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Protection of KALIMER Upper Internal Structure against Thermal Striping Loads

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ABSTRACT

The Upper Internal Structure(UIS) for Korea Advanced Liquid Metal Reactor(KALIMER) has been conceptually designed and its bottom plate is approximately 90cm above the core outlet. The UIS bottom region is subjected to a thermal striping load during steady state operation due to the mixing of the sodium jets from different core assemblies with various velocities and temperatures. In this paper, a simple procedure for UIS striping analysis was proposed and the Inconel 718 liner plate was introduced to protect the UIS bottom plate from severe thermal striping load. The analysis results of this study indicated that the conceptually designed UIS by attaching the Inconel 718 liner plate under the UIS bottom plate could be protected against severe thermal striping load by attaching.

1. INTRODUCTION

Thermal striping is characterized by random temperature fluctuations which occurs in the mixing region of hot and cold fluid streams; e.g., near the UIS bottom region where hot sodium flowing out of active fuel assemblies and cold sodium flowing out of control rod assemblies mixed during steady state operation. Imperfect mixing of hot and cold sodium streams acts as dynamic fluctuating temperature loadings on the surface of structure and could induce severe thermal stresses. This might initiate surface cracks due to high cycle thermal fatigue and the growth of these cracks can cause component failure leading to loss of its function.

Many researchers made efforts to understand the characteristics of random temperature fluctuations, the attenuation behavior of fluctuating temperatures due to boundary layer effect, and the structural behavior against striping loads by experiments and analytical methods.

Tenchine[1] examined the boundary layer attenuation in turbulent sodium flows and found that the attenuation effect increases with the frequency of temperature fluctuations. Zhukov[2] performed experiments on the mixing of sodium jets of different temperatures from seven model assemblies of BN-350 type and observed the effect of velocity ratio on pulsation intensity. As the velocity in the central subassembly decreases compared with the ones in surrounding subassemblies, the temperature fluctuations become more intensive. He also observed that the frequency contents of temperature fluctuations are between 0.5Hz and 10Hz, and that high frequencies show up highly in the distance compared to the immediate over-subassembly area. Wakamatsu[3] conducted experiments to examine the surface attenuation using two models with water and sodium simulating the subassembly array of a LMFBR(Liquid Metal Fast Breeder Reactor) core. In his experiment, boundary layer effects on the attenuation of thermal cycle variations from a bulk sodium stream from the jets to the structure surface with variable distances and velocities are examined. When the hot and cold sodium jets' velocities are the same and varied from 0.34m/s to 6.72m/s, the surface attenuation ratio decreases with the jet flow rate and the surface temperature fluctuation is nearly dependent on the distance. In addition, the surface attenuation ratios in the sodium tests are smaller than those in the water tests under the same velocity, as expected. But the effect of the velocity ratios of hot and cold streams was not examined.

Muramatsu[4] evaluated the frequency of temperature fluctuation near the structure surface using sodium and water jets experiments simulating the LMFBR core and UIS conditions. The dominant frequency band of the gain is about 3Hz~10Hz for the transfer functions of the outer position to the inner position of the laminar sub-layer, and of the inner position of the laminar sub-layer to the test piece surface. And higher frequency components decreases drastically on the test piece surface due to the presence of a filtering effect by the laminar sub-layer and heat transfer to the surface from the coolant. The frequency range of fluctuating temperature of the test piece surface seems to be 0.5Hz~10Hz, depending thermocouple location on the surface. But his results shows no dependence of the transfer function on the nozzle velocities and this is contradictory to the result of Wakamatsu[3]. Ushakov[5] investigated sodium temperature pulsations using the seven assemblies model and the dominant frequency contents are 0.7Hz~4Hz in his test results. Lee[6] investigated the behavior of fatigue crack under thermal striping loads in tee junction of the secondary pipe in LMFBR using a Green's function approach.

In general, the velocity of sodium in fuel subassemblies is higher than that in the control rod assemblies and this velocity ratio affects the mixing of streams[7]. As the velocity ratio becomes smaller, the attenuation of temperature fluctuation gets smaller. Thus, the regions near the Control Rod Driveline(CRD) shroud tube extensions are the typical areas which undergo severe thermal striping loads. In the conceptual design of KALIMER core assemblies, the sodium velocities in active fuel assemblies are 4~5m/s and the sodium velocities in the control rod assemblies are 1~2m/s or less[8]. It is essential to obtain the characteristics of turbulent sodium temperature fluctuations out of the core exit region, e.g, the amplitude and the frequency contents, to carry out the structural evaluation of the UIS bottom structures. It is also necessary to know the amount of boundary layer attenuation of sodium temperature fluctuation to the surface of the structure through pertinent test models. Since no thermal striping test regarding UIS was performed for the KALIMER, conservative assumptions based upon literature and engineering judgement are used to evaluate thermal striping effects on KALIMER UIS for the sake of structural integrity.

In this study, a simple procedure of thermal stress evaluation for the KALIMER UIS structures subjected to thermal striping loads, based upon the conceptual design of core assemblies, was proposed and the thermal striping protection device was suggested.

2. UIS STRIPING ANALYSIS

The KALIMER[9] is a pool-type liquid metal reactor and its UIS has been conceptually designed. Its overall length and outer diameter are about 865 cm and 240cm respectively and the bottom plate is approximately 90cm above the core outlet. The wall thicknesses of the UIS cylinder and the bottom plate are designed as 2.5cm and the CRD shroud tubes extend to within 5.0 cm of the top of the core assemblies during normal operation as shown in Fig. 1. While increasing by about 160°C after passing through the fuel assemblies, the temperature of cold sodium(386°C) increases by about 4~7°C after passing through the control rod assemblies. There occurs mixing of hot and cold streams with temperature differences of up to typically 160°C between the core exit region and the UIS bottom area. The magnitude of sodium temperature differences are attenuated due to the mixing and boundary layer effects between structure surface and sodium, and the attenuated temperature fluctuation on the surface of the structure might induce high cycle fatigue failure during steady state operation.

It is necessary to evaluate the structural integrity of the UIS bottom plate and the CRD shroud tube extensions against a thermal striping load if a crack is initiated in this region due to high cycle thermal fatigue. The analysis procedure involves three steps: the estimation of striping potential flowing out of core assemblies and the attenuation of striping loads; heat transfer analysis of structures including the boundary layer between structure and fluid; and the calculation of thermal stress and the evaluation of structural integrity.

2.1 Thermal Striping Loads

The thermal striping calculation uses a combination of data from thermal hydraulic tests and analyses. These involve the estimation of the core exit striping potential from core thermal hydraulic analyses and of the coolant striping attenuation in transit to the structure surface from appropriate mixing tests. The test and analysis information required for striping stress calculation is not presently available for the KALIMER. The KALIMER UIS assessment subjected to thermal striping is assumed to be conservative conditions based on the experience and literature.

The maximum difference in the core exit coolant temperatures between core assemblies is termed by the striping potential which the structure may experience. The striping potential generally results from the difference of coolant temperatures between from control assemblies and from adjacent fuel assemblies. This difference is generally larger than the increase in the bulk coolant temperature through the core because of the uncertainty factors. The coolant striping at the UIS bottom surface will be lower than the core exit striping potential because of the coolant mixing in transit. This striping attenuation can be best estimated in mixing tests with prototypical geometry and flow conditions. Depending on relative velocities, flow rates, geometry in the mixing region and the distance of the structure surface from the core exit plane, the attenuation may vary as the location of interest. Since such tests are not available and the objective of present analysis is to examine the general behavior of the bottom plate under striping loads, the striping potential is used for conservatism without the attenuation effect.

According to the conceptual design of the KALIMER core[8] shown in Fig.2, the maximum temperature difference is about 160°C between the inner core assembly and the adjacent control rod assembly. It is conservatively assumed as 200°C which is close to the striping potential value[10] used for ALMR(Advanced Liquid Metal Reactor)[11].

2.2 Parametric Heat Transfer Analysis

A parametric study with various frequencies of fluctuating temperature and various values of film coefficients was performed to examine the boundary layer attenuation of a striping potential to the surface of the structure. For simplicity, sinusoidal striping loads for the frequencies of 0.1Hz~10Hz were chosen according to the test results of Muramatsu[4] and Ushakov[5].

Thermal stresses will depend on the depth of penetration of a striping in the structure. For the UIS components of interest, this may be conservatively estimated by one-dimensional heat transfer analysis for a flat plate or a tubular component. The striping reduction across the surface boundary layer depends on the film coefficient and the striping frequency. The experimental dynamic film coefficients in the striping environment are generally not known because of its complexity. Although many researchers conduct experiments to examine the boundary layer attenuation effect, those results cannot be directly applied to LMFBR design with a certain physical condition. Therefore parametric analyses were performed with various film coefficient values of 28400, 56800, 113600, 284000, and 454400 J/sec-m^2-°C based upon engineering judgement. The frequency effects on the striping penetration were studied for the cases of 0.1, 0.5, 1, 2, 5, and 10 Hz.

One dimensional heat transfer analysis was performed using ANSYS finite element code[12] with four node thermal elements(PLANE55). Fig.3 shows one dimensional finite element analysis model and the length of model is 3.7cm. The thickness of the UIS bottom plate is 2.5cm and the thickness of the 316SS liner, which is welded to protect from thermal shock, is 1.2cm as shown in Fig.1. The average temperature of striping load is assumed as 530°C, which is the average core outlet temperature, and the amplitude is 100°C as shown in Fig. 3. Striping loads were applied on the bottom of the plate and the top of the plate was held at hot pool temperature 530°C during normal operation. Both 316SS and Inconel 718 were analyzed with their material properties at 530°C. The integration time step criteria used for one dimensional finite element thermal conduction analysis is

$$\Delta t \le h^2 / (2k / \rho c),$$

where h is element dimension, k is heat conduction coefficient, ρ is density, and c is specific heat[13]. This is 0.1sec and time step size of 0.028sec was used in this study. The density, specific heat, and thermal conductivity for 316SS are 7744 Kg/m^3, 576.7 J/Kg-°C, and 21.4 W/m-°C, respectively, and those for Inconel 718 are 8039 Kg/m^3, 496.4 J/Kg-°C, and 18.52 W/m-°C, respectively.

Thermal stresses depend on the depth of penetration of striping loads in the structure. Analyses results for 316SS were obtained and striping history results were enveloped to show the depth of penetration of striping. The depth of striping penetration for striping frequencies of 0.1, 0.5, 1, 2, 5 and 10 Hz are shown in Fig. 4 and Fig. 5 with respect to film coefficient of 28400 and 454400 J/sec-m^2-°C, respectively. It is observed that the temperature fluctuations near the surface are attenuated as the striping frequency increases while the striping penetration thickness almost remains same regardless of film coefficients. Fig. 6 and Fig. 7 show the striping reduction along thickness direction for film coefficients of 28400, 56800, 113600, 284000, and 454400 J/sec-m^2-°C with respect to striping frequency of 0.5Hz and 10Hz, respectively. It can be seen that the temperature fluctuations of high frequency(10Hz) on the surface are attenuated significantly as the film coefficient decreases while the temperature fluctuations of low frequency(0.5Hz) on the surface are attenuated slightly as the film coefficient decreases. It is shown that the striping penetration depth of low frequency component is much larger than that of high frequency component.

Analysis results indicate that the striping penetration depth is influenced by the frequency components and the surface attenuation is mostly influenced by film coefficients. High frequency component cannot penetrate into structure thickness deeply and is attenuated significantly on the surface depending on the film coefficients. Fig. 8 shows the surface attenuation of striping loads with respect to frequencies and film coefficients. Frequency component of 0.1Hz is attenuated by 13% with film coefficient of 28400 J/sec-m^2-°C while frequency component of 10Hz is attenuated by 81% with same value of film coefficient. On the other hand, frequency component of 0.1Hz is attenuated by only 1% with film coefficient of 454400 J/sec-m^2-°C while frequency component of 10Hz is attenuated by 9% with same value of film coefficient. Since the variation of the amount of surface attenuation is large, it is essential to know the actual frequency contents of striping loads and the boundary layer attenuation from the experiments. Otherwise, it is safe to use the most conservative value on the surface of the structure because this surface temperature fluctuation might initiate surface cracks by high cycle fatigue.

The typical striping frequency of 1Hz corresponds to 9.5×10^{8} cycles during 30 year service life far exceed ASME B&PV Code[14] data base for fatigue limits of which fatigue cycles up to 1×10^{6}. Thus it is necessary to introduce a device to protect the UIS bottom plate from potential severe thermal striping loads. One method is to use a baffle plate between the KALIMER UIS bottom plate and the core exit region but a baffle plate is not appropriate because it will disturb IVTM movement for fuel transfer. In this study, instead of using baffle plate, it is proposed to install lining plate made of Inconel 718, which is known as excellent fatigue endurable material, to prevent striping load to be delivered to the UIS bottom plate and to use Inconel 718 as CRD shroud tube material. To determine the proper thickness of the Inconel 718 lining plate beneath the UIS bottom plate, heat transfer analyses with both Inconel 718 and 316SS were performed to compare heat conduction behavior of two materials and there was no big difference between the results for the two materials. According to these results, heat transfer characteristics for 316SS was used in substitute for Inconel 718.

From Fig. 4 ~ Fig. 7, it is noticed that the striping amplitude reduces to small values within about 0.3cm from the surface and essentially disappears within 0.6cm from the surface except extreme low frequency component of 0.1Hz. Therefore, the thickness of the Inconel 718 lining plate and the thickness of the Inconel 718 shroud tube are preliminarily determined as 0.6cm.

2.3 Striping Stresses and Structural Integrity

Since the variation of the amount of surface attenuation was between 1% and 81% depending upon frequency component and the film coefficient, it is not proper to assume certain values for frequency and film coefficient until they are to be obtained by actual tests. From the safe design point of view, striping stresses may be conservatively estimated by assuming that the metal surface striping is 95% of the local coolant striping and a linear reduction to zero striping is within the striping penetration depth (t_S) from the surface.

If a alternating temperature is applied to limited region in a plate and it affects only the surface of the structure, then the local thermal stress can be estimated by considering that the local area be completely restrained by surrounding area in two dimensions. Then the biaxial thermal stresses in local area are

$$\sigma_{\text{thermal}} = \pm E \alpha (\Delta T / 2) / (1-v)$$

where ΔT is the peak-to-peak alternating temperature on the surface.

It is assumed that the striping loads are applied to the surface of a whole plate and they penetrate into small depth t_S. A simple formula is derived to calculate corresponding biaxial thermal striping stress assuming linear temperature gradient in the striping penetration depth and suppressing bending condition as follows;

$$\sigma_{\text{striping}} = \pm E\alpha (1 - 0.5\, t_S / t) (T_{\text{striping}}/2)/(1-v)$$

where T_{striping} is the peak-to-peak alternating temperature, t is the component wall thickness, and t_S is the striping penetration depth which is usually a fraction of wall thickness. Above stress formula is verified by ANSYS stress analysis using three dimensional 8-node thermal solid elements(SOLID70) and 8-node structural solid elements(SOLID45). Young's modulus, Poisson's ratio, and thermal expansion coefficient for 316SS at 530°C are 156.1GPa, 0.29, 18.36×10^{-6}/°C, respectively and those for Inconel 718 at 530°C are 171.7GPa, 0.273, and 14.35×10^{-6}/°C, respectively. Peak to peak metal striping on the surface from above analysis is about 190°C, which is 95% of local coolant striping temperature, and the thickness of the Inconel 718 liner plate is 0.6 cm.

Striping stress for the 316SS plate without the Inconel 718 liner is calculated to be 368MPa for the striping penetration depth 0.3cm and this is much higher than the yield stress 117MPa at 530°C[14]. The elastically calculated corresponding strain range is 0.36%, which is smaller than the actual elastic-plastic strain range, and this strain range result in a number of allowable cycles as 3700. The fatigue damage factor far exceed an allowable value of 1 and fatigue crack would be initiated. Even though actual stresses would be smaller because of surface attenuation, the nonperiodic temperature variation in a plate, and the nonuniform temperature distributions which would lead to accommodation of some of the thermal expansions at a point by the surrounding material at different temperatures, the 316SS bottom plate without the Inconel 718 liner seems to be not appropriate against striping loads.

In the case of adopting 0.6cm thickness of the Inconel 718 liner, striping stress became 310MPa considering striping penetration depth 0.3cm and corresponding elastic strain range is 0.32%. Considering Inconel 718's yield stress of 890MPa at 530°C, there will be no plastic deformation and this strain range is close to the actual strain range. Even though the ASME Code does not specify a design fatigue curve for Inconel 718, it is expected that the number of allowable cycles is larger than 10^9 for the strain range of 0.4% and there would be no fatigue crack initiated in the Inconel 718 liner. The most conservative cases were considered in this study using the maximum value of a striping potential 200°C without considering the attenuation of a striping potential with respect to the distance. And the least surface attenuation of 5% was applied to the calculation of thermal striping stresses.

A thorough analysis and experiments are required for the careful design of the UIS bottom structures including shroud tube. It is, however, supposed to satisfy the conceptual design requirement by introducing the Inconel 718 liner beneath the UIS bottom plate.

3. CONCLUSIONS

In this paper, a simplified analysis on the UIS bottom area subjected to severe thermal striping load was conducted with assumed conservative value of striping potential under the condition of absence of actual experimental data. The results of the present analyses show that the striping penetration depth is affected by the frequency contents of striping loads and the surface attenuation is mostly influenced by the film coefficient. Considering the ASME Code fatigue limits and the allowable stress intensity, the Inconel 718 liner plate was introduced to protect the UIS bottom plate from severe thermal striping load. The analysis results of this study indicat that the conceptually designed upper internal structure bottom area attached by the Inconel 718 liner plate could be protected against severe thermal striping load. In the next design stage, a detailed analysis and experiments are necessary for the safe design of the UIS bottom region and the proper method of fastening the Inconel 718 liner plate needs to be developed.

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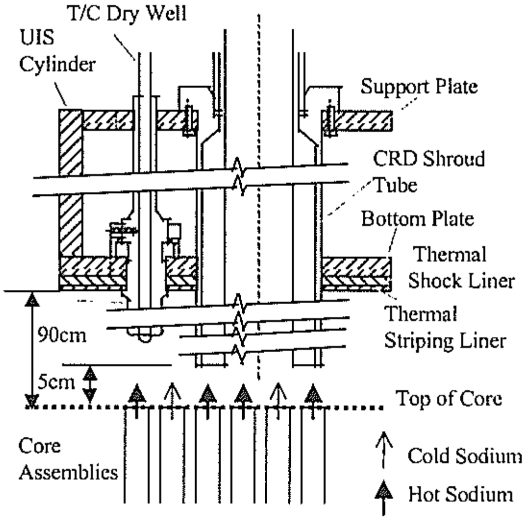

Fig. 1 Schematic of KALIMER UIS Bottom Area

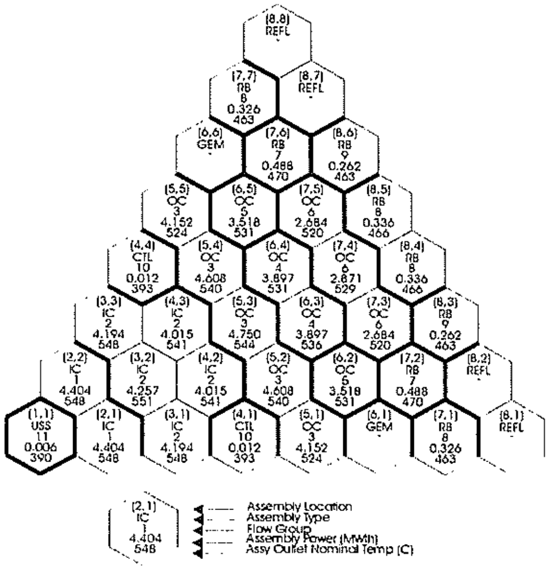

Fig. 2 KALIMER Core Outlet

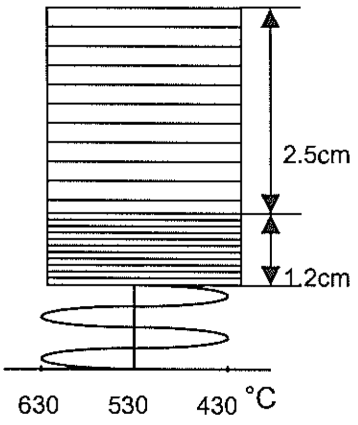

Fig. 3 FEM Model and Striping Load

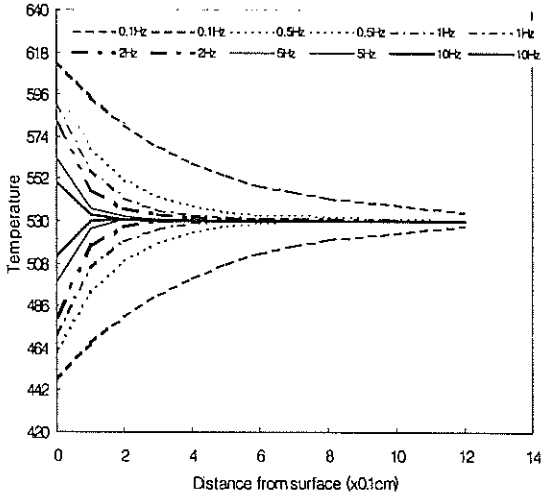

Fig. 4 Striping Penetration for Various Striping Frequencies(Film=28400 J/sec-m^2-°C)

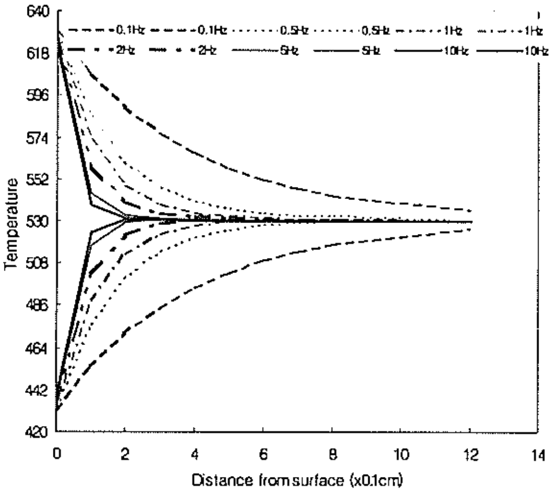

Fig. 5 Striping Penetration for Various Striping Frequencies(Film=454400 J/sec-m^2-°C)

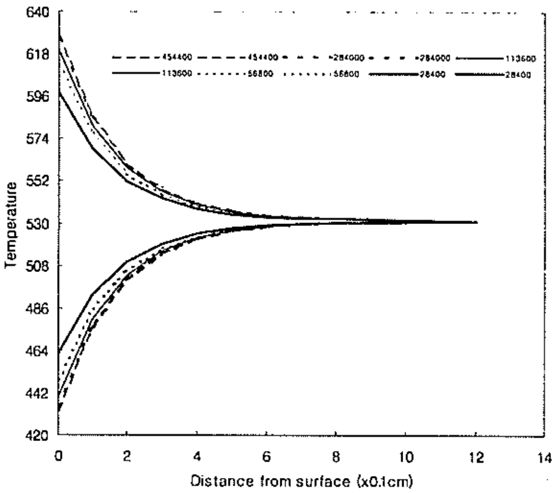

Fig. 6 Striping Penetration for Various Film Coefficients(Frequency=0.5Hz)

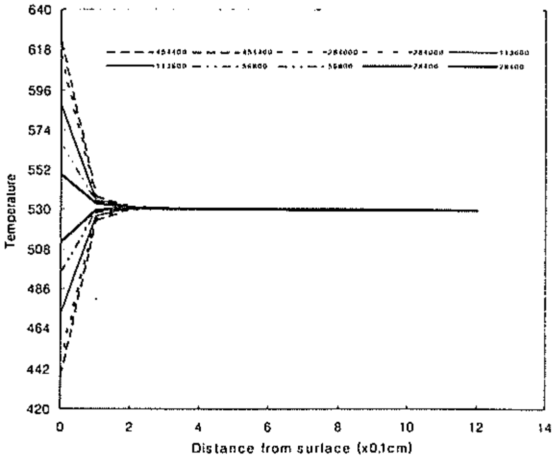

Fig. 7 Striping Penetration for Various Film Coefficients(Frequency=10Hz)

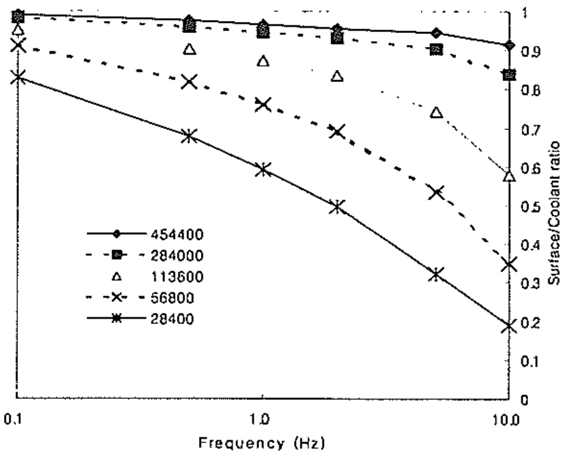

Fig. 8 Surface to Coolant Temperature Fluctuation Ratio