Determination of integral turbulence model parameters as applied to the calculation of flows in fuel assemblies of fast reactors in porous-body approximation

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Abstract. This work aimed to correct the integral turbulence model developed earlier for assemblies of smooth rods. Two variants of the fuel assembly design were considered. In the first variant, the fuel rods were spaced using spacer grids. The presence of a spacer grid does not require a change in the form of the system of equations but leads to a change in the form of the resistance tensor and the generation of turbulence in the spacer grid region. In the second variant, a wire-wrapped fuel bundle was analyzed. The presence of a wire-wrapped fuel bundle requires an additional term in the equation for the conservation of momentum and change in the form of the resistance tensor. The simulations were obtained by CFD code ANSYS CFX and aimed at the determination of parameters involved in an integral model of turbulence being developed for modeling nuclear-reactor cores and heat exchangers in anisotropic porous-body approximation.

1. Introduction

The present work aimed to correct the integral turbulence model developed earlier for assemblies of smooth rods. We considered two variants of the fuel assembly design. In the first variant, the fuel rods were spaced using spacer grids. In the second variant, a wire-wrapped fuel bundle was analyzed.

The paper is organized as follows. In Section II, we present the equations of the anisotropic porous body with an integral turbulence model and a set of closing relations for smooth rod bundles. In Section III, we form a set of closing relations for a fuel assembly with spacers. In Section IV, form a set of closing relations for a wire-wrapped fuel bundle. Finally, we summarize this paper.

2. The anisotropic porous body model with the integral turbulence model

The anisotropic porous body model with integral turbulence model was developed before [1]:

$$\frac{\partial}{\partial x_j} \left( \bar{u}_j \right) = 0$$  (1)
\[
\frac{\partial}{\partial \tau} \rho \phi \langle u_i \rangle^i + \frac{\partial}{\partial x_j} \phi \langle u_i u_i \rangle^j = \rho \phi g_i + k_{ii} \langle \bar{u}_i \rangle^i - \frac{\partial}{\partial x_j} \phi \langle P \rangle^j + \\
+ \frac{\partial}{\partial x_j} \mu \left( \frac{\partial \langle u_i \rangle^i}{\partial x_j} + \frac{\partial \langle \bar{u}_i \rangle^i}{\partial x_j} \right), \quad i = 1, 2, 3 
\]

(2)

\[
\rho_c \phi \frac{\partial \langle i \rangle^i}{\partial \tau} + \frac{\partial}{\partial x_j} \rho_c \phi \langle u_i t_j \rangle^i = \phi \bar{u}_i + \frac{\partial}{\partial x_j} \lambda^j_{ii} \frac{\partial \langle i \rangle^i}{\partial x_j} - k_{ij} \left( \langle i \rangle^i - \langle t_i \rangle^i \right) 
\]

(3)

In the equations (1), (2), and (3), \( u \) is velocity, \( \phi \) is porosity, \( \rho \) is density, \( g_i \) is a component of the gravitational acceleration vector, \( k_{ii} = k_{ii} \delta_{ij} + (k_{ij} - k_{ii}) n_i n_j \) is a component of the resistance tensor, \( k_{ij}(\beta) \) and \( k_{ii}(\beta) \) is the longitudinal and transverse component of the resistance tensor, \( \langle P \rangle^i = \langle p \delta_{ij} \rangle^i + \rho c_p \langle \bar{u}_i \rangle^i \delta_{ij} \) is effective pressure, \( \mu = (\nu + \langle v_i \rangle^i) (\phi - \phi) \rho \) is effective viscosity, \( t \) is the fluid temperature, \( c_p \) is the specific heat capacity, \( q_v \) is volumetric energy release, \( \lambda^j_{ii} \) is the effective thermal conductivity tensor, \( k_{ii} \) is the heat transfer coefficient, \( t_i \) is the rod temperature.

The integral turbulence model was obtained by applying the local averaging procedure to the equations of the \( k-\varepsilon \) turbulence model over the periodicity-cell volume of rod assembly structure [1]:

\[
\frac{\partial}{\partial \tau} \phi \langle k \rangle^i + \langle \bar{u}_i \rangle^i \frac{\partial}{\partial x_j} \phi \langle k \rangle^j = \frac{\partial}{\partial x_j} a_k \frac{\partial}{\partial x_j} \phi \langle k \rangle^j + P_u + P_d - \phi \langle \varepsilon \rangle^j 
\]

(4)

\[
\frac{\partial}{\partial \tau} \phi \langle \varepsilon \rangle^i + \langle \bar{u}_i \rangle^i \frac{\partial}{\partial x_j} \phi \langle \varepsilon \rangle^j = \frac{\partial}{\partial x_j} a_{\varepsilon} \frac{\partial}{\partial x_j} \phi \langle \varepsilon \rangle^j + C_{\varepsilon} \frac{\langle \varepsilon \rangle^j}{\langle k \rangle^j} \left[ P_u + P_d - \phi \langle \varepsilon \rangle^j \right] 
\]

(5)

\[
\langle v_i \rangle^i = \left( c_v \right)_{ii} \frac{\langle k \rangle^i}{\langle \varepsilon \rangle^i} 
\]

(6)

In the equations (4), (5) and (6), \( \langle k \rangle^i \) and \( \langle \varepsilon \rangle^i \) are the turbulent kinetic energy and the rate of dissipation of turbulent kinetic energy, \( a_k \) and \( a_{\varepsilon} \) are the effective coefficients of the diffusion transfer of turbulence kinetic energy and the rate of dissipation of turbulent kinetic energy, \( P_u \) and \( P_d \) are the rate of turbulent production due to the average motion and due to deflection velocities, \( C_{\varepsilon} \) is a constant, \( \langle v_i \rangle^i \) is turbulent viscosity, \( \left( c_v \right)_{ii} \) is an integral coefficient. The integral coefficient \( \langle c_v \rangle^i \) relates to the turbulent viscosity \( \langle v_i \rangle^i \) with turbulence kinetic energy \( \langle k \rangle^i \) and the rate of dissipation of turbulent kinetic energy \( \langle \varepsilon \rangle^i \).

A set of closing relations for smooth bundles of rods was obtained earlier [2].

It contains the integral coefficient \( \langle c_v \rangle^i \):

\[
\langle c_v \rangle^i = 0.0134 \cdot \left( \left( \text{Re} \right)^{0.25} \cdot \beta + 0.117 \cdot (1 - \beta) \right) 
\]

(7)
and a share of power transmitted to turbulent pulsations \( \langle \alpha_i \rangle^\prime \):

\[
\langle \alpha_i \rangle^\prime = 0.1 \ln \left( \langle \text{Re} \rangle^\prime \right) - 0.63
\]

In a modern nuclear reactor rods in a fuel assembly are separated by spacers. The spacer elements influence the flow dynamics and heat transfer. It requires an appropriate correction of the anisotropic porous body model with the integral turbulence model.

3. The set of closing relations for a fuel assembly with spacers

The presence of a spacer grid does not require a change in the form of the system of equations. The system of equations contains equations (1) - (6). The set of closing relations for a fuel assembly outside of the spacer region coincides with the set of closing relations for smooth bundles of rods (7) - (8). In the spacer grid region, the form of the resistance tensor and rate of turbulent production due to deflection velocities change.

The coefficient of hydraulic resistance can be calculated using the following formula [3]:

\[
\varepsilon_{ix} = \frac{(1-m)(1.4-0.5m)}{m^2} + 0.11 \left( \frac{64}{\text{Re}_p} + \frac{\Delta}{d_i} \right)^{0.25} \frac{l_p}{m^2 d_i},
\]

In the equation (9), \( \varepsilon_{ix} \) is the constraint coefficient equals to the ratio of the cross-sectional area to the area of the flow area of the channel, \( m = 1 - \varepsilon_{ix} \) is the narrowing coefficient, \( l_p \) is the height of the spacer grid, \( \Delta \) is the roughness of the spacer grid.

The rate of turbulent production due to deflection velocities \( P_d \) can be calculated using the following formula:

\[
P_d(z) = \langle \alpha_i \rangle^\prime \frac{\rho \langle \hat{u}_i \rangle^2}{l_p} \frac{l_p}{2} = \langle \alpha_i \rangle^\prime P_d \frac{1}{l_p} \phi \equiv P_d \frac{1}{l_p}, \quad z_i - \frac{l_p}{2} \leq z \leq z_i + \frac{l_p}{2},
\]

In the equation (10), \( P_d \equiv \langle \alpha_i \rangle^\prime \frac{\rho \langle \hat{u}_i \rangle^2}{2} \langle \hat{u}_i \rangle^\prime \phi \) is the total turbulence energy generated by the \( i \)th spacer grid and it doesn’t equal zero only in the spacer grid region, \( \varepsilon_{ix} \) is the longitudinal coefficient of hydraulic resistance for a spacer grid, \( \langle \hat{u}_i \rangle^\prime \) is the inlet flow velocity in the spacer grid region.

The value of the \( \langle \alpha_i \rangle^\prime \) coefficient has to be determined for a spacer grid with the help of CFD modeling.

4. The set of closing relations for a wire-wrapped fuel bundle

The presence of a wire spacer requires a change in the form of the system of equations. The following term is added in the equation for conservation of momentum: \( \frac{1}{2} \frac{\text{rot} (\tilde{M}^\prime)}{l_p} \). It takes into account the internal moment of forces acting on the coolant. The value of the internal moment \( \tilde{M}^\prime \) for a two-way wire spacer was obtained during CFD simulation. The internal moment \( \tilde{M}^\prime \) can be calculated using the following formula:
\[ \langle m_i \rangle = 1.51 \cdot 10^{-3} \cdot \left( \frac{\text{Re}}{\text{Re}} \right)^{0.88}, \]  

(11)

In the equation (11), \( \langle m_i \rangle = M_i / \left( \rho_u \overline{u}^2 \right) \) is the dimensionless internal moment density.

The coefficients of hydraulic resistance can be calculated using the following formulas [4]:

\[ \lambda_{\varphi t} = \lambda_0 \left( 1 + 600 \left( \frac{d}{T} \right)^2 \left( \frac{s}{d} - 1 \right) \right), \]  

(12)

\[ \lambda_{\varphi \perp} = \lambda_0 \left[ 1 + 600 \left( \frac{d}{T} \right)^2 \left( \frac{s}{d} - 1 \right) \right] \left( \frac{0.16}{(\frac{s}{d} - 1)^2} + 24 \cdot \frac{s}{d} \right), \]  

(13)

In the equations (12) and (13), \( \lambda_0 \) is the coefficient of hydraulic resistance for smooth rods, \( T \) is the wire lead length, \( d \) is the rod diameter, \( s \) is the rod pitch.

The values of the integral coefficient \( \langle c_i \rangle \) and \( \langle \alpha_i \rangle \) coefficient for two-way wire spacer were obtained during CFD simulation. The dependences of the integral coefficient \( \langle c_i \rangle \) and \( \langle \alpha_i \rangle \) coefficient on the Re number are shown in Figs. 1 and 2.

**Figure 1.** The integral coefficient \( \langle c_i \rangle \) for two-way wire spacer versus the Re number: 1 – two-way wire wrap bundle; 2 – smooth bundles of rods.
Figure 2. The share of power transmitted to turbulent pulsations $\langle \alpha_v \rangle^i$ for two-way wire spacer versus the Re number: line – two-way wire wrap bundle; dots – smooth bundles of rods.

An analysis of the obtained data (Figs. 1 and 2) has shown that for the two-way wire spacer is possible to use the set of closing relations for smooth bundles of rods for the integral coefficient $\langle c_v \rangle^i$ and $\langle \alpha_v \rangle^i$.

5. Conclusions
This work aimed to correct the integral turbulence model developed earlier for assemblies of smooth rods. Two variants of the fuel assembly design were considered. In the first variant, the fuel rods were spaced using spacer grids. The presence of a spacer grid does not require a change in the form of the system of equations but leads to a change in the form of the resistance tensor and the generation of turbulence in the spacer grid region. In the second variant, a wire-wrapped fuel bundle was analyzed. The presence of a wire-wrapped fuel bundle requires an additional term in the equation for the conservation of momentum and change in the form of the resistance tensor.

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