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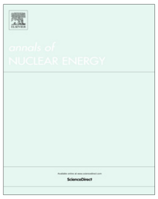

# Stored energy analysis in the scaled-down test facilities

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ABSTRACT

In the scaled-down test facilities that simulate the accident transient process of the prototype nuclear power plant, the stored energy release in the metal structures has an important influence on the accuracy and effectiveness of the experimental data. Three methods of stored energy analysis are developed, and the mechanism behind stored energy distortion in the test facilities is revealed. Moreover, the application of stored energy analysis is demonstrated for the ACME test facility newly built in China. The results show that the similarity requirements of three methods analyzing the stored energy release decrease gradually. The physical mechanism of stored energy release process can be characterized by the dimensionless numbers including Stanton number, Fourier number and Biot number. Under the premise of satisfying the overall similarity of natural circulation, the stored energy release process in the scale-down test facilities cannot maintain exact similarity. The results of the application of stored energy analysis illustrate that both the transient release process and integral total stored energy of the reactor pressure vessel wall of CAP1400 power plant can be well reproduced in the ACME test facility.

## 1. Introduction

During the normal operation of nuclear power plants, the metal structures such as reactor pressure vessel and its internal components almost maintain equal temperature with the reactor coolant, thus a considerable portion of heat energy is stored in the metal structures. Once the loss of coolant accident (LOCA) occurs, the heat of coolant is taken away through the break and thereafter the cold water from safety injection systems is injected into the core, therefore the coolant temperature decreases gradually. As one of the heat sources in the system, the stored energy in the metal structures will be released to the reactor fluid, which will have an impact on the system depressurization rate, and may further affect the action process of related safety systems. Previous studies showed that the stored energy in the metal structures of nuclear power plants wouldn't cause significant impact on the reactor safety (Bill and Robert, 2001). However, for the scaled-down test facilities simulating nuclear power plants, relatively more heat energy is generally stored in the metal structures of test facilities than that of the prototype plants due to the differences of the design pressure, structural material properties, initial conditions and geometry sizes. The distortion of stored energy probably play a key role in the accuracy and effectiveness of the experimental results that reproduce important thermal–hydraulic phenomena of prototype nuclear plants.

Several integral thermal–hydraulic test facilities have been built to obtain validating data for AP600/AP1000, including SPES-2 (Friend et al., 1998) in Piacenza Italy, ROSA (Kukita et al., 1996) in Tokai-mura Japan and APEX (Wright, 2007) in Oregon USA. Nuclear Regulatory Commission (NRC) has respectively carried out independent experiments in these test facilities to provide supporting data for the design verification and safety assessment of AP600/AP1000. The three test facilities have their own advantages and limitations. SPES-2 and ROSA are both full-height and full-pressure test facilities, so their experiments could cover wide pressure range. However, the metal stored energy in the two facilities is largely distorted under high-pressure conditions, which leads to inaccurate experimental data during the low pressure safety injection and long-term cooling stages. Thus, only the experimental data in high-pressure stage of the SPES-2 and ROSA test facilities is applicable for the design verification and code validation of AP600/AP1000 (Wright et al., 1996). The APEX test facility is designed with 1/4 height ratio and low initial pressure, which almost assures the similarity of stored energy release. Therefore, the experimental data in the low-pressure stage of APEX is quite accurate and applicable for test validation, but the

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## Nomenclature

| | |
|---|---|
| $\rho$ | density, kg/m$^3$ |
| $C_p$ | specific heat, J/(kg K) |
| $T$ | temperature, K |
| $t$ | time, s |
| $u$ | velocity, m/s |
| $z$ | axial position, m |
| $r$ | radial position, m |
| $h$ | convective heat transfer coefficient, w/(m$^2$ K) |
| $l$ | length, m |
| $d$ | internal diameter, m |
| $\alpha$ | thermal diffusivity, m$^2$/s |
| $\lambda$ | thermal conductivity, w/(m K) |
| $\mu$ | dynamic viscosity, Pa s |
| $\delta$ | wall thickness, m |
| $\tau$ | characteristic time, s |
| $\Pi_{st}$ | Stanton number |
| $\Pi_{Fo}$ | Fourier number |
| $\Pi_{Bi}$ | Biot number |
| $V$ | volume, m$^3$ |
| $A$ | area, m$^2$ |
| $M$ | mass, kg |
| $Nu$ | Nusselt number |
| $Re$ | Reynolds number |
| $Pr$ | Prandtl number |
| $q$ | power, w |
| $q_{sys}$ | net system power, w |
| $q_{core}$ | core decay power, w |
| $q_{metal}$ | metal structure heat storage, w |
| $q_{SG}$ | heat exchange of steam generator, w |
| $q_{PRHRS}$ | heat exchange of passive residual heat removal system, w |
| $q''$ | heat flux, MW/m$^2$ |
| $p$ | pressure, MPa |
| $\Delta t_s$ | superheat degree, K |
| $E_s$ | stored energy, J |
| $E_{release}$ | stored energy released into the fluid, J |
| $q_{release}$ | heat transfer rate from the wall |
| $\varepsilon$ | scaling distortion degree |

*Subscripts*

| | |
|---|---|
| $l$ | fluid |
| $s$ | solid |
| $w$ | wall |
| $sat$ | saturation |
| $0$ | initial value (or reference value) |
| $R$ | ratio of model to prototype |
| $ave$ | average value |

*Superscripts*

| | |
|---|---|
| + | the variable is dimensionless |

thermal–hydraulic process during early high-pressure stage cannot be well reproduced due to different pressure conditions (Reyes and Hochreiter, 1998).

Recently, a large integral test facility named ACME (Advanced Core-cooling Mechanism Experiment) has been constructed to simulate CAP1400, which is a large advanced nuclear power plant developed in China (Deng et al., 2012). CAP1400 has similar design of passive safety systems as AP1000, but with higher core power. The ACME test facility is designed with a length ratio of 1/3 on the basis of H2TS scaling method. The main test objective is to simulate various small break loss of coolant accident (SBLOCA) transients. The saturated blow-down starting point of prototype plant is selected as the initial pressure of the ACME facility, which is an obvious difference from the existing test facilities. High-pressure design feature facilitates ACME to well simulate almost all stages of SBLOCA transient process except initial blow-down stage (Li et al., 2010). For the ACME test facility with new features, the stored energy release during the accident transients has important effect on the accuracy and effectiveness of the experimental results. So it is very necessary to perform the analysis and assessment of stored energy for the ACME test facility.

In this paper, three methods of stored energy analysis are firstly developed, and then further theoretical analysis is carried out to study the mechanism behind stored energy distortion in scaled-down test facilities. Furthermore, the lumped parameter method and integral power method are respectively applied to the reactor pressure vessel (RPV) of the ACME test facility to analyze and evaluate its stored energy release process.

## 2. Methods of stored energy analysis

Suppose one of flow channels in nuclear reactor systems has a typical cylinder structure, an ideal analytical model is built as shown in Fig. 1. For the solid wall, the density is $\rho_s$, the internal diameter is $d$, the length is $l$, and the wall thickness is $\delta$. The fluid with density of $\rho_l$ flows through the cylinder at the speed of $u$. The temperature of solid wall is $T_s$, and the temperature of fluid is $T_l$. Here $T_s$ is larger than $T_l$. Since the natural convection heat transfer between the outer wall and the air is very weak, the outer wall is assumed to be adiabatic. Thus, heat energy is transported only through the inner wall to the fluid. Based on this ideal cylinder model, three methods are built to analyze the stored energy release process.

### 2.1. Governing equation method

Based on the fundamental energy equations of the fluid and the solid and corresponding boundary conditions, governing equation method is established to analyze the release of stored energy.

Energy equation of the fluid:

$$\rho_l C_{pl}\left(\frac{\partial T_l}{\partial t}+u\frac{\partial T_l}{\partial z}\right)=\frac{4h}{d}(T_s-T_l) \tag{1}$$

Energy equation of the solid:

$$\frac{\partial T_s}{\partial t}=\alpha\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_s}{\partial r}\right) \tag{2}$$

Boundary condition of the inner wall:

$$-\lambda_s\frac{\partial T_s}{\partial r}\bigg|_{r=0}=h(T_s-T_l) \tag{3}$$

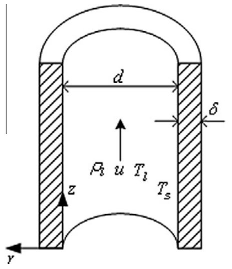

**Fig. 1.** Stored energy analytical model.