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Dynamics in Neighbored Two Steam Jets Condensation in Subcooled Water
- Proposal of a New Parameter -

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Abstract

In order to understand the effect of steam jet interaction on the pressure oscillation in submerged steam jet condensation, typical three types for two-hole steam jet condensation test were considered; a case where the two holes are located in opposite direction each other and no interaction between jets are expected (B-type), a case where the two holes are located up and down and continuous interactions are expected (C-type), and a case where two holes are located with some angle and interactions are expected only near the holes (D-type). Overall oscillation trend of two-hole test was similar with that of single-hole, however the frequencies were lower than single-hole test. For a few test sets of C- and D-type, where the two jets were close and not overlapped, two dominant frequencies were observed. From this fact, it was found that the concentrative condensation occurs in the end part of jet. In particular, the dominant frequencies of B-type were lower than those of single-hole, in spite that there was no interaction between jets. This phenomenon was successfully explained by introducing liquid velocity of boundary layer near steam jet. In order to check the effect of liquid velocity once more, tests with much less water inventory in pool were performed, and the lower frequencies were obtained.

1. Introduction

Submerged steam jet condensation in a subcooled water pool can occur in a number of industrial operations. In particular, Advanced Power Reactor 1400MW (APR1400), an advanced type of pressurized water reactor (PWR), is currently under development. One of the key features of the APR1400 is to adopt an In-containment Refueling Water Storage Tank (IRWST) and spargers in it, which increases the quenching efficiency of steam and alleviates probable pressure surge induced by the sudden discharge of the high pressure steam from Reactor Coolant System (RCS) during postulated accident (La et al., 1999). In order to properly design the sparger and to predict the thermal hydraulic phenomena in the postulated accident, it is essential to understand the phenomena of submerged steam jet condensation in multi-hole system. Especially, the pressure oscillation during steam jet condensation may directly damage the structures or resonate with the structures. Eventually, the structure may be directly damaged or the fatigue can cumulate in them.

Steam jet condensation has been interested in following four areas; jet shape and length, heat transfer coefficient, condensation regime map, and pressure oscillation. Most of these have been investigated as the function of steam mass flux, pool subcooling (pool temperature) and nozzle diameter. For the wide range of steam mass flux and pool temperature, the jet penetration length and heat transfer coefficient have been studied. For the condensation regime map, Cho et al.'s (1998) covers up to steam mass flux 450kg/m^{2}s and pool temperature 95℃ as shown in Figure 1. Pressure oscillation was also studied by several investigators. Chan (1978) measured the oscillation frequency and found that the frequency is inversely proportional to nozzle diameter. He explained it by the aid of Rayleigh bubble equation. But, in 1982, he together with Simpson (1982) again suggested an experimental frequency correlation using Strouhal number for frequency (St), steam Reynolds number (Re) and pool Jacob number (Ja). The frequency is proportional to steam mass flux and pool subcooling, but inversely proportional to nozzle diameter. More intensive study was conducted by Damasio et al. (1985) with a good many test sets up to maximum steam mass flux 250kg/m^{2}s. They also suggested an similar experimental frequency correlation to Simpson et al.'s (1982), but added Weber number (We) for the better prediction. Nariai et al. (1986) analytically studied on the pressure oscillation, and well predicted experimental data. Hong (2001) measured the oscillation frequency for the steam mass flux 200~900kg/m^{2}s and pool temperature 30~95℃. He found that when the steam mass flux was under 300kg/m^{2}s the frequency increased as the steam mass flux increased, however when the steam mass flux was over 300kg/m^{2}s the frequency decreased as the steam mass flux increased. He explained this trend related with condensation regime map. Also, he proposed a simple model for the pressure oscillation and showed good agreement with experimental data. However, all these have been for the single nozzle or single hole. Cho et al. (2001) investigated the pressure oscillation in 20-hole sparger. However, this study did not explain the effect of jet interaction with neighbored jets.

Therefore, the objective of this study is to investigate the effect of jet interaction on the pressure oscillation in two-hole system. Two-hole system is the simplest system of multi-hole system. Thus, this study is a fundamental study toward multi-hole system. Three typical types of two-hole were considered; diverging in opposite direction, arranged in up and down and arranged with some angle. Each test result was compared with single-hole test result and each other. From this comparison, we found another new important parameter that significantly affected the steam jet condensation.

2. Description of Experiment

GIRLS (General Investigation Rig for Liquid/Steam Jet Direct Contact Condensation) was constructed as shown in Figures 2 and 3, and the used spargers are shown in Figure 4. All water was demineralized and degassed. Saturated steam from a steam generator was provided through a main steam line, and the flowrate was controlled by flow control valve. Cylinder pool was used in this study, whose diameter is 1.8m, height 1.5m, water level 1.3m. Sparger was specially manufactured as a dual pipe in order to prevent heat loss of submerged part. And the sparger was a pipe of 1 inch and schedule 40. Near the end of the sparger, the steam was horizontally discharged into subcooled water through the hole of diameter 10mm. The submergence of the steam jet is 1.1m. In the cylinder pool, a cooling system was installed for the sake of easy control of pool temperature, and acoustic sponge covered the inner wall in order to prevent the resonance of pressure oscillation with the wall.

The uncertainties of measurement instruments are listed in Table 1. For the dynamic pressure transducers (DPTs), noise level tests were conducted, and the maximum noise level was turned out to be about 1.6Pa (Hong, 2001).

Important test conditions are presented in Table 2. Pool temperature was represented by the average of 6 measurements. The standard deviation of pool temperature was maintained within 0.5℃, and that of steam flowrate was within 2.0kg/hr during the measurement time.

3. Development of Data Analysis Method

The dynamic characteristics of steam jet condensation are known to be extremely complex and to have strong randomness. Thus, it is very difficult to find the dominant frequency. Fourier transform (or Fast Fourier Transform (FFT)) is known to be a powerful tool to find the frequency by transforming the time domain to frequency domain. Based on this FFT, an advanced method to analyze the frequency was developed. The idea is based on the averaging method. In other words, the total samplings, at first, are divided into several subsets, and each set is processed by FFT. Then each result is the set of pair of frequency and complex number. The complex number is again expressed as polar form with amplitude and phase. For the same frequency of each set, the corresponding amplitudes are averaged throughout the subsets. These processes were coded with C++ computer language, and named as GAPF (GIRLS Analysis Program based on FFT). GAPF has the effect of several tests by just one test, and the randomness greatly decreases. The GAPF makes the curves smooth and makes it easy to find the dominant frequency. More detailed description, benchmarking, and performance are attributed to Hong (2001).

4. Experiments and Discussions

Figure 5 shows the results of the effect of direct jet interaction or its boundary layer interaction for steam mass flux about 200kg/m^2s and pool temperature about 45℃ in this study. As shown in Figure 6, the closely neighbored jets can interact with each other, or their boundaries can interact. Thus, in some tests of C- and D-series, the effect of interaction was revealed as the form of two frequency peaks and frequency shift. In Figure 5, differently from A- and B-series, two peaks of frequency can be clearly seen. The frequency peak, which is expected if it were not for the interaction, was designated as primary frequency, and the other peak of frequency as secondary peak in this study.

The summarized results for primary frequency are presented in Figure 7 for A-, B-, C- and D-series, respectively. Regardless of sparger type, the overall trends of B-, C-, and D-series are similar to that of A-series. Figure 8 compares the result of each type of sparger for each pool temperature. And the secondary frequencies in C- and D-series are presented for some tests. There did not always exist the secondary frequency. In C-series, the secondary frequencies was always generated at the pool temperature 35℃ and 45℃ for the tested steam mass flux (<500kg/m^2s), and were generated at the pool temperature 55℃ only when the steam mass flux is lower than 128kg/m^{2}s. In D-series, the secondary frequencies were always observed ed at the pool temperature 35℃, and at pool temperature 45℃ they were found only when the steam mass flux is lower than 400kg/m^{2}s.

Even though the secondary frequencies were detected in C- and D-series only for limited conditions, the demolishing mechanism of the secondary frequency as the steam mass flux increases is completely different. Generally, the submerged jet tends to expand when the jet progresses. Thus, in type C (C-series) when the jet length is prolonged, the jet overlaps the neighbored jet and the two jets behave like a single jet. Figure 6 shows that the jets are just before being overlapped or that the jet are nearly overlapped. In type D (D-series), as the jets are prolonged, the ends of jets get too far from each other to interact. Here, from the consideration of these facts for C- and D-series, it can be induced that the important part of the steam jet for the direct contact condensation is not the beginning part but the end part.

Carefully observing the Figure 6, it is very reasonable that the important part is the end of jet for condensation. At the jet end the steam jet breaks up into extremely many small bubbles, and the interfacial heat transfer area between vapor and liquid enlarges enormously. Thus, striking condensation occurs at the end part of the jet. Kim, H. Y. (2001) concluded similarly. He performed a numerical analysis for steam jet shape using the method of characteristics, and compared the shape of steam jet with that of non-condensing jet. From this analysis, he found that the shapes of the beginning parts of the jets are similar with each other, and concluded that the heat transfer in beginning part of jet is negligible.

For the region where secondary frequencies do not appear, the frequencies of the two-hole tests were lower than those of the single-hole test. Especially, C-series showed the lowest frequency among all types of sparger considered in this study. Generally, the frequency is inversely proportional to the jet diameter (Chan, 1978; Simpson et al, 1982; Sonin, 1984; Damasio et al. 1985, Nariai et al. 1986). In type C, when the steam jet is prolonged, the jets are overlapped each other and behave like a single jet. At this time, the effective diameter is enlarged, and the resultant frequency is lowered.

For D-series, the secondary frequency appeared when the pool temperature was lower than 45℃ and the steam mass flux was lower than 388kg/m^{2}s (D45388). For the test D45388, the distance of jet ends can be calculated as shown in Figure 9. The jet length can be calculated from the correlation of Kim, H. Y. (2001), and the resultant length is 29.7mm. Noting that the outer radius of pipe is 16.9mm, and the distance of holes is 20mm, the distance of jet ends is 65.6mm from the cosine theorem. Therefore, when the pitch-to-diameter (P/d_0) is over about 6.6, the interaction of jet is expected not to appear. Referring to Cho et al. (2001), the effect of jet interaction appears at $P/d_0=5$, which is the maximum P/d_0 of their study.

For B-series, even though there is no interaction between jets, the frequencies are always lower than the frequencies of A-series as shown in Figure 8. Moreover, the frequencies of B-series are very similar to those of D-series for the steam mass flux over 300kg/m^2s, where there are no secondary frequencies. This fact is related with liquid velocity near the jet, which is a new finding of this study, and will be discussed in next section.

5. Effect of Ambient Liquid Velocity

5.1 Discussion on the Effect of Liquid Velocity

Traditionally, steam jet condensation is usually explained only by steam mass flux and pool temperature. Kerney et al. (1972) explained that the pool temperature is the driving potential for the condensation and that the steam mass flux is the transport modulus, which is familiar to Stanton number of convective heat transfer. However, using only these two parameters, there is no way to explain why the frequencies of B-series are lower than those of A-series and why those of B-series are similar to those of D-series.

Looking at the Figure 8 again, the frequencies of B-series are lower than those of A-series by the amount that is expected when the pool temperature rises by 10℃. However, it is very unreasonable to assume that the local pool temperature near the steam jet is higher by 10℃ in B-series.

In order to solve the problem, we newly introduced liquid velocity near the jet. The relative velocity between liquid and steam jet is important in the steam jet condensation. The velocity in water side is developed by interfacial shear between steam and water as shown in Figure 10 (a). The actual velocity profile in Figure 10 (a) can be converted into relative velocity profile using reference velocity as the steam mean velocity in Figure 10 (b). Figure 10 (b) shows that the development of velocity is similar to the velocity profile in the classical boundary layer problems, except that the velocity is faster by the amount of the relative interfacial velocity (actual interfacial velocity vector minus mean steam velocity vector). In the relative coordinate without incident liquid velocity, the fully developed velocity of liquid is corresponding to the steam mean velocity. Under the condition of no incident liquid velocity, the liquid velocity near the steam jet can be determined uniquely by the steam velocity. Hence, the steam jet condensation can be explained by the steam mass flux, as the previous investigators did. However, if the liquid is issued in the front of steam jet, then the resultant fully developed velocity of liquid in relative coordinate becomes smaller by the incident velocity as shown in Figures 10 (c) and (d). In the stand of velocity profile, only the relative interfacial velocity is decreased by the amount of incident velocity.

The fully developed velocity is important in convective heat transfer, and the heat transfer is generally proportional to the velocity. The slower velocity results in the lower heat transfer, and the steam jet inevitably becomes longer in order to condense all the injected steam. The prolonged length of steam jet induces the lower frequency (Hong, 2001). Noting that the steam jet condensation considered in industries occurs mainly not in infinite medium but in finite pool and that the pool circulation is absolutely formed in finite pool, the liquid velocity also should be counted in order to explain the dynamics of steam jet condensations, moreover to explain the phenomena of steam jet condensation, since the pool circulation largely depends on the geometry of pool.

Using above explanation on the liquid velocity, apparently the liquid velocity is faster in B-series than in A-series, since the B-series have the twice of the driving potential of A-series for the same steam mass flux. Thus, the jet length in B-series is longer than that in A-series, and resultantly the lower frequencies were obtained. The pool circulation of D-series is similar to that of B-series, and the frequencies of D-series, when there is no effect of jet interaction, are similar to those of B-series.

5.2 Application to Previous Works

In the classical turbulent submerged jet, the jet is composed of initial region, transition region, and fully developed region (Blevins, 1984 Chap. 9) as shown in Figure 11. Initial region or the core is corresponding to the jet length for the case of steam jet condensation. For such a submerged turbulent jet, when the jet issues into fluid flowing in the same direction as the jet, it is called as co-flow jet. One of the characteristics for the co-flow jet is that the initial region is prolonged proportional to the velocity of co-flowing stream. Such a phenomenon is identical with the above explanation on the jet length by incident liquid velocity.

Chun, J. H. (1983) and Sonin et al (1986) explained that the condensation heat transfer is related with liquid turbulent intensity. And the heat transfer increases as the turbulent intensity increases. When the stream velocity near the steam jet increases, the difference between liquid velocity and steam velocity decreases, and resultantly the turbulent intensity is also expected to decrease. Thus, the steam jet becomes long and the frequency decreases. As like this, the explanation with turbulent intensity can cover the effect of incident liquid velocity.

Cho et al. (2001) reported the effect of pitch-to-diameter for the sparger of 20 holes. They showed that the frequency increases as the pitch-to-diameter increases. Such an effect of pitch-to-diameter (P/d_0) can be partially explained by the velocity profile in liquid side. If the pitch-to-diameter is smaller, the steam jets can intensively and concentratively push the pool water and the more rapid liquid velocity is formed near the jets. Thus the frequencies of smaller pitch-to-diameter become lower. Of course, the local pool temperature between jets are also an important parameter. When the jets are closer, the higher local pool temperature is formed. Thus, since both the local pool temperature and liquid velocity increases as the pitch-to-diameter decrease, the effect of pitch-to-diameter is consistent.

The effect of liquid velocity can be seen in steam jet length. Even though Kerney et al, (1972) and Kim, H. Y. (2001) took the similar definition on the steam jet length, the length by Kerney et al. is slightly longer than that by Kim, H. Y.. Such a difference also can be partially explained by liquid velocity. The pool used by Kerney et al. was 0.76m high, 0.76m wide and 1.52m long rectangular bath. The pool by Kim, H. Y. was a horizontal cylinder pool with diameter 1m and length 1.5m. The smaller pool results in more rapid liquid velocity. Thus, the length by Kerney et al. is longer than that by Kim, H. Y..

5.3 Tests with Smaller Water Inventory

The easiest way to show the effect of liquid velocity using type A sparger is to perform the tests with smaller water inventory. As shown in Table 2, the I-series were conducted with about 30% water inventory of A-series for two steam mass flux. The test results are presented in Figure 12. For all temperatures the I-series resulted in the lower frequencies than A-series, as expected

6. Concluding Remarks

Experimental apparatus GIRLS was set up, and GAPF was developed based on FFT and averaging technique. For two-hole test, typical three types were considered; a case where the two holes are located in opposite direction each other and no interaction between jets are expected (B-type), a case where the two holes are located up and down and continuous interactions are expected (C-type), and a case where two holes are located with some angle and interactions are expected only near the holes (D-type). Each hole was 10mm diameter, and distance between the centers of hole was 20mm.

Overall trend of two-hole tests was similar to that of single-hole test, however the frequencies were lower than single-hole test. For a few test sets of C- and D-type, where the two jets were close and not overlapped, two dominant frequencies were identified. As the steam jet gets long, for type C the two steam jets collapses, and for type D, the two jets gets far enough not to interact each other. From this fact, it was found that the concentrative condensation occurs in the end part of jet. In particular, the dominant frequency of B-type was lower than that of A-type, in spite that there was no interaction between jets. This phenomenon was successfully explained by introducing liquid velocity of boundary layer near steam jet. This fact also successfully applied to several previous works. In order to check the effect of liquid velocity once more, tests with much less water inventory in pool were performed, and the lower frequencies were resulted in.
In further study, the effect of liquid velocity should be quantitatively evaluated.

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Table 1 Uncertainties of Instruments

Instruments	Uncertainties
TC (K-type)	0.6℃
PT	0.0005MPa (0.5kPa)
FT (Vortex Type)	1.35% for reading value 4kg/hr for 300kg/hr
DPT (Piezoelectric Type)	Negligible delay of response (its natural frequency: 15kHz)
Steam Table	0.05%

Table 2 Test Matrix and Important Test Conditions

Test Series	Sparger Type	Water Level (m)	Submergence (m)	Pool Temperature (℃)	Steam Mass Flux (kg/m^2s)
A-series	A	1.3	1.1	35~95	200~900
B-series	B	1.3	1.1	35~95	100~500
C-series	C	1.3	1.1	35~95	100~500
D-series	D	1.3	1.1	35~95	100~500
I-series	A	0.4	0.2	35~85	400, 800

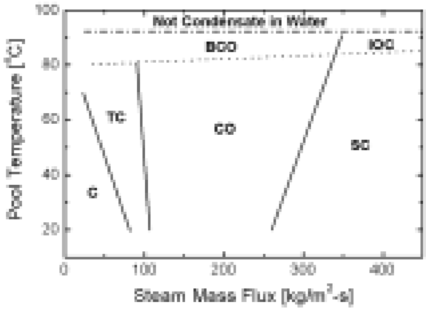
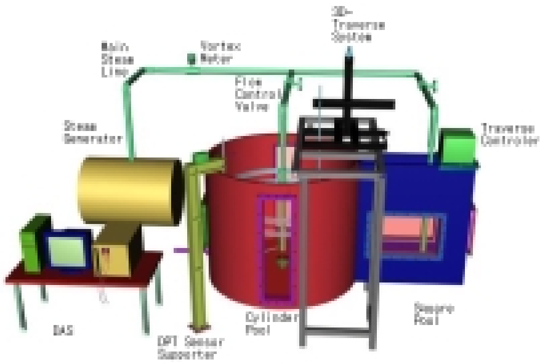


Figure 1 Condensation Regime Map by Cho et al. (1998)



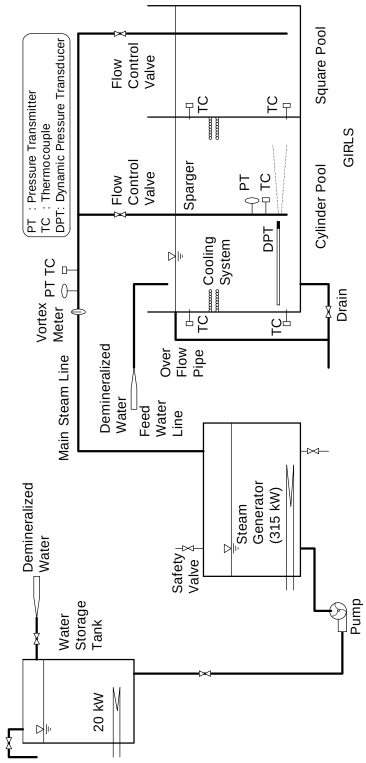


Figure 2 Bird's Eye View of GIRLS **Figure 3 Schematic Diagram of the Test Facility**

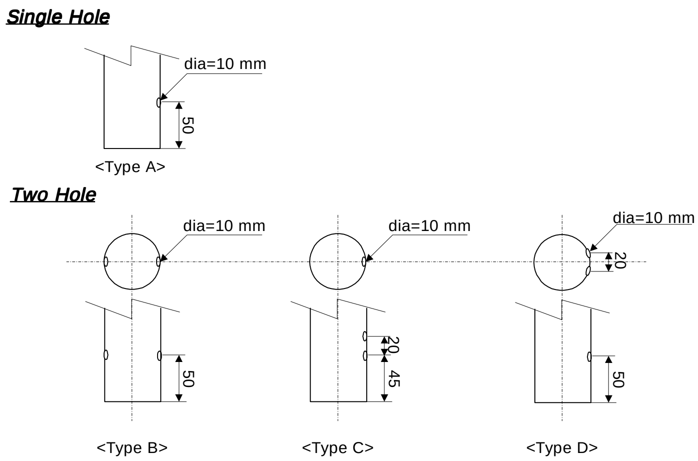


Figure 4 Designation of Sparger in This Study

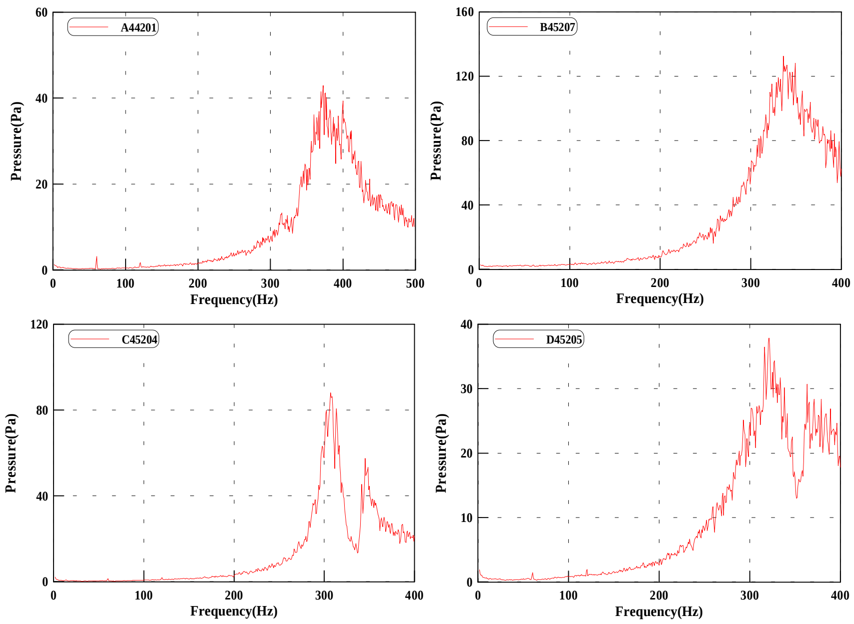


Figure 5 Secondary Frequency in C-series and D-series

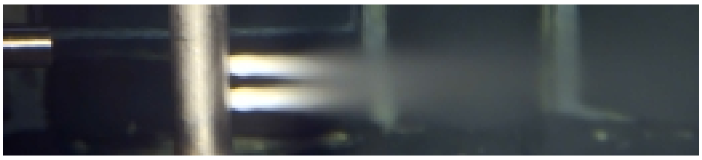


Figure 6 Photograph of C-series Test

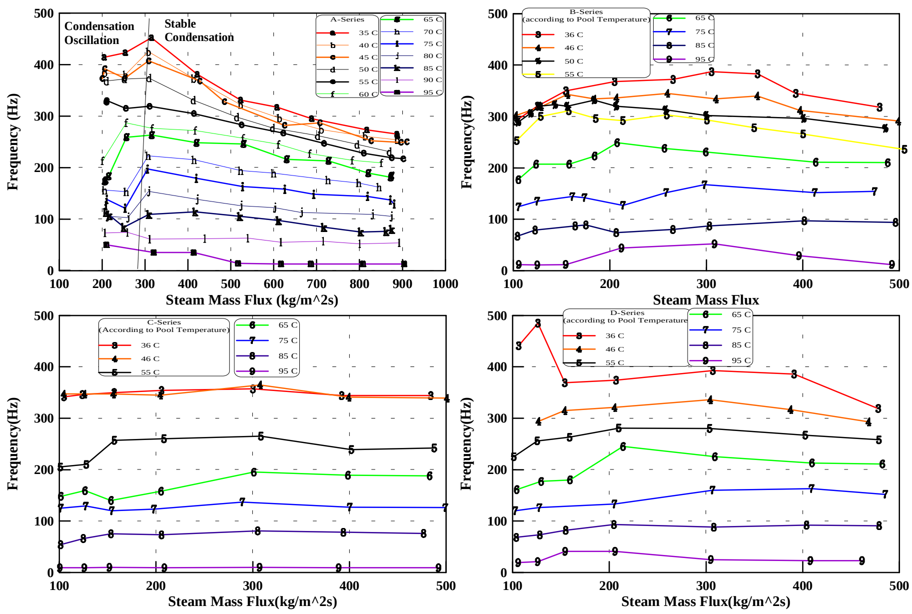


Figure 7 Test Results (Frequency vs. Steam Mass Flux)

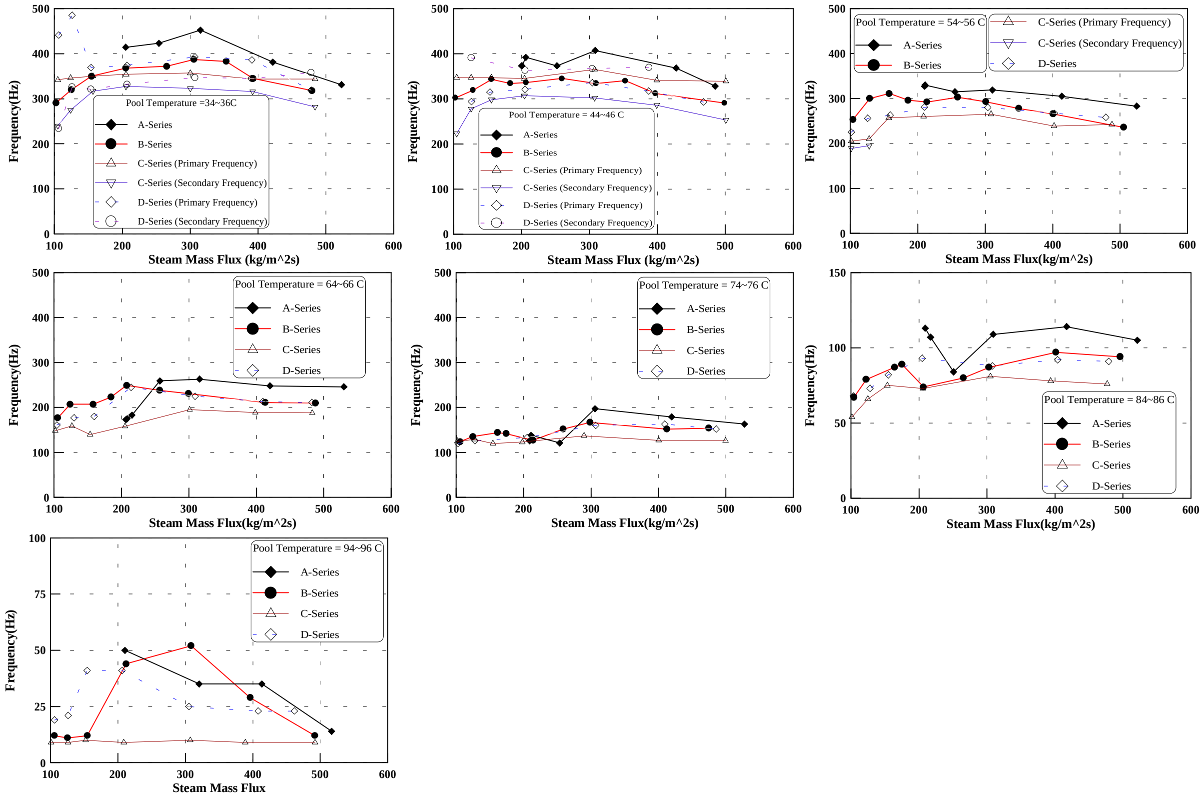


Figure 8 Comparison of Frequency for each Pool Temperature

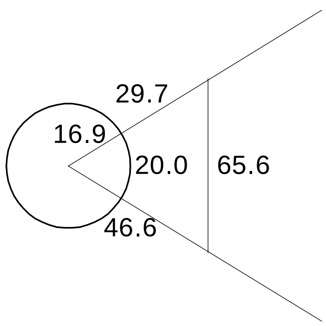


Figure 9 Distance of Jet Ends at D45388

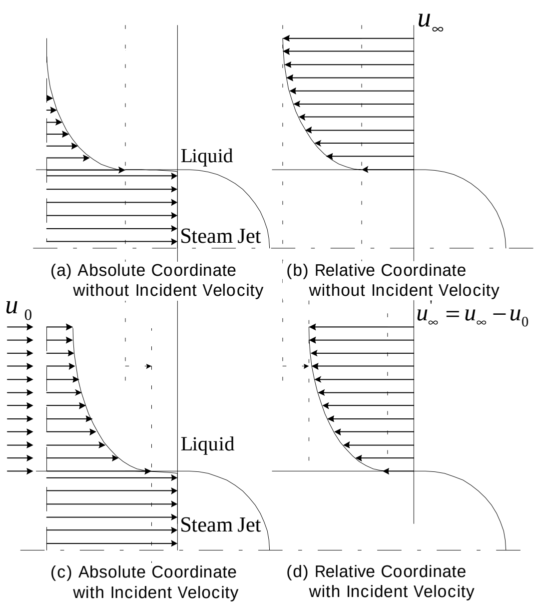


Figure 10 Velocity Profile near the Steam Jet

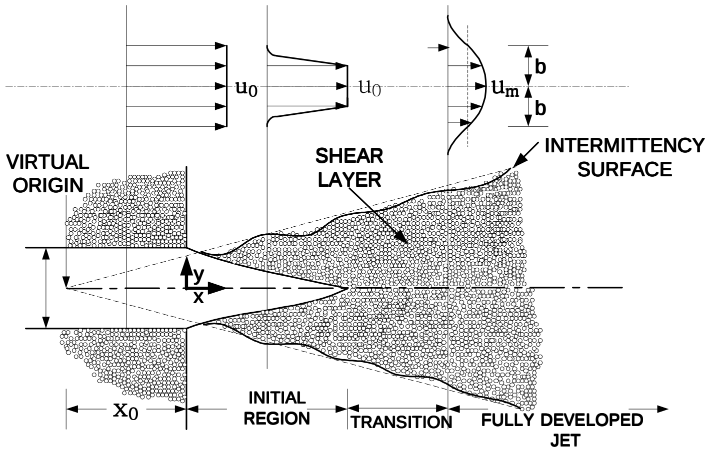


Figure 11 Submerged Turbulent Jet

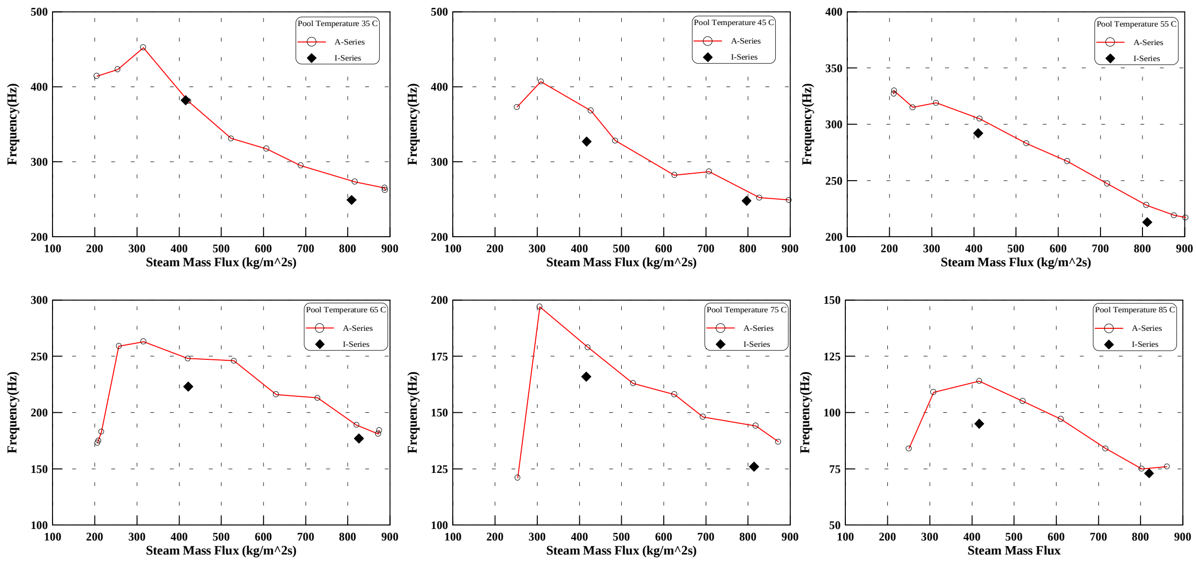


Figure 12 Results of I-series and Comparison with A-series