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Characteristics of pressure oscillation induced by direct contact condensation of steam discharged through sparger in a pool of subcooled water

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ABSTRACT

A experimental study was carried out to present the characteristics of pressure oscillations generated from the steam-water direct contact condensation(DCC). Steam is discharged through an I-type spargers whose pitch over diameter(P/D) ratios vary from 2 to 5. Dynamic pressure was measured at the quench tank side wall by using a piezo-electric type pressure sensor. The test conditions were restricted to condensation oscillation. The amplitude and frequency of the dynamic pressure resulting from the DCC of the steam jets discharging into subcooled water has been measured as a function of steam mass flux and water temperature. Steam is discharged in a horizontal direction through eight different kinds of I-type spargers placed in the middle of a quench tank, which contains subcooled water at various temperatures. Eight different spargers with a hole diameter of 5mm were used under the various test conditions of the steam mass flux in the range of 70 ~ 215 kg/m^2-s and the pool water temperature in the range of 30 ~ 95°C. In the present study, two different types of hole-patterned-sparger were used, i.e. staggered and parallel type spargers.

It is observed from the test results that the trends of dynamic pressure in the case of using a multi-hole discharging device(sparger) are very similar to those using a single-hole discharging device(nozzle) in spite of the fact that the amplitude shows quite different values. The dynamic pressure tends to increase with pool temperature at the beginning. The amplitude reached a peak at a pool temperature around 50 ~ 80°C depending on the kinds of spargers and the steam mass flux and then the amplitude decreased rapidly before the pool water reached saturation temperature. The peak amplitude tends to increase slightly with an increasing P/D ratio with the same types of spargers. The amplitude at the low steam mass flux reached its peak when the pool temperature is about 50 °C, but this temperature increases with the steam mass flux, the amplitude peak at the relatively high mass flux was found at around 80 °C. The frequency of pressure oscillation is also analyzed by using the fast Fourier transformation technique from the original data. The results show that the dominant frequency increases with the subcooling temperature of water, the P/D ratio of sparger and the steam mass flux. The dominant frequencies lie in the range of 120 ~ 760Hz.

1. INTRODUCTION

Direct contact condensation (DCC) phenomena will be encountered in various pieces of components of a nuclear power plant during some transient or accident conditions. For example, in the loss of coolant accident (LOCA) of a pressurized water reactor, steam and hot water may come into direct contact with cold water provided from the emergency core cooling system in several locations such as the cold leg, the downcomer, the hot leg , and the upper and the lower plenums. DCC phenomena are also expected to occur in the in-containment refueling water storage tank of the Korea next generation reactor when the reactor depressurization system valves or the pressurizer safety valves are open to discharge steam into the tank through spargers. All of these operations involve direct contact condensation. Therefore, an understanding of the DCC phenomena, such as the characteristics of dynamic pressure pulse will be very useful for ensuring the structural integrity of the reactor systems and their safe operations. Although a large number of studies on the DCC phenomena have been previously investigated theoretically and experimentally due to its wide applications, details of the phenomena are not well understood yet. Chan(1978) investigated the details of sonic jet dynamics with a parametric study of pool subcooling, steam mass flux, and nozzle diameter. He reported pulse amplitude increases with jet diameter and increasing pool temperature, but it decreases rapidly near saturation temperatures in every case. Similar results had been obtained by Sonin(1984) who proposed the dynamic pressure loads in the pool peak at a finite subcooling in the order of 20K, and approach very small values as subcooling approaches zero. Simpson et al. investigated the basic mechanism of steam jet condensation at relatively low mass flux, and observed that the dynamics of subsonic jets are quite different from those of sonic jets. Cho(1998). insisted that in some operating conditions condensation takes place with unstable flow patterns; the steam jet begins to oscillate and relatively large pressure pulses are observed. They emphasized that the transition between an unstable and stable regime depends on the nozzle diameter, the steam mass flux, and the pool water temperature. The objectives of these previous works were mainly focused on the heat transfer coefficient and dimensionless jet length to correlate them with a steam mass flux and a pool water temperature. Moreover, a large number of these studies were carried out by using a single nozzle to investigate the basic mechanism of the DCC phenomena. Therefore, there are only a few systematic studies that are readily accessible to all on the characteristics of dynamic pressure pulse resulting from the condensation of steam discharging through a sparger into subcooled water in the range of test conditions such as steam mass flux, pool water temperature, and types of spargers.

It has been observed that steam injection into subcooled water produces unsteady phenomena such as chugging or condensation oscillation. These phenomena have been studied extensively concerning transient phenomena in the light water reactor pressure suppression system. Arinobu(1980) had experimental studies to investigate the dynamic phenomena for chugging and condensation oscillation taking place in the low steam mass flux conditions and insisted the frequency of dynamic pressure pulse decreases with increasing pool temperature, and nozzle diameter. But the frequency increases with increasing steam mass flux. According to these experimental observations, he proposed the frequency relation in Eq.(1).

$$f = 0.8V/D[(C_p\Delta T)/h_{fg}]^{1.4} \quad (1)$$

where, f is the dominant frequency(Hz), V means steam velocity at the exit of the vent pipe(m/s) and D is vent pipe inner diameter(m). Aya(1980) also maintained the dominant frequency of chugging and condensation oscillation is about 2 ~ 8Hz and 100 ~ 200Hz, respectively. This simply implies the basic bubble dynamics in the case of a single nozzle(or vent tube). In order to expand this relation to a multi-hole sparger, the interaction of steam with neighboring jets and the effect of it upon pressure oscillation must be fully investigated.

The objectives of this study are to characterize the dynamic pressure oscillation with respect to amplitude and frequency occurring when steam is fed through spargers in subcooled water. The characteristics of dynamic pressure trends over a range of steam mass flux and pool water temperatures were experimentally investigated by using eight different kinds of spargers. These data will be used to construct a basic data base on the performance of several types of spargers.

2. EXPERIMENTAL METHOD

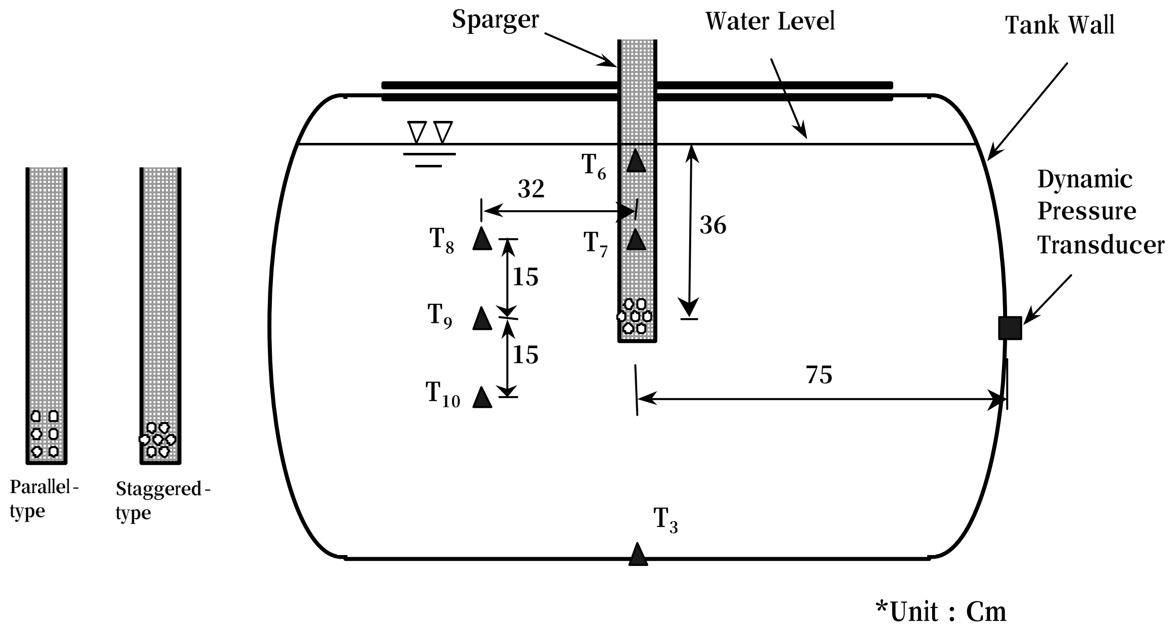

Fig. 1 A schematic diagram of sparger and the locations of instruments.

A schematic diagram of the sparger and the locations of instruments in the quench tank used in this study is shown in Fig. 1. The experimental facility consists of a steam generator, a quenching tank, steam supply lines, valves and instruments. The steam generator with electric heaters of 300kW produces steam continuously with a quality higher than 99 %. The maximum operating pressure is 1.03 MPa and the maximum steam flow rate is 0.12 kg/sec. Subcooled water is contained in a quenching tank equipped with two plexiglass windows for visual observation and video camera imaging. The quenching tank is a horizontal cylindrical tank, which is open to the atmosphere, with the diameter and length of 1 m and 1.5 m, respectively. In order to supply the wide range of steam mass flux, two different size steam supply lines were constructed between the steam generator and the discharge nozzle due to the flow range restriction of steam flow meters installed in the steam supply lines. The size of the steam supply lines are 1 inch and 1/2 inch. The preheat line, which by-passes the steam flow meter, is installed at the steam supply line in order to avoid a steam flow meter failure which might occur due to a sudden temperature increase in the initial operating conditions. The steam supply line is heated by trace heaters and insulated in order to maintain the supplied steam saturated with 100% dryness during testing. A vortex type of steam flow meter, a manual flow control valve, a drain valve, an isolation valve, a pressure transmitter, and a thermocouple are installed in each steam supply line. Eight thermocouples are also installed inside the quenching tank to measure the pool temperature, and a dynamic pressure sensor of the resistive type is installed on the tank wall, 75cm from the axis of sparger. A video camera with halogen lamps is used for taking pictures of steam jets. All signals except video images are processed using the data acquisition system, which consists of an IBM-compatible industrial computer and a 16-bit A/D converter. All the instruments were calibrated before testing. Specifically, vortex flow meter was calibrated using the so-called constant volume method by measuring the weight of overflowed water after the discharged steam condensed completely in the pool water. Eight different kinds of spargers with the internal diameter of 5mm were tested for various combination of steam mass flux and pool temperature. The steam mass flux is controlled with the manual flow control valve installed in the steam supply line. The condensation phenomena was observed through plexiglass windows located on the cylindrical tank wall and the submergence of the center line of the vertically distributed injection holes of sparger was maintained constant, during the test, about 36cm below the free surface of the pool water.

When the steam generator isolation valves are open, a small amount of water and air inside the steam supply line is discharged first. After clearing out the water and air in the line, steam from the steam generator is continuously discharged into the pool. At the initial stage of the steam discharge, it was observed that some dissolved gas in the pool changes into a lot of tiny gas bubbles, which make video camera imaging unclear. These unclear images were somewhat enhanced by using a forward lighting method. As the pool temperature increases to higher than 30 °C, the tiny gas bubbles disappear. As steam is continuously discharged into the pool, the mean temperature of the subcooled water in the quench tank begins to increase until it reaches the pre-setting value. The mean temperature was evaluated from the data of three different thermocouples located in the quench tank. Test conditions of this study can be seen in Table 1.

Table 1. Test Conditions and specifications of spargers

No. of sparger	Sp1	Sp2	Sp3	Sp4	Sp5	Sp6	Sp7	Sp8
Pattern of hole (S : staggered, P : parallel)	S	P	S	P	S	P	S	P
Total number of hole (EA)	20		21		20		20	
P/D ratio	2	2	3	3	4	4	5	5
Hole diameter (mm)	5							
Inner dia. of sparger (mm)	26.6 (1inch, Sch80 tube)							
Total hole area / Flow area of sparger (%)	70.7		74.2		70.7		70.7	
Steam mass flux (kg/m^2-s)	70 ~ 215							
Pool temperature (°C)	30 ~ 95							

3. EXPERIMENTAL RESULTS AND DISCUSSION

The condensation phenomena are classified mainly by steam mass flux and water temperature. In the case of steam mass flux lower than 55 ~ 65kg/m^2-s, chugging phenomena may occur. In some case of steam mass flux higher than 70kg/m^2-s, periodic pressure oscillation induced by oscillating movement of the Steam-water interface is observed in the pool and sparger. These phenomena are called condensation oscillation. In the present study, the dynamic pressure behavior of the wall will be described with respect to two different points, that is, amplitude and frequency. The typical pressure signals of the steam mass flux 140kg/m^2-s and when using Sp8 can be seen in Fig. 2. In Fig. 2, the pressure signals are reconstructed by using a linear interpolation method to clearly present not only the amplitude but also the frequency of original data. As can be seen in Fig. 2, the amplitude in the case of low temperature is very small but the frequency is relatively high. As the pool temperature increases, the amplitude of the dynamic pressure reaches its peak and then it decreases rapidly with decreasing subcooling. The frequency continuously decreases with decreasing subcooling. The pressure signals in Fig. 2 show that both steam mass flux and pool temperature have a strong influence on the oscillation amplitude and frequency. This influence is summarized graphically in Fig. 3 and 6. The frequency varies from 120 ~ 760Hz within the range and conditions of the present study.

3.1 Amplitude of dynamic pressure

The influence of the parameters on the wall pressure amplitude has been investigated experimentally.

Fig. 3 shows the variation of the dynamic pressure amplitude defined by the root mean square value with the variation of the steam mass flux and the pool temperature for each sparger, respectively. According to the previous work of the author(1998), it is presented that the amplitude of dynamic pressure is very closely related to the condensation mode. In other words, the dynamic pressure pulses in the condensation oscillation mode show far greater amplitude than those in the stable condensation when the pool temperature is maintained constantly. The difference of the amplitude of these two regions becomes smaller as pool temperature increases. As a result of this reason as well as the limitations of the test facility, the test conditions are limited to the condensation oscillation. It was observed from the previous studies of Tin (1978, 1982), Sonin (1984), and Cho (1998), in general, the dynamic pressure initially tends to increase with increasing pool temperature. The amplitude reaches a peak value with the pool temperature around 60 ~ 80°C, depending on the kinds of spargers or nozzle and the steam mass flux. Then the dynamic pressure decreases steeply before the water reaches a saturation temperature. This trend is also observed in the present study and presented in Fig. 3 for the eight different kinds of spargers tested with the variation in such parameters as steam mass flux and pool temperature. In the present study, the peak can be observed in the lower pool temperature range than stated above, specifically in the case of low steam mass flux conditions of Sparger-1 and Sparger-2. This trend may be described by the interaction of steam jets. The P/D ratio of Sparger-1 and 2 is 2. So steam tends to become very interactive with neighboring jets. In the process steam jets are readily combined with other jets to build a large bubble around the sparger looking just like a doughnut and, in consequence, the temperature of water in the vicinity of this large bubble-water interface increases more rapidly than the mean temperature of pool water. Chun & Sonin (1983) insisted that the peak may occur at a finite subcooling due to the facts that the necessary conditions of peak amplitude require a low enough subcooling to have a large bubble and high enough subcooling to have a short collapse time. It can be seen from Fig.3 that the peaks of the dynamic pressure are in the range of about 50°C ~ 80°C and the temperature which the peaks can be observed, in the case of constant steam mass flux, increases with the increase of the steam mass flux. It should be also noted that the amplitude increases not only with increasing steam mass flux but also with the P/D ratio of the sparger. The amplitude of staggered-type spargers is slightly larger than that of parallel-type spargers. According to these observations above, it may be said that the distribution pattern of holes is less important than the P/D effect. In this situation, it is very meaningful work to compare the thermal mixing effect of each spargers used in this study. Fig. 4 shows the temperature difference between mean temperature of pool water and the thermocouple-3, located in the bottom of the tank(see Fig. 1), with steam mass flux 71kg/m^2-s. As mentioned above, the mean temperature is calculated with three different thermocouples located in the quench tank, namely thermocouple-7, 8, 10. Therefore, the temperature difference means the potential thermal mixing performance of each sparger. Strictly speaking, the larger the temperature difference is, the poorer the efficiency of the thermal mixing. It can be observed in Fig. 4, the temperature difference of the staggered type spargers (Sp1, Sp3, Sp5) is much larger than that of the parallel type spargers (Sp2, Sp4, Sp6). For this reason, the thermal mixing effects of sparger as well as the characteristics of pressure pulse, such as amplitude and frequency, have to be considered to design and/or select a sparger.

3.2 Frequency of pressure oscillation

As mentioned above, periodic pressure oscillation is observed on the quench tank wall. The location of the dynamic pressure sensor, whose resonant frequency is greater than 60kHz, is depicted in Fig. 1(b). In the present study, the frequency of pressure oscillation is analyzed by the Fast Fourier Transformation(FFT) technique. The typical time domain signal of dynamic pressure can be seen in Fig. 2. From the original time domain signal, the frequency-amplitude relation can be obtained by FFT. Fig. 5 shows the features of the FFT results presented in the frequency-amplitude domain with the variation of pool temperature. Expect for the case of pool temperature of 90°C, all the signals are so good that the dominant frequencies can be readily selectable. Moreover, it is quite noticeable that the dominant frequency shifts to a low frequency region as the pool temperature increases. Arinobu(1980) maintained that the dominant frequency of pressure oscillation becomes lower with increase in water temperature and decrease in steam mass flux. Fukuda(1982) also asserted that the dominant frequency

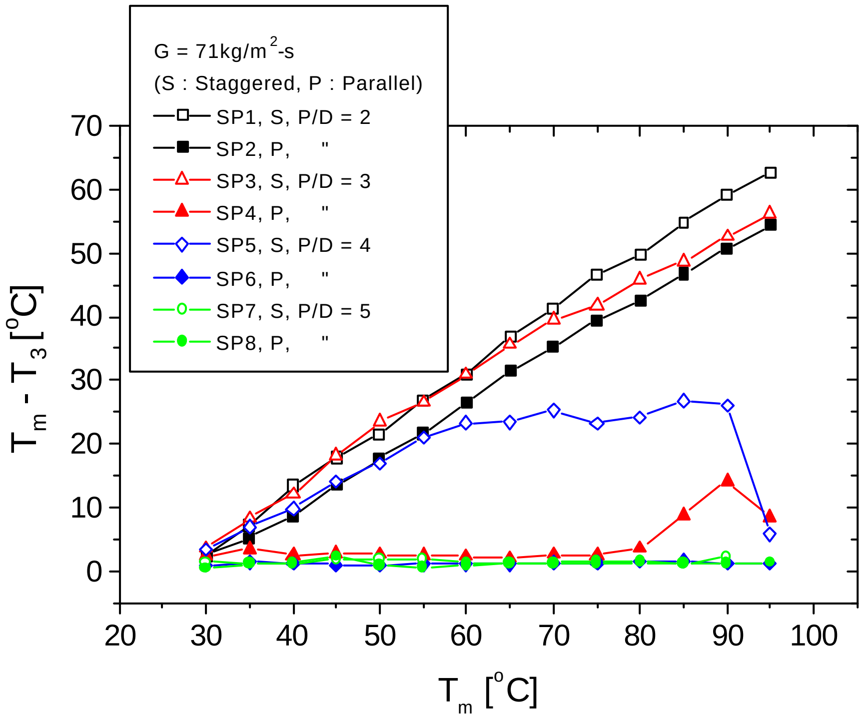

Fig. 4 The temperature difference between mean temperature and T_3 with the variation of spargers

is in proportion to the degree of pool water subcooling and in reverse proportion to inner diameter of the nozzle. In accordance with this speculation he suggested the simple frequency relation in Eq. (2)

$$f = 60.0\ \Delta T / D_i \qquad (2)$$

where, ΔT is subcooling temperature of water(°C) and D_i is inner diameter of the vent pipe(mm). In the present study, the tendencies mentioned above are also observed. In Fig. 6 the characteristics of frequency can be observed with the variations of the degree of pool water subcooling. It can also be seen in Fig. 5 and 6 that the dominant frequency is reversely proportional to the temperature of pool water. As mentioned above, the behavior of dynamic pressure is closely related to the bubble dynamics, such as size and movement of individual bubbles. In low temperature conditions, discharged steam has a tendency to break up into small bubbles whose speed is relatively fast and their lifetime is quite short. As pool temperature increases, the size and lifetime of the bubbles gets larger. Accordingly, the dominant frequency decreases with increasing pool temperature. The dominant frequency slightly increases with steam mass flux(see Fig. 6(a), (b)). Moreover, as the P/D ratio increases the dominant frequency also increases(see Fig. 6(c)). Thus it is reasonable to think that the configuration of sparger, such as hole pattern, P/D ratio, etc., as well as dimensions of the sparger is also an important factor in affecting the frequency. The reason why the dominant frequency increases in proportion to the increase in steam velocity and P/D ratio is not clear. The mechanism regarding steam bubble oscillation in water has to be studied more precisely. It is noted that the dominant frequencies presented in this study are dependent on the dimension of a system. Accordingly, to understand the characteristics of frequency it is strongly recommended that additional studies with various kinds of spargers must be carried out.

4. CONCLUSIONS

Experimental investigations on dynamic pressure induced by direct contact condensation of steam discharging into subcooled water have been performed for eight different kinds of spargers under various conditions of steam mass flux and pool water temperature. The main parameters affecting the trend of the dynamic pressure are the steam mass flux and pool water temperature. The amplitude of the dynamic pressure on the wall shows a peak at a finite pool temperature of around 50°C ~ 80 °C. The P/D ratio has strong effect on the amplitude. As the P/D ratio increases, it can be observed that the amplitude of the dynamic pressure also increases. The effects of distribution pattern of holes is relatively smaller than that of P/D ratio. Otherwise, the thermal mixing effects of staggered-type spargers, specifically when the P/D ratio is less than 5, are much poorer than the parallel-type. Consequently, the thermal mixing effects of a sparger, as well as the characteristics of the pressure pulse, such as amplitude and frequency, have to be considered to design and/or select a sparger. The dominant frequency which is analyzed by FFT increases with the degree of pool water subcooling, P/D ratio of sparger and steam mass flux. The dominant frequencies lie in the range of 120 ~ 760Hz.

The values of the amplitude and frequency presented here are system dependent. Nonetheless, the values represent a step toward classifying the dynamics of pressure oscillation commonly induced by direct contact condensation of steam discharging through various types of spargers in a pool of subcooled water.

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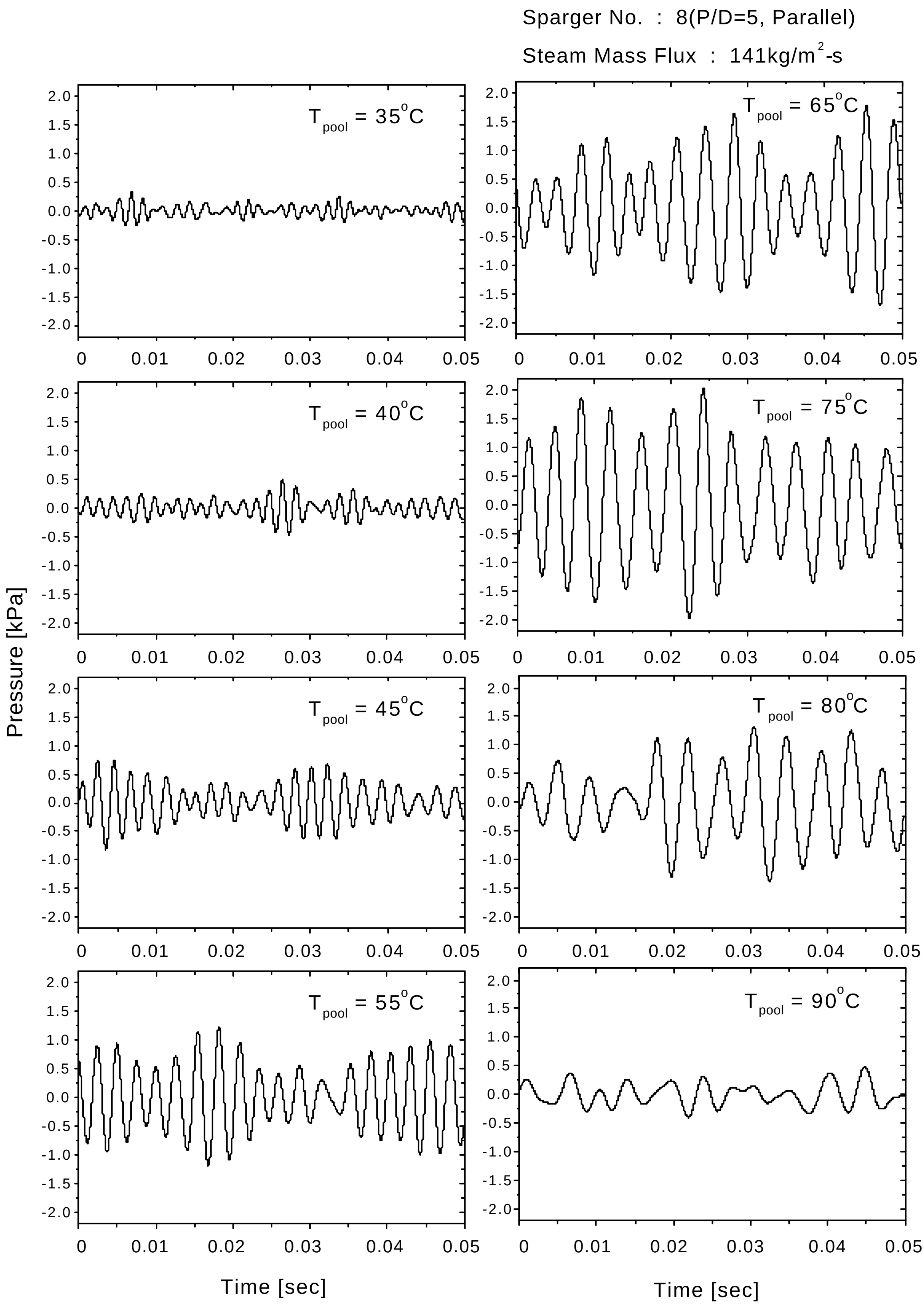

Fig. 2 Dynamic pressure signal measured at the wall with the variation of pool temperature. (No. of sparger : 8, Steam mass flux : G=141kg/m²-s)

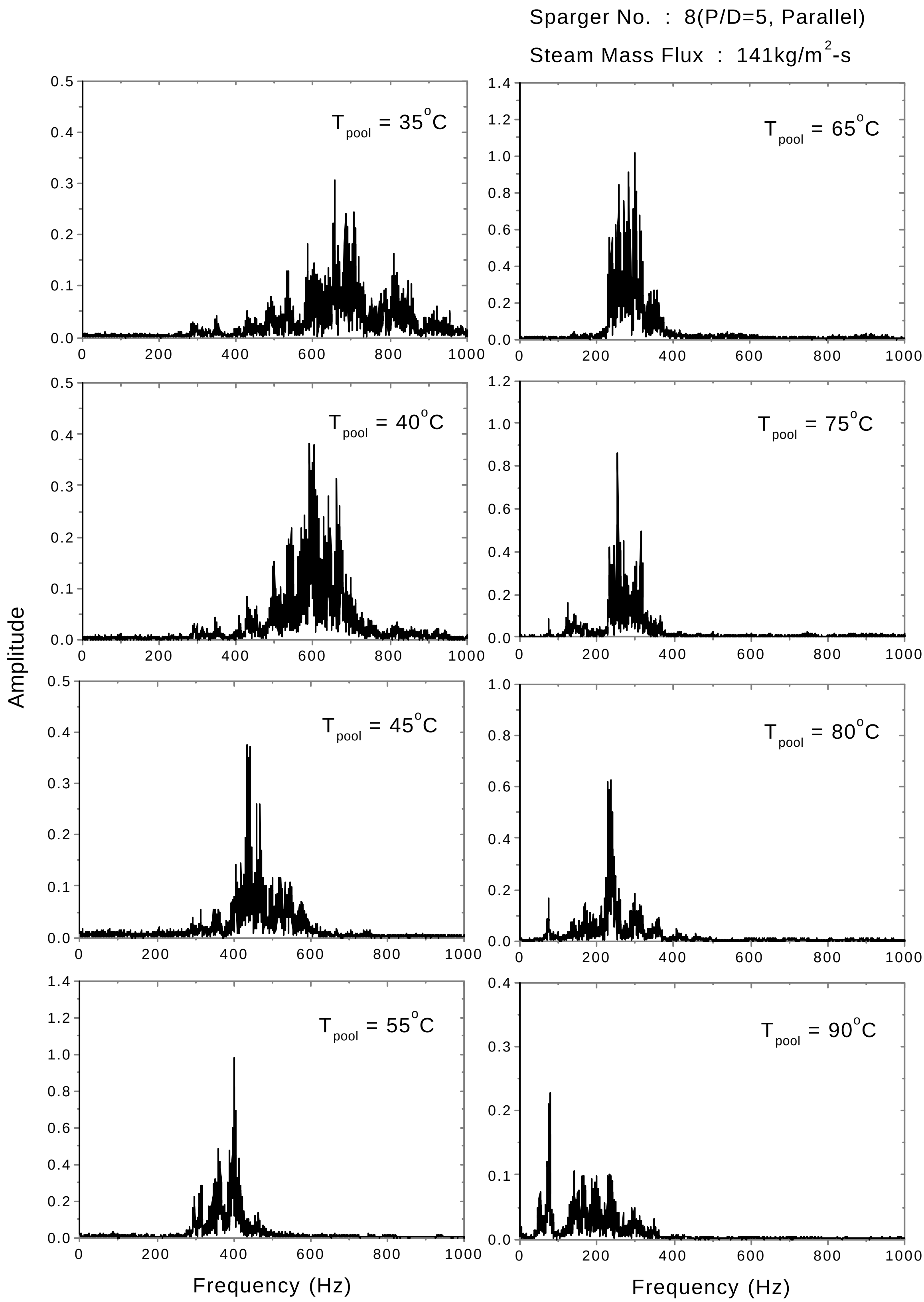

Fig. 5 Results of frequency analysis by FFT (No. of sparger : 8, Steam mass flux : G= 141kg/m²-s)

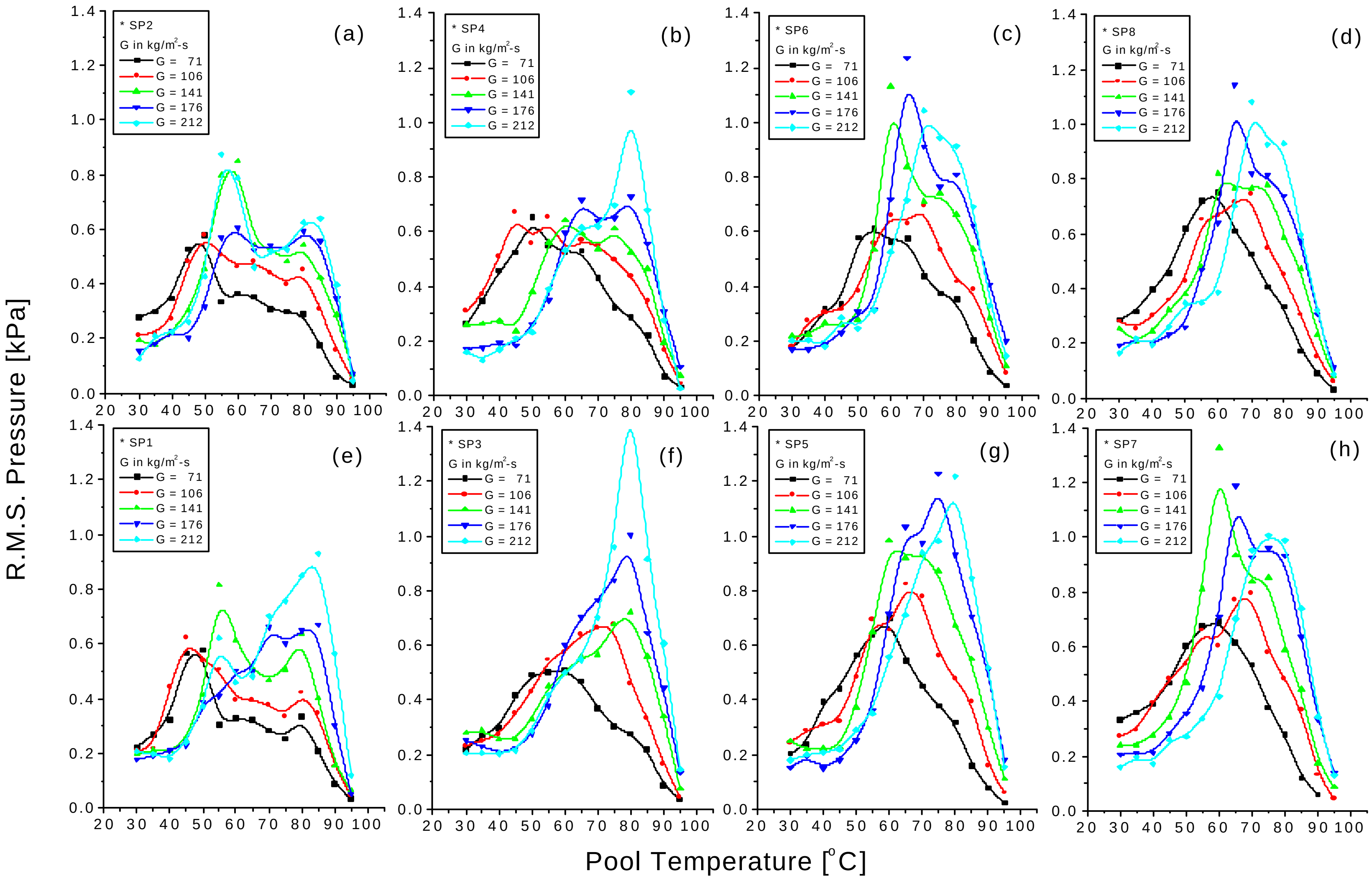

Fig. 3 Variation of dynamic pressure amplitude at the wall.(a: Sp2, b:Sp4, c:Sp6, d:Sp8, e: Sp1, f:Sp3, g:Sp5, h:Sp7)

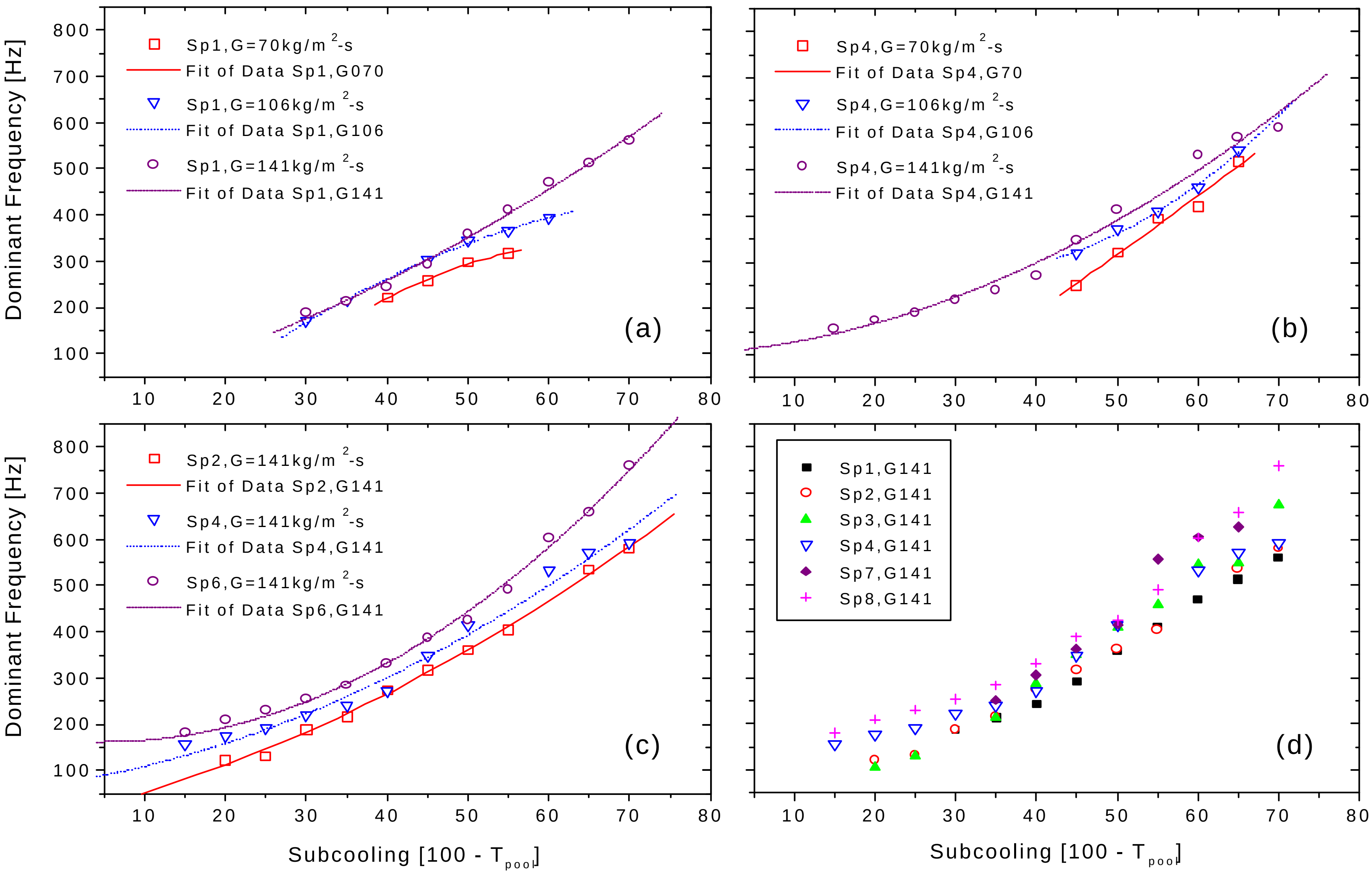

Fig. 6 Variation of dominant frequency with pool temperature