# THERMAL STRATIFICATION IN THE PRESSURIZER

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## ABSTRACT

*The thermal stratification in the pressurizer due to the insurge from the hot leg to the pressurizer has been studied. The insurge flow of the cold water into the pressurizer takes place during the heatup/cooldown and the normal or abnormal transients during power operation. The pressurizer vessel can undergo significant thermal fatigue usage caused by insurges and outsurges. Two-dimensional axisymmetric transient analysis for the thermal stratification in the pressurizer is performed using the computational fluid dynamics code, FLUENT, to get the velocity and temperature distribution. Parametric study has been carried out to investigate the effect of the inlet velocity and the temperature difference between the hot leg and the pressurizer on the thermal stratification. The results show that the insurge flow of cold water into the pressurizer does not mix well with hot water, and the cold water remains only in the lower portion of the pressurizer, which leads to the thermal stratification in the pressurizer. The thermal load on the pressurizer due to the thermal stratification or the cyclic thermal transient should be examined with respect to the mechanical integrity and this study can serve the design data for the stress analysis.*

## 1. INTRODUCTION

The Korean Standard Nuclear Power Plant (KSNP) is a Pressurized Water Reactor (PWR) with thermal output of 2825MWt. The major components of the reactor coolant system (RCS) are a reactor vessel, two parallel heat transfer loops, each containing one steam generator and two pumps, and a pressurizer connected to the hot leg in one RCS loop with surge line.

The pressurizer controls the RCS pressure by maintaining the temperature of the pressurizer liquid at the saturation temperature corresponding to the desired system pressure with the heaters and spray.

During the load changes the pressurizer limits pressure variations caused by insurge or outsurge of the reactor coolant. A reduction in load causes the average reactor coolant temperature to reduce to its programmed value for the lower power level. The contraction of reactor coolant makes the pressurizer water level and the RCS pressure drop. On the other hand an increase in load causes the average reactor coolant temperature to increase to its programmed value for the higher power level. The resulting expansion of reactor coolant causes a surge of water into the pressurizer compressing the steam and raising the RCS pressure.

The pressurizer vessel can undergo significant thermal fatigue usage caused by (i) heatups and cooldowns, (ii) variations in water level caused by insurges and outsurges, and (iii) the effects of the subcooled spray water contacting the upper shell[1]. Twenty six cracks were found inside the Connecticut Yankee pressurizer during a visual inspection with a video camera, with three cracks extending through the cladding into the 140mm thick base metal[2]. The cracks were in the vertical wall of the pressurizer near the heater support plates. Although two of the cracks extended through the cladding, they merely resulted in surface flaws in the base metal. However, the third crack had penetrated deeper into the base metal. The Connecticut Yankee pressurizer cracks appear to have been caused by high thermal stress and thermal fatigue rather than stress corrosion cracking. The mechanical integrity of the pressurizer shell is very important for a life extension, since a crack in the vessel wall must be repaired and might even require replacement of the entire vessel.

The Alloy 600 penetrations are susceptible to primary water stress corrosion cracking (PWSCC) if high residual tensile stresses are present. For example, PWSCC of an Alloy 600 heater sheath at the Arkansas Nuclear One Unit 2 plant resulted in a pressurizer leak in 1987[3]. Stress corrosion cracks in the heater sheath exposed the electric insulation within the sheath to the pressurizer coolant, which caused expansion of the insulation, axial cracks in the penetration sleeve and in the sleeve weld, and leakage of pressurizer coolant into the containment. The KSNP pressurizer has sheath-type immersion heaters which protrude vertically into the pressurizer through sleeves welded in the lower head. Another instance of pressurizer leaks in the U.S. occurred at Calvert Cliffs Unit 2 in May 1989, where 22 of 120 heater penetrations fabricated from Alloy 600 were found to be leaking[4]. In addition, Alloy 600 pressure/level instrument penetrations in the pressurizer have also leaked at several plants. Immersion heater sheaths can also experience mechanical wear and thinning caused by rubbing against their support plates during thermal expansions and contractions[5]. A crack in the seal weld on the diaphragm of a heater bundle in the Oconee Unit 1 pressurizer caused a primary system leak in 1989[6]. It is speculated that the thermal stress during the operational life could cause the cracks in the heater sheath and the seal weld as well as in the pressurizer wall.

ASME Boiler and Pressure Vessel Code Section III, Article NB3000-Design defines the thermal stress which should be considered in the design of the vessel, piping and other components. Thermal stress is self-balancing stress produced by a nonuniform distribution of temperature or by differing thermal coefficients of expansion. Two types of thermal stresses are recognized depending on the volume or area in which distortion takes place, as described in (a) and (b) below. (a)General thermal stress is the secondary stress associated with distortion of the structure in which it occurs. It is, for example. a stress produced by the temperature difference between a nozzle and the shell to which it is attached. (b)The local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses shall be considered only from the fatigue standpoint[7]. The examples of the local stress are the stress in a small hot spot in a vessel wall and the stress in a cladding material which has a coefficient of expansion different from that of the base metal.

The insurge or outsurge flow may occur during the volume expansion and contraction process of the bubble formation in the pressurizer, filling of Safety Injection Tank, pressurizer heaters on and off, Reactor Coolant Pump on and off, or during the normal or upset events on power operation. It is known that the thermal stratification in the surge line caused by the temperature difference between the pressurizer and the hot leg may result in excessive thermal stress and fatigue problem[8,9,10]. The design temperature difference of 178 °C between the pressurizer and the hot leg is used for the thermal stratification of the surge line in the KSNP, which assumes maximum temperature of the pressurizer and minimum RCS temperature conservatively during RCS heatup and cooldown process.

The objective of this study is to predict thermal hydraulic behavior in the pressurizer during the insurge of the cold water into the pressurizer in the case of the heatup and cooldown and the normal and abnormal transients during power operation. Since the severe temperature distribution or the thermal shock on the pressurizer wall can result in excessive thermal stress and lead to a crack due to thermal fatigue, several cases have been analyzed to determine the sensitivity of the inlet velocity and the temperature difference on the thermal stratification. The unsteady water temperature and stream function distributions as well as the wall temperature are obtained as the cold water flows into the pressurizer. The results of this study can serve the design data for the stress analysis.

## 2. ANALYSIS

### 2.1 Analysis Method

The thermal hydraulic behavior in the pressurizer has been analyzed for the case of insurge flow to the pressurizer. As the cold water begins to enter the pressurizer which is initially filled with hot water, mixing of the cold water with hot water depends on the conditions of the incoming cold water velocity and the temperature difference. The thermal stratification in the pressurizer is established by the balance between the inertial force and the buoyancy force.

The computational fluid dynamics code, FLUENT V.5.3 [11] with SIMPLE algorithm, has been used. The standard k-¥åturbulence model, which is widely used for engineering purpose, has been utilized in the analysis. Here, k and ¥åstand for the turbulent kinetic energy and the dissipation rate, respectively. The governing equations for the two-dimensional axisymmetric unsteady state include the conservation of mass, momentum and energy. In the momentum equation the Boussinesq approximation is used, which models the buoyancy force in terms of the temperature instead of the density variation. Finite element method with triangular elements and the QUICK algorithm are adopted.

### 2.2 Analysis Model

The pressurizer of the KSNP, as shown in Figure 1, is a vertically mounted, bottom-supported, cylindrical pressure vessel. The pressurizer surge nozzle is furnished with a thermal sleeve to withstand specified plant transients. Insurge flow comes through the small holes of the surge screen to which the heater support plates are attached (Figure 2). The lower half of the pressurizer which is filled with water is modeled as in Figure 3(a).

The boundary of the axisymmetric analysis model consists of the inner surface of the pressurizer wall, the inlet screen, the axis, the inlet and outlet. The pressurizer inside diameter is 2.44m, and the height of the half pressurizer is 5.91m. Total number of 36,350 triangular elements is employed after the adequacy of the elements has been reviewed. Figure 3(b) shows the elements for the analysis.

The pressurizer wall is assumed to be insulated perfectly so that there is no heat loss to ambient. And the radiation heat transfer is also neglected. Since the pressurizer wall itself is not included in the analysis model, the heat conduction through the wall is neglected. These assumptions would result in a conservative temperature distribution for the stress analysis of the pressurizer.

The pressurizer is initially filled with hot water at temperature $T_h$, and the cold water at temperature $T_c$ begins to enter the pressurizer through two inlets. The actual inlet of many small drilled holes is modeled as small slit.

## 3. RESULTS AND DISCUSSIONS

When the cold water enters the pressurizer which is initially filled with hot water, the cold water from two inlets of the surge screen flows into the hot water like a fall or a jet depending on the force balance between inertia of inlet flow and buoyancy of hot water. When the inlet flow velocity is low and temperature difference is large, cold water flows downward to the bottom of pressurizer and piles up.

During the plant operation there occur many events causing the insurge or outsurge flow to the pressurizer. In the plant design the insurge flow is considered for the normal events of 'steady state operation with process parameter variations in the power change', 'daily load follow operation between 100% and 50% power', 'turbine load change', etc. ; for upset events of 'increase or decrease in heat removal by secondary system or in RCS inventory', and so on. The outsurge flow takes place in the opposite events to the insurge cases, but in most events insurge and outsurge take place in turn as the pressure and level are controlled or the reactor is tripped[12]. There are also several events, which cause both insurge and outsurge in sequence. During the heatup/cooldown and startup of the plant there also occur insurge and outsurge flow.

The typical insurge flowrates during the normal, upset and faulted events are up to 0.075 $m^3/s$, 0.504 $m^3/s$ and 1.386 $m^3/s$, respectively. The temperature difference is up to 50 °C during normal transient including startup. The temperature difference between pressurizer and hotleg during 100% power operation in the design is 18 °C, but the actual temperature difference is larger than 18 °C due to the operational margin and becomes larger when the operating hot leg temperature is reduced. The temperature difference during the heatup and cooldown is conservatively assumed 178 °C for the surge line design.

Parametric study has been carried to investigate the effect of the inlet flow velocity and the temperature difference on the thermal stratification in the pressurizer. The inlet velocities chosen in this study are 0.1m/s, 1m/s and 4 m/s which represent the insurge flowrates of the typical normal, upset and faulted events corresponding to $0.0168m^3/s$, $0.168m^3/s$, and $0.63m^3/s$, respectively. With small inlet velocity the flow near the inlet becomes locally turbulent, but the large inlet velocity makes most lower region turbulent. The temperature differences between the hot water in the pressurizer and incoming cold water considered in the analysis are 100 °C, 50 °C and 18 °C for typical heatup and cooldown, normal transient and design operational condition, respectively.

Figures of 4, 5 and 6 show the results of the typical cases of the temperature difference of 50 °C with three inlet velocities, but the trend of other cases of different temperature are similar. Figures 4 shows the transient behavior of he thermal stratification phenomena during a typical case of the small insurge during normal events. Reynolds Number at the inlet 1 in this case based on the inlet velocity of 0.1m/s and the inlet 1 gap size of 0.057m is $4.75x10^4$. The thermal stratification in the pressurizer is well established and is not likely to mix to a homogeneous condition. The cold inlet flow is so small that the flow goes immediately downward along the insurge screen wall. As the inlet flow continues, the lower portion of the pressurizer is filled with the cold water.

Figure 5 shows the transient behavior when the inlet velocity is 1 m/s, and the temperature difference is 50 °C. When the insurge begins, the flow is deflected downward a little bit due to the buoyancy force, and as the cold water in the pressurizer increases, the insurge flow goes straight to the pressurizer wall with the smaller effect from the buoyancy force. But the inertia of the flow from the inlet 2 is not large enough to go upward against the buoyancy resistance, and it crawls downwards.

Figure 6 represents the high insurge transient behavior. The velocity and the temperature difference is 4m/s and 50 °C, respectively. The inlet flow is fast enough to maintain the straight to the pressurizer wall from the inlet and make the cold spot on the pressurizer wall. And the flow from the inlet 2 goes far vertically, which indicates that the inertial force of the inlet flow is greater than the buoyancy force. As the insurge continues, the cold region increases with the rapid temperature change in the interfacing surface between hot and cold water.

Figure 7 shows the unsteady outsurge case from the stratified condition. The outsurge begins with the outlet velocity of 1 m/s after there has been an insurge for 24 seconds with the inlet velocity of 0.1 m/s and the temperature difference of 50 °C. As shown on the figure, the cold water is not likely to be removed from the pressurizer, but remains for a long while. The hot water above the cold water comes out instead during the outsurge, which makes the wall temperature gradient larger, therefore, the pressurizer experiences the severe thermal stratification until the cold water is heated.

Figure 8 shows the time-dependent temperature distribution along the pressurizer wall from the bottom. The wall temperature distribution is affected by the cold water flow: how fast it flows, how large the temperature difference is, how long the insurge flow is made. Most cases indicate the large temperature variation in narrow region of about 0.1m when the thermal stratification is established. Figure 8 (b), (e) and (f) also indicate the large temperature gradient near the corner of the bottom due to the recirculating region. Figure 8(d) shows that the wall temperature gradient in the outsurge case of following insurge of Figure 7 becomes larger, which means that the repeated insurge and outsurge will impose the large thermal cyclic load. The wall where the temperature gradient is large may also experience the thermal striping when the interface between hot and cold water moves up and down due to the unstable insurge and outsurge flow condition. Table 1 lists the peak temperature gradients of the cases in Figure 8.

The results also show that the saturation condition of the vapor and hot water in the pressurizer can be influenced only by the liquid volume change due to the insurge not by the liquid phase bulk temperature reduction because the insurged cold water remains stratified in the lower portion of the pressurizer. Furthermore, cold water is not easily removed by the outsurge flow, therefore, the heater may need to be automatically turned on to maintain the bulk liquid in the pressurizer at the saturation condition when the insurge is large.

This study shows that the insurge flow or the outsurge flow following insurge leads to the serious thermal stratification in the pressurizer. The thermal stratification due to the transient operation such as a daily load following operation may impose an additional thermal load on the pressurizer wall. The thermal striping may also take place near the interface between hot and cold water due to the fluctuation or disturbance of the RCS, which is another thermal load to be considered in the pressurizer design. The effect of the thermal stratification or the thermal transient on the pressurizer wall should be examined with respect to the mechanical integrity in accordance with ASME Code[7]. The administrative control to minimize the operation inducing the frequent insurge should also be considered as well.

## 4. CONCLUSIONS

A computational analysis has been performed to simulate the thermal stratification phenomena in the pressurizer and to investigate the effect of the inlet velocity and the temperature difference on the thermal stratification. From the results of this study, it is concluded that:

1) Insurge flow of cold water into the pressurizer during normal and upset events does not mix well with hot water, which leads to the thermal stratification in the pressurizer.
2) The thermal stratification is limited only in the lower portion of the pressurizer such that the saturation condition of the vapor and hot water is not influenced by the temperature reduction of bulk liquid.
3) The operation at the reduced hot leg temperature with the pressurizer temperature unchanged will aggravate the thermal stratification in the pressurizer and the surge line.
4) The effect of the thermal stratification in the pressurizer on the thermal fatigue cracking on the pressurizer wall and the heater weld needs further investigation.
5) The pressurizer heater on-off control program should take account of the amount of insurge flow to heat up the cold water.
6) Administrative control to avoid frequent insurge should be considered to reduce the thermal fatigue usage.

## NOMENCLATURE

D, H Diameter and height of the pressurizer
$T_c$, $T_h$ Temperature of the insurging cold water and the pressurizer hot water
DT Temperature increment between isothermal lines
t Time
$V_{in}$,$V_{out}$ Insurge and outsurge velocity
r, z Axisymmetric coordinate
Coordinate along the pressurizer wall

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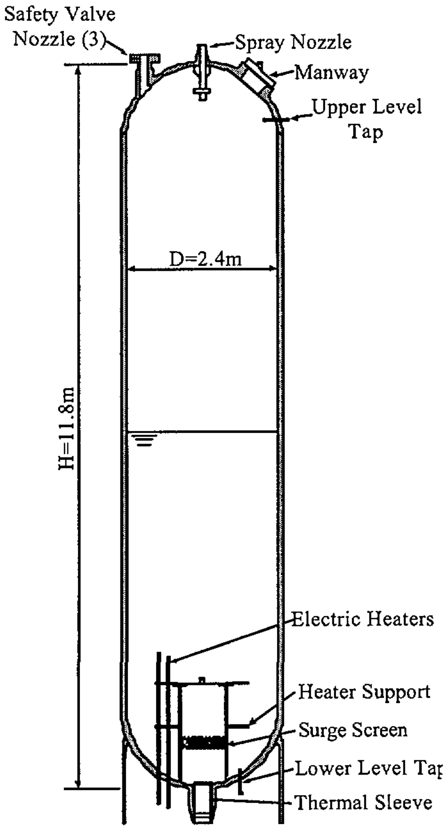



**Figure 1** Pressurizer in KSNP

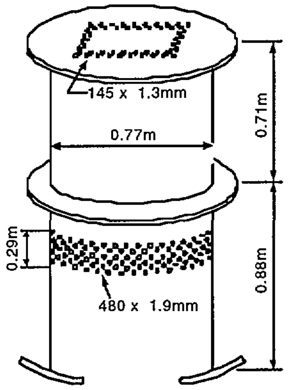
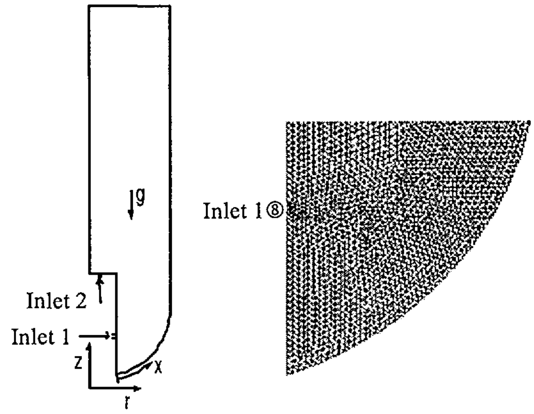
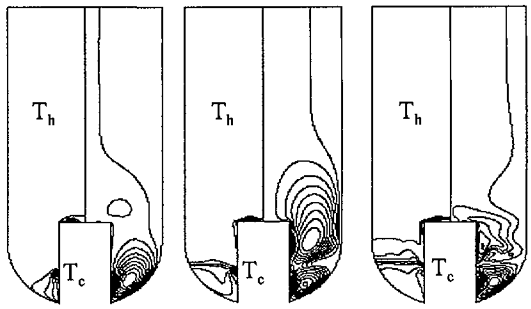



**Figure 2** Surge Screen



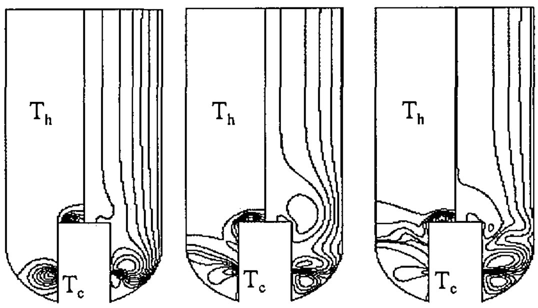

(a) Analysis Domain (b) Grid of Lower Portion

**Figure 3** Analysis Model



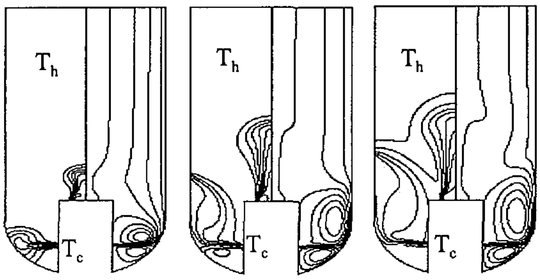

(a) t=5s (b) t=20s (c) t=50s

**Figure 4** Temperature and Stream Function
($T_h$=345°C, $T_c$=295°C, $V_{in}$=0.1m/s, DT=5°C)



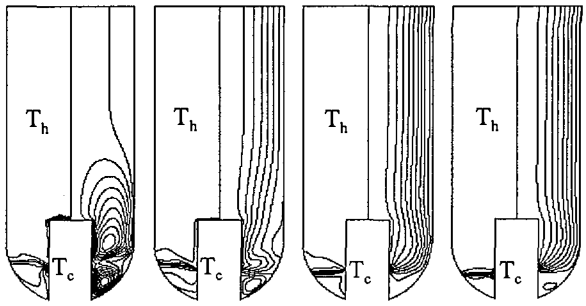

(a) t=3s (b) t=10s (c) t=20s

**Figure 5** Temperature and Stream Function
($T_h$=345°C, $T_c$=295°C, $V_{in}$=1m/s, DT=5°C)




(a) t=5s (b) t=20s (c) t=50s

**Figure 6** Temperature and Stream Function
($T_h$=345°C, $T_c$=295°C, $V_{in}$=4m/s, DT=5°C)

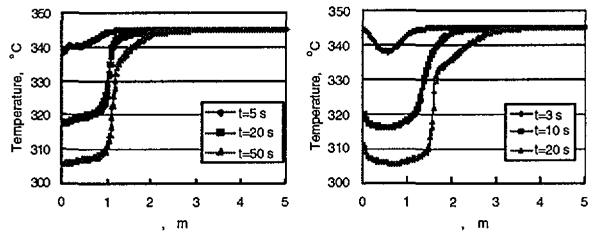



(a) t=24s (b) t=25s (c) t=32s (d) t=42s

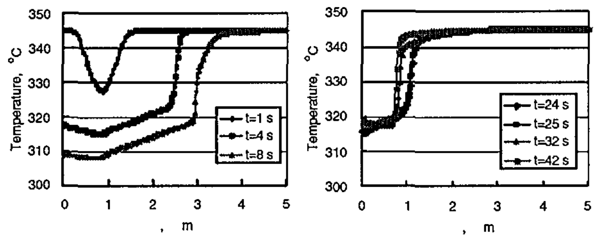
**Figure 7** Temperature and Stream Function of Outsurge
($T_h$=345°C, $T_c$=295°C, $V_{out}$=1m/s, DT=5°C)

**Table 1** Peak Temperature Gradients

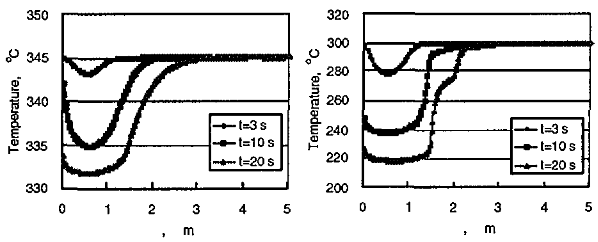
| Case | Peak T Grad. dT/d (°C/m) | Location (m) | Time (sec) |
|---|---|---|---|
| Figure 8(a) | 28.67 | 0.060 | 5 |
| | 155.84 | 1.087 | 20 |
| | 163.23 | 1.148 | 50 |
| Figure 8(b) | 4.72 | 0.222 | 3 |
| | 68.43 | 0.060 | 10 |
| | 14.81 | 1.309 | |
| | 29.43 | 0.060 | 20 |
| | 16.35 | 1.530 | |
| Figure 8(c) | 43.10 | 0.463 | 1 |
| | 42.44 | 1.188 | |
| | 146.90 | 2.550 | 4 |
| | 169.10 | 2.990 | 8 |
| Figure 8(d) | 172.56 | 1.127 | 24 |
| | 170.96 | 1.107 | 25 |
| | 229.64 | 0.866 | 32 |
| | 289.61 | 0.785 | 42 |
| Figure 8(e) | 17.89 | 0.201 | 3 |
| | 56.35 | 0.060 | 10 |
| | 72.05 | 1.340 | |
| | 77.02 | 0.060 | 20 |
| | 235.80 | 1.610 | |
| Figure 8(f) | 81.30 | 0.060 | 3 |
| | 44.19 | 1.027 | |
| | 135.00 | 0.060 | 10 |
| | 303.80 | 1.409 | |
| | 137.00 | 0.060 | 20 |
| | 374.25 | 1.550 | |
| | 164.00 | 2.090 | |




(a) $T_h$=345°C, $T_c$=295°C, $V_{in}$=0.1m/s (b) $T_h$=345°C, $T_c$=295°C, $V_{in}$=1m/s




(c) $T_h$=345°C, $T_c$=295°C, $V_{in}$=4m/s (d) Outsurge from t=24s, $V_{out}$=1m/s




(e) $T_h$=345°C, $T_c$=327°C, $V_{in}$=1m/s (f) $T_h$=300°C, $T_c$=200°C, $V_{in}$=4m/s

**Figure 8** Time –Dependent Wall Temperature Distributions