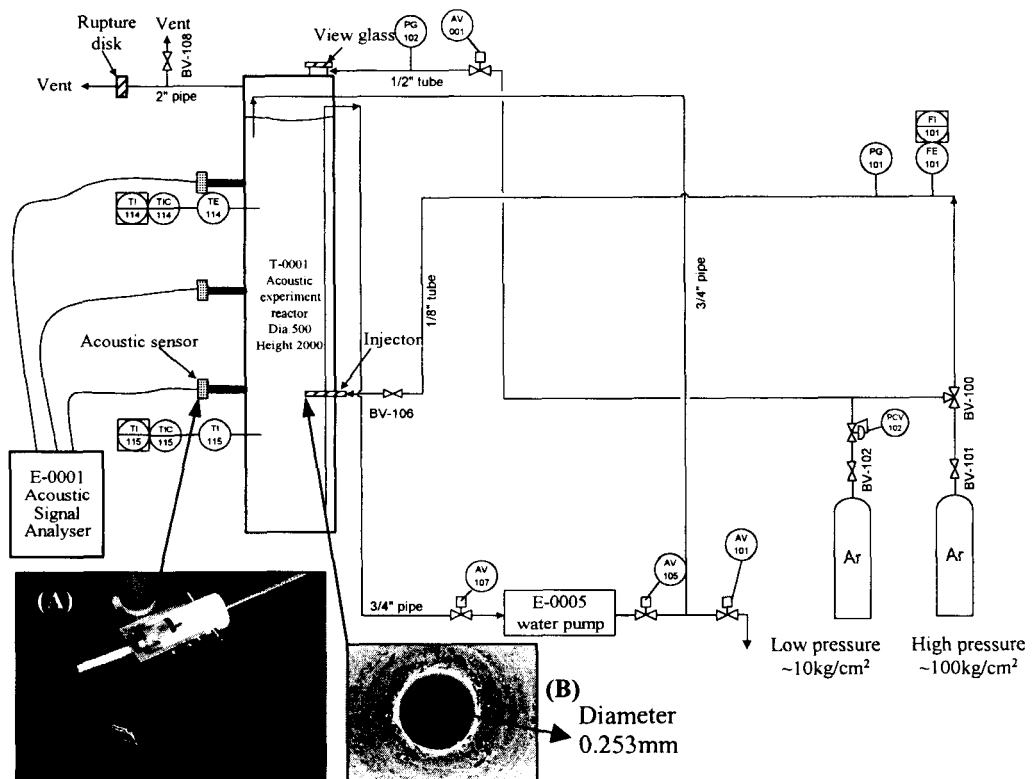

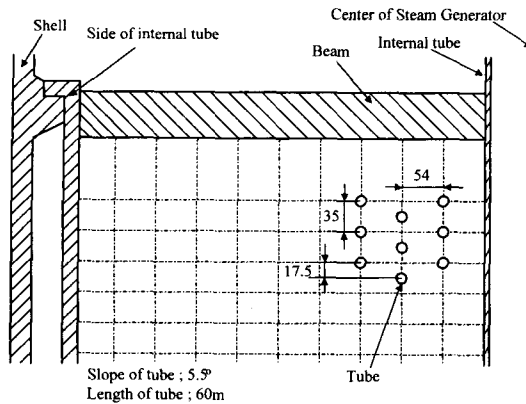Fig. 1. The Schematic Diagram of the Experimental Equipment System

Fig. 2. KALIMER Tube Bundle Arrangement

Fig. 3. KALIMER Tube Bundle Design

us to realize a more beneficial possibility with comparison between the conditions of the BN-600 and SuperPhenix SG for leak detection and secondary leak protection. First of all, it provides more time for detecting a leak of the same rate.

In our mock-up experiments the conditions of the unchanged parameters are the differential pressure of argon gas and the size of the defect. It was established [2], that for the water steam into sodium leak, which has its flow rate more than 0.1 g/sec (material of tube - steel 2.25 Cr - 1Mo) the size of the defect should be about 0.1 mm.

Apparently, in accordance with the location of a leak (in a part of the KALIMER tube bundle in the superheater or economizer) the transition of a leak from a bubble mode to an jet mode will descend at different values of the water-steam leak. Thus the determining influence on the process of expiration will render the kinematic viscosity and rate of sound velocity in an elapsed steam-water mixture. The sound velocity [3] in a steam-water mixture in the conditions of the SG was determined, as shown in Fig.4 and Fig.5.

Therefore, the volume-flow of a small water steam leak in the sub-cooled regime of an SG will be in the limits from 0.013 cm^3/sec based on a water-steam leak of 0.01g/sec up to 1.3 cm^3/sec
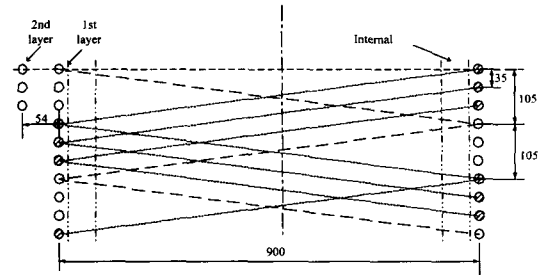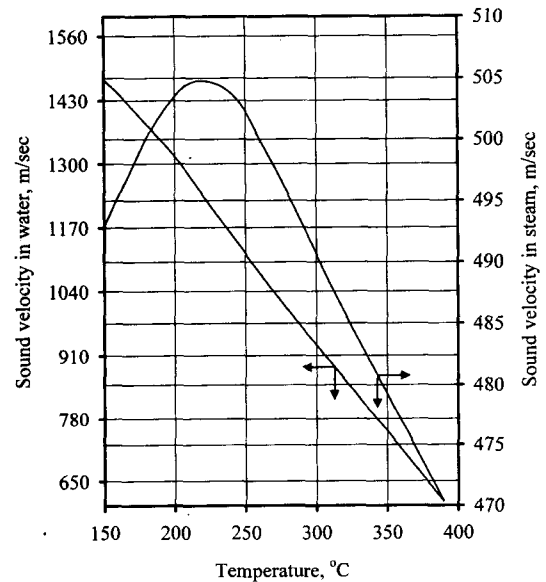

Fig. 4. Sound Velocity on a Water-Steam Saturated Line

based on a water-steam leak of 1g/sec. In the super-heated regime of the SG it will be equal to 0.131 ~ 13.1 cm^3/sec based on water-steam leak of 0.01 ~ 1 g/sec, as shown in Table 1. According to these conditions, the volume-flow of argon at the injection in water should be in the limits from approximately 50 up to 100 cm^3/sec, for injection rate equal to 0.1~0.2g/sec, in which it is very simply calculated by using the density of a water-steam mixture and argon gas.

The transition to the turbulence regime for the KALIMER SG in its bottom tube bundle part is

Table 1. The Characteristics of the Water-Steam Mixture in the Three Regions of the KALIMER SG

Design leak rate(g/sec)	Sectioned region in KALIMER SG	Volume fraction of steam	Temp.($^{\circ}$C), Pressure(Atm), Density(g/cm^3)	Sound velocity of mixture (m/sec)	Real steam leakate (cm^3/sec)
0.1	Subcooled region	0	280 175 0.775	1420	0.13
	Saturated region	0.6	350 165 0.106	275	0.94
	Superheated region	1	375 160 0.076	480	1.31
0.01	Subcooled region	0	280 175 0.775	1420	0.013
	Saturated region	0.6	350 165 0.106	275	0.094
	Superheated region	1	375 160 0.076	480	0.131

expected by a water-steam flow rate of $(1 \sim 10)$ 10^{-3} cm^3/sec for water-steam flow rate 1×10^{-3} cm^3/sec estimated Reynolds number (Re) is equal to $Re_{0.001} = 357$. For argon gas injection this regime is expected by an argon gas flow rate of approximately $(1 \sim 10)$ cm^3/sec For water-steam flow rate 1×10^{-3} cm^3/sec. estimated Reynolds number (Re) is equal to $Re_{0.01} = 1111$.

4. Mechanism of Noise Generation During Injection of Argon Gas into Water

4.1. Mode of Argon Motion

During argon out-flow into water, acoustic signals origination (noise of a leak) depends on the property of argon-gas, the mode of its motion through an efflux channel and on the property of water. Basically during argon out-flow its motion through an efflux channel can be molecular or viscous. In the conditions of the experiment, during gas out-flow with over-pressure; the molecular motion of argon through an efflux channel is inaccessible.

The viscous motion of argon through an efflux channel can be laminar or turbulent. During laminar motion, owing to the high orderliness of motion, the acoustic signals are missed. During the turbulent motion of argon through an efflux channel there are transient vortexes, which produce a wall boundary pulsation of pressure oscillation (pseudo-sound pressure) and a lone acoustic signal of leak noise (noise of a turbulence).
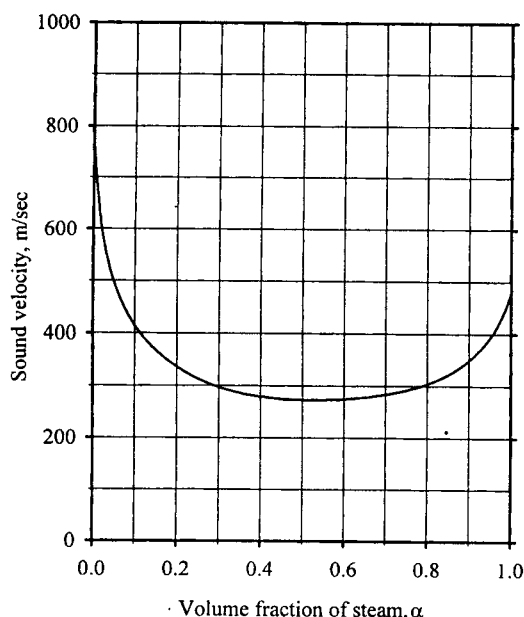
Fig. 5. Sound Velocity in the Water-Steam Mixture for Different Steam Volume Fractions

4.2. Bubbling Mode of Argon Out-Flow

During argon out-flow into water at very small pressure differentials the gas progression is precluded by the demarcation surface of argon and water in the exit section because of the surface tension forces of water. The motion of argon bubbles start at a definite pressure differential, sufficient for overcoming the surface tension forces of water. Thus, in the region of the exit section of an efflux channel the argon bubbles will be derived. The arising acoustic signals have a pulse nature and are connected to the dynamic effects at the collapse and separation from the foramen of out-flow of each bubble of gas. At a pressure differential increase the cause of acoustic signals generation is the splitting of a gas jet into separate bubbles.

The volume oscillation frequency of argon bubble in water can be determined under the following formula for its Mode [4], [5].

For 0 Mode,

$$f_o = \frac{1}{2\pi R_o} \sqrt{\frac{3\gamma P_o}{\rho_w}} \tag{1}$$

For 2 Mode, 3 Mode, and then,

$$f_n = \frac{1}{2\pi R_o} \sqrt{\frac{(n^2-1)(n+2)\sigma}{\rho R_o}}, \quad n = 2,3,..... \tag{2}$$

The radius of an argon bubble; R_0, can be determined for the equilibrium condition under the following relationship at the moment of its separation from the defected injection nozzle.

$$d\sigma = (\rho_w - \rho_{Ar})\frac{4}{3}\pi R_o^3. \tag{3}$$

Using equation (1), (2), (3) and the results of the experiment as shown in (A) and (B) of Fig. 6, the size of defect could be calculated. From results published [8, 9], the jet type leak dimension of the defect can be established equal to 0.1 mm and more than 0.1 mm. For a bubbling leak this dimension of a defect is equal to 0.01 mm and less than 0.01 mm.

The peak of maximum frequency is moved to the side of the high frequency band as shown in (B) of Fig. 6, according to an increase of the gas flow rate. When based on the above prediction and the explanation in Table 2, in the jetting of a high flow rate of argon gas into water, the bubble size seems to reduce. In the reverse, we can predict that if the peak frequency is located to the high frequency band, the bubble size will decrease during argon gas jetting or under another jetting situation such as Hydrogen gas or under a real leak situation such as a water-steam into sodium leak.

For understanding the properties of frequency in the above experiment, the resonant frequencies of argon bubbles in water for this condition are presented in Fig. 7. In Fig. 7, the resonance frequencies as shown in Eq. (2) are in the 0 Mode
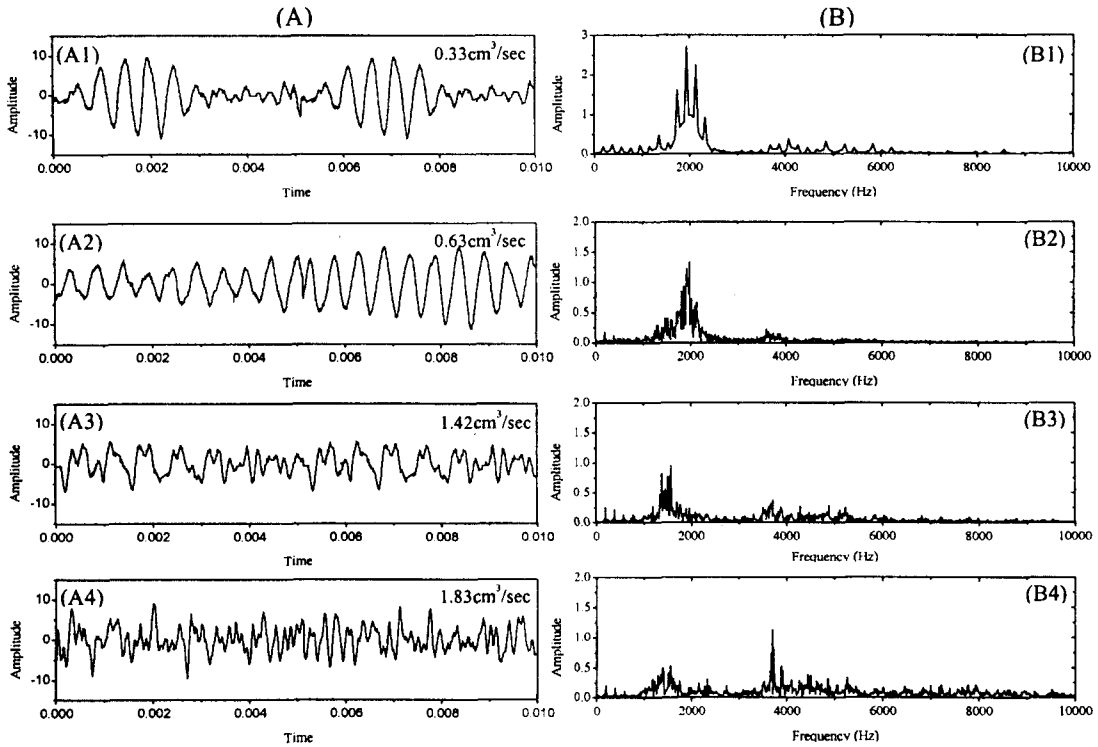
Fig. 6. Patterns of Raw Acoustic Signals and FFT Results for the Signals Relative by Changing the Flow Rate, When Injected with Argon Gas to the Water Phase

Table 2. Hydrodynamics of Argon Gas into Water Injection Experiments

Exp. No.	Flow rate, cm3/sec	Number of Mach	Number of Reynolds	Argon gas injection flow characteristic
1	0.33	0.02	118.5	Argon gas flow is stable, no flow separation, no vortex, and no turbulence.
2	0.63	0.039	226.4	Argon gas flow has become slightly unstable.
3	1.42	0.088	510.5	Argon gas flow has becomes early stage of turbulence.
4	1.83	0.114	657.8	Argon gas flow has becomes early stage of turbulence.

with the motion of expansion and contraction of the bubble by itself, in the 2 Mode with the motion up and down perpendicularly, and in the 3 Mode with non-spherical motion on the interface between the phases of argon gas and water. Each resonance frequency in 2 Mode and 3 Mode are as follows, the resonant frequencies of 0.77mm argon bubble size in water for the defect size of 0.253mm for this experimental injector are 2177Hz in 0 Mode, 70Hz in 2 Mode,
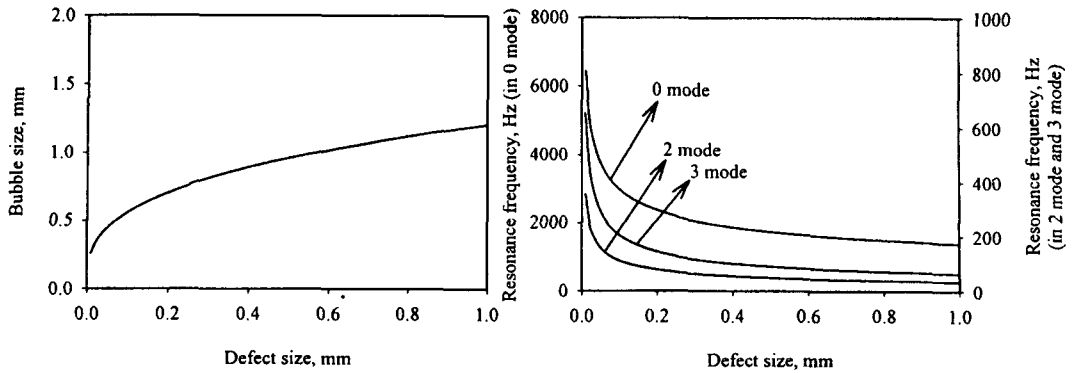
Fig.7. Oscillation Frequency Characteristics of Argon Bubbles in Water

and 128Hz in 3 Mode as shown in Fig. 7. The oscillation resonance frequency of the regime in the bubbling of argon gas, 2177Hz, can be identified near the frequency band of about 2kHz in Fig. 6.

At this moment, the argon pressure inside the bubble associated with the surface tension of water is following with Eq. 4, which is calculated with using Eq. 3. The pressure inside of bubble, p_i, is larger than P_0 1.73% in the case of mm, 0.3% in the case of d=0.01mm, comparing the difference between P_0 and $2\sigma/R_0$ which is negligible.

$$p_i = P_o + \frac{2\sigma}{R_o} \qquad (4)$$

4.3. Turbulent Argon Flow through an Efflux Channel

The turbulent flow of argon through an efflux channel arises at a velocity conforming to the Reynolds critical number,

$$Re = \frac{(2r)\rho v}{\mu} \qquad (5)$$

For the calculation of the argon efflux it is necessary to allow for its compressibility, and also pressure loss, bound with the activity of friction

forces. Then, the maximum flow velocity could be determined, and the argon gas velocity in turbulence is nearly similar to the sound velocity in the jet regime. Therefore, we can express with the relationship as follows, and it is also possible to predict the minimum size of the equivalent defect in the turbulent regime.

$$(2r) = \frac{\mu Re_c}{c\rho_{Ar}} \qquad (6)$$

4.4. Wall Boundary Pressure Pulsation

The acoustic signals at the out-flow of argon in water can arise due to the pressure pulsations on the channel walls owing to a non-steady-state flow. These pulsations are conditioned by a vortex formation at the turbulence. The frequencies of these pulsations are determined by the frequency of vortex formation, which can be determined with the following formula.

$$f_s = Sh\frac{v_h}{2r}m, \qquad (m = 1,2,3\ldots\ldots) \qquad (7)$$

Using equation (7), for the well-developed turbulence the Strouhal number is Sh=0.2 and the main energy of the pressure pulsation is massed in the low frequency field.

For an argon jet into water injection this frequency should start from approximately $f=252kHz$. The used values for the calculation are that the sound velocity is 319m/sec, the defect size is 0.253mm and the Strouhal number is 0.2. Thus, from the reduced relations it follows that the pressure pulsation due to turbulence are low enough. During the argon out-flow into water through a mesh size defect, the frequency of the lowest overtones can not get in an effective range from above is $f_1=9.252MHz$, $f_2=2 \times 0.252MHz$, $f_3=3 \times 0.252MHz$ and then it is like that.

These frequencies decrease with an increase of the defect size. A similar effect also produces the slowing down of argon gas out-flow. Thus, for argon out-flow into water, the pressure pulsation can also give an acoustic signal.

4.5. Jet Noise

According to Lighthill' s theory of aerodynamic sound [6], sound is expected to be such a very small component of the argon jet motion that, once generated, its back-reaction on the main flow of the argon jet is usually negligible.

The aerodynamic sound generated by a turbulent argon jet can usually be attributed to several different sources. As usual the gas flow regime is determined by means of the Mach number. Thus,

$$M_{Ar} = \frac{v}{c_{Ar}} \tag{8}$$

If assuming the argon flow to be adiabatic, the Mach number to express another one will be as follows.

$$M_{Ar} = \sqrt{\frac{2}{\gamma - 1} \left(\left(\frac{P_r}{P} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right)} \tag{9}$$

According to this formula the local velocity of

the argon jet will be approximately equal to the sound velocity in argon, when $P_r /P > 2$.

For a turbulent argon jet into water, wide frequency band noise primarily in the range of 1 ~ 20 kHz is generated [5]. The cause of noise origination is the turbulent mixing of an argon jet with ambient water, which is called the mixing noise. An increase above a pressure drop more than twice in an elapsed jet of argon shocks cells downstream and a choking of the flow appears. This phenomenon leads to the formation of the jet noise spectra. The typical jet noise spectra are presented in Fig. 8 [6].

In Fig. 6, the row acoustic signals and the FFT spectra of its signal for 0.33, 0.63, 1.42, 1.83cm^3/sec argon jet into water are presented. It is clear from these results that the regime from the bubbling mode for a flow rate of 0.33 cm^3/sec increases in the flow rate of the argon jet and passes to an early stage of the jetting mode with a flow rate of 1.83 cm^3/sec. Around 1.83 cm^3/sec it seems that the regime is transition from a bubbling situation to a jetting situation, which is clearly indicated in the experiment with a high pressure of 10kg/cm^2, 20kg/cm^2 as shown in Fig. 9. Fig. 9 show that the high flow rate is influenced with mixing noise of a higher frequency than near 2kHz. The conditions of these experiments were same as the experiment with a small flow rate in Fig. 6.

5. Conclusions

From these experimental and simulated results, we show the possibility of detection of a micro-leak or small leak to simulate bubbling and jetting. The main experimental and calculated results of the given work can be formulated as follows;

- We could show that experimental techniques and acoustic measurement instrumentation allows us to simulate and measure and to identify the
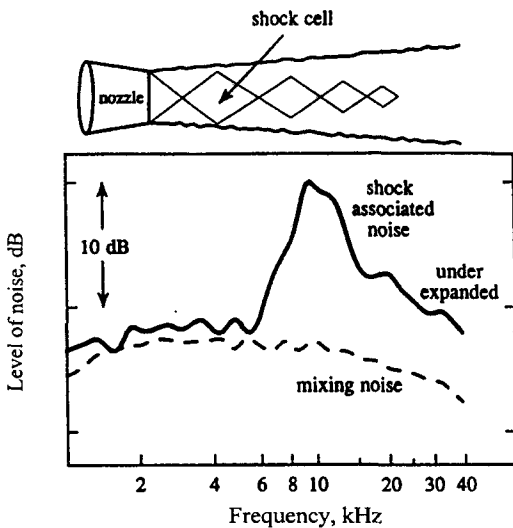
Fig. 8. Jet Noise Spectra for a Shock-Free and Under Expanded Jet

bubble and jet modes of a leak in the KALIMER SG by means of controlled injection of argon in water, and to identify the oscillations of separate bubbles at the expiration of argon in water.

- We applied the defect size, 0.253mm, which was generated the frequency of about 2kHz band in this experiment. This frequency band was nearly similar within the simulated results, and the frequency band was mainly the signal detected with AE sensor same as the frequency band generated by Mode 0, the volumetric oscillation

of contraction and expansion.

- The obtained results allow us to pass to the subsequent development stages of the acoustic leak detection system in the KALIMER SG, namely, to study resonance sound absorption on argon bubbles in the conditions of a micro leak. The following stages are in the next work.

- It is necessary to expand the experimental capabilities at the expense of using a special injecting device for the controlled injection of argon under pressure, conforming to the pressure of water-steam in the KALIMER SG, through a defect with a minimum equivalent diameter of 0.01 mm designed specially for micro-leak detection.

- It is necessary to realize the acoustic measurement of the jet mode of a leak for study of the factors influencing the leak of a jet mode and on the detection time defined in the KALIMER SG. And we will experiment with several defect sizes and flow rates similar with the operational conditions of KALIMER SG.

Acknowledgment
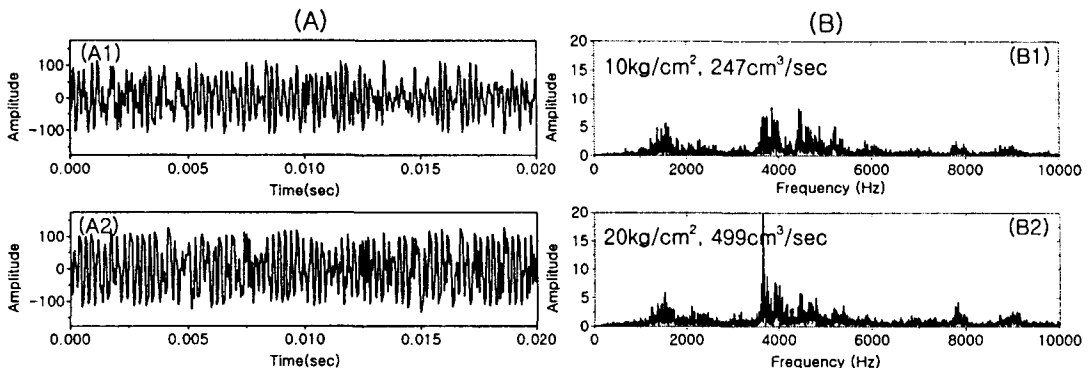
Fig. 9. Patterns of Raw Acoustic Signals and FFT Results for the Signals

Nomenclature and abbreviation

c Isothermal sound velocity in argon flow

C_{Ar} Local velocity of sound

d Orifice diameter of injector (defect size)

f_n Oscillation resonance frequency in n Mode

n Number of over-tone (2, 3...)

m Number of over-tone (1, 2, 3...)

p Local pressure in the argon jet

P_i Instantaneous pressure inside the bubble

P_0 Static pressure in the liquid

P_r Argon pressure value before the injection device

r Equivalent radius of the defect

R_0 Radius of argon bubbles in water.

Sh Strouhal number

v Gas velocity

v_h Gas velocity of argon

AE   Acoustic Emission

KALDS   KALIMER Acoustic Leak Detection System

KALIMER   Korea Advanced LIquid MEtal Reactor

SG   Steam Generator

Greek Letters

$\gamma = C_p / C_v = 1.67$

μ Dynamic viscosity of argon

ρ_w Density of water

ρ_{Ar} Density of argon

σ Surface tension

$\lambda = \dfrac{L}{2r}$ Aspect ratio of the channel

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