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# Calculation and analysis of thermal–hydraulics fluctuations in pressurized water reactors

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ABSTRACT

Analysis of thermal–hydraulics fluctuations in pressurized water reactors (e.g., local and global temperature or density fluctuations, as well as primary and charging pumps fluctuations) has various applications in calculation or measurement of the core dynamical parameters (temperature or density reactivity coefficients) in addition to thermal–hydraulics surveillance and diagnostics.

In this paper, the thermal–hydraulics fluctuations in PWRs are investigated. At first, the single-phase thermal–hydraulics noise equations (in the frequency domain) are originally derived, without any simplifying assumptions. The fluctuations of all the coolant parameters, as well as the radial distribution of the temperature fluctuations in the fuel, gap and cladding are taken into account. Then, the derived governing equations are discretized using the finite volume method (FVM). Based on the discretized equations and the proposed algorithm of solving, a single heated channel noise calculation code (SHC-Noise) is developed, by which the steady-state and fluctuating parameters of PWR fuel assemblies can be calculated.

The noise sources include the inlet coolant temperature and velocity fluctuations, in addition to the power density noises. The developed SHC-Noise code is benchmarked in different cases and scenarios. Furthermore, to show the effects of the power feedbacks, the closed-loop calculations are performed by means of the point kinetics noise theory. Both the space- and frequency-dependence of the temperature fluctuations are analyzed in this work.



## 1. Introduction

Noise analysis or the study of the fluctuations, i.e., the time-variations of a parameter from its mean value, assuming that all processes are stationary in time, has a variety of applications in reactor core diagnostics and monitoring (Williams, 1974; Thie, 1981; Pázsit and Demazière, 2010).

Thermal–hydraulics fluctuations in PWRs (e.g., Local and global temperature or density fluctuations, as well as primary and charging pumps fluctuations) were investigated first in the early 1970s (Kosály and Williams, 1971; Kosály and Meskó, 1972). In these early works, a lumped model of thermal–hydraulics calculations (full of simplifying approximations) was used, which cannot show the exact behavior of the real systems. Katona et al. (1982) identified three sources of coolant temperature fluctuations, such as inlet temperature, coolant velocity and power fluctuations. Later on, Valkó (1992) investigated PWR in-core generated temperature fluctuations versus fluctuations already present at inlet.

The main reasons for the study of the thermal–hydraulics fluctuations in PWRs are: (1) calculation or measurement of the Moderator Temperature Coefficient (MTC) (Glöckler, 1989; Demazière, 2002) and (2) the thermal–hydraulics surveillance and monitoring (Kostić et al., 1988; Pór et al., 2003).

Recently, Larsson and Demazière (2012) developed a computational tool for the coupled neutronics and thermal–hydraulics calculations in PWR core. However, they have made some simplifying approximations in the thermal–hydraulics section as: (1) one-dimensional flow along the axial direction. Thus, the cross flows between fuel assemblies were neglected. (2) Uniform pressure and neglecting the effect of stresses. Consequently, the momentum equation was ignored and the energy equation was simplified. (3) Time-independent heat transfer coefficient through the perturbed calculations. Therefore, the fluctuations of the heat transfer coefficient were neglected. (4) Lumped model of the heat transfer from the fuel to the coolant. Hence, the radial distribution of the fuel temperature and heat transfer in the gap and cladding were ignored.

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**Nomenclature**

| | |
|---|---|
| $\rho$ | density (kg/m$^3$) |
| $v$ | velocity (m/s) |
| $t$ | time (s) |
| $P$ | pressure (kg/m s$^2$) |
| $g$ | acceleration of gravity (m/s$^2$) |
| $h$ | specific enthalpy (J/kg) |
| $q$ | heat power (W) |
| $q''$ | heat flux (W/m$^2$) |
| $q'''$ | volumetric heat power (W/m$^3$) |
| $C_p$ | specific heat capacity (J/kg °C) |
| $T$ | temperature (°C) |
| $k$ | heat conductivity (W/m °C) |
| $\mu$ | dynamic viscosity (kg/m s) |
| $h_s$ | heat transfer coefficient (W/m$^2$ °C) |
| $D_e$ | equivalent hydraulic diameter (m) |
| $f$ | Darcy (Moody) friction factor |
| $P_w$ | wetted perimeter (m) |
| $P_h$ | heated perimeter (m) |
| Re | Reynolds number, $\rho v D_e/\mu$ |
| Pr | Prandtl number, $\mu C_p/k$ |
| Nu | Nusselt number, $h_s D_e/k$ |
| $r$ | radius (m) |
| $\omega$ | angular frequency (rad/s) |
| R | reactivity |
| $G_0$ | zero-power transfer function |
| $H$ | feedback transfer function |
| $\alpha$ | feedback reactivity coefficient |
| $\beta$ | effective fraction of delayed neutrons |
| $\lambda$ | decay constant of delayed neutrons (s$^{-1}$) |
| $\Lambda$ | neutron generation time (s) |

*Subscripts*

| | |
|---|---|
| $m$ | coolant |
| $f$ | fuel |
| $c$ | cladding |
| $g$ | gap |
| $co$ | cladding outer surface |
| $ci$ | cladding inner surface |
| $fo$ | fuel outer surface |
| $fi$ | fuel inner surface |

The first-order single-phase thermal–hydraulics noise equations, without the aforementioned simplifying approximations, are originally derived in this paper. Discretizing the derived equations by means of the finite volume method (FVM) and considering the single heated channel analysis approach (Todreas and Kazimi, 2001), a thermal–hydraulics noise calculation code (called SHC-Noise) is developed and presented. Steady-state calculation results are benchmarked against the well-known COBRA-EN code in some different cases, and noise calculation results are benchmarked in various scenarios. Consequently, the SHC-Noise code is proved efficient for investigation of the single-phase thermal–hydraulics fluctuations in any PWR core.

Considering the axially gradient pressure and the effect of stresses, along with the radial distribution of the temperature in the fuel, gap and cladding, as well as the fluctuations of the heat transfer coefficient, in the calculations of the thermal–hydraulics fluctuations, are the main contributions of this paper. Furthermore, analyzing the space- and frequency-dependence of the fluctuations and interpreting the results are of the key novelties of this work. Moreover, the space-frequency dependent feedback transfer function is calculated using the proposed approach.

In the following and in Section 2, the first-order single-phase thermal–hydraulics noise equations are presented. Section 3 describes the spatial discretization of the governing equations using the finite volume method. Steady-state and noise calculation results in different benchmark cases and scenarios are then discussed in Section 4. Furthermore, the closed-loop calculations are presented in Section 5. Finally, Section 6 concludes the paper.

## 2. Single-phase thermal–hydraulics noise equations

In order to derive the single-phase thermal–hydraulics noise equations, one starts with the mass, momentum and energy conservation laws for the single-phase coolant as follows (Todreas and Kazimi, 2001):

$$\frac{\partial \rho_m}{\partial t} + \nabla.\left(\rho_m \vec{v}_m\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho_m \vec{v}_m\right) + \nabla.\left(\rho_m \vec{v}_m \vec{v}_m\right) = \nabla.\left(\bar{\bar{\tau}} - P\bar{\bar{I}}\right) + \rho_m \vec{g} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho_m h_m - P) + \nabla.\left(\rho_m h_m \vec{v}_m\right) = -\nabla.\vec{q''} + \vec{v}_m.\left[\nabla.\left(\bar{\bar{\tau}} - P\bar{\bar{I}}\right)\right] \tag{3}$$

where $\nabla.\bar{\bar{\tau}}$ denotes the internal stress force and $\bar{\bar{I}}$ is the identity tensor. Furthermore, $\vec{v}_m \vec{v}_m$ is a dyadic product of all the velocity components. Moreover, the convection heat flux $(q'')$ can be expressed as:

$$q'' = h_{sm}(T_{co} - T_m) \tag{4}$$

The energy equation describing the temperature distribution in a PWR fuel element (which is assumed to be an incompressible material with negligible thermal expansion) can be written as (Todreas and Kazimi, 2001):

$$\rho C_p \frac{\partial T}{\partial t} = -\nabla.\vec{q''} + q''' \tag{5}$$

where by definition the conduction heat flux is given by $\vec{q''} = -k\nabla T$. Eq. (5) can be used for the gap and cladding as well, omitting the heat power term $(q''')$.

Expressing all the time-dependent terms in the transient conservation equations (Eqs. (1)–(5)) as:

$$X(\mathbf{r}, t) = X_0(\mathbf{r}) + \delta X(\mathbf{r}, t) \tag{6}$$

and removing all the second-order terms, then removing the steady-state equations ($\partial / \partial t = 0$ in Eqs. (1)–(5)) and finally performing a temporal Fourier transform on the remaining terms as:

$$\delta X(\mathbf{r}, \omega) = \int_{-\infty}^{+\infty} \delta X(\mathbf{r}, t) \exp(-\mathbf{i}\omega t) dt \tag{7}$$

lead to the thermal–hydraulics noise equations as follows:

$$\mathbf{i}\omega\delta\rho_m + \nabla.\left(\rho_{m,0}\delta\vec{v}_m + \vec{v}_{m,0}\delta\rho_m\right) = 0 \tag{8}$$

$$\begin{aligned}&\mathbf{i}\omega\left(\rho_{m,0}\overrightarrow{\delta v}_m + \vec{v}_{m,0}\delta\rho_m\right) + \nabla.\left(\vec{v}_{m,0}\vec{v}_{m,0}\delta\rho_m + 2\rho_{m,0}\vec{v}_{m,0}\overrightarrow{\delta v}_m\right)\\ &\quad = \nabla.\left(\overline{\overline{\delta\tau}} - \delta P\bar{\bar{I}}\right) + \vec{g}\delta\rho_m\end{aligned} \tag{9}$$

$$\begin{aligned}&\mathbf{i}\omega\left(\rho_{m,0}\delta h_m + h_{m,0}\delta\rho_m - \delta P\right)\\ &\quad + \nabla.\left(\rho_{m,0}h_{m,0}\overrightarrow{\delta v}_m + \rho_{m,0}\vec{v}_{m,0}\delta h_m + h_{m,0}\vec{v}_{m,0}\delta\rho_m\right)\\ &\quad = -\nabla.\overrightarrow{\delta q''} + \vec{v}_{m,0}.\left[\nabla.\left(\overline{\overline{\delta\tau}} - \delta P\bar{\bar{I}}\right)\right] + \left[\nabla.\left(\overline{\overline{\tau_0}} - P_0\bar{\bar{I}}\right)\right].\overrightarrow{\delta v}_m\end{aligned} \tag{10}$$