3D CFD model of thermogasdynamic state of the New Safe Confinement of Chernobyl NPP

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Abstract: The article provides the requirements and description of the 3D CFD model of the thermogasdynamic and radiation state of the New Safe Confinement (NSC) of the Chernobyl Nuclear Power Plant (ChNPP) in Ukraine. Discussed main ideas and assumptions are put forward in solving problems of conformity of a model to a real object and introduction of own mathematical model and submodels, implementing the necessary physical properties of the NSC. The CFD model provides reliable analysis and state prediction of the NSC under different scenarios.

Key-Words: Chernobyl NPP, New Safe Confinement, destroyed reactor, radioactive aerosols, environment, modelling

Abbreviations:
ChNPP – Chernobyl Nuclear Power Plant,
NSC – New Safe Confinement,
OS - Object "Shelter",
RA - Radioactive Aerosols,
FCM - Fuel Containing Materials,
AS – Annular Space,
AHU - air handling unit.

1 Introduction

This article is a continuation of the article [10] and is devoted to modeling the Reactor Unit 4 of Chernobyl Nuclear Power Plant (ChNPP) that was destroyed on 26 April 1986. This accident is the worst accident in history in terms of resulting deaths, health issues, environment and costs. The sarcophagus or Shelter Object (OS) (1986) (Fig.1) and New Safe Confinement (NSC) over the OS (was built and slid over in November 2016 by VINCI Construction Grands Projects / Bouygues Travaux Publics NOVARKA) were designed and built to limit radioactive contamination of the environment following the 1986 Chernobyl disaster, by encasing the most dangerous area and protecting it from climate expos [1] during the OS dismantling and the 100 years operation of the NSC.

The NSC as a barrier between destroyed reactor and environment was designed with several design goals in mind:

1. Convert the destroyed ChNPP Unit 4 into an environmentally safe system (i.e. to stop radioactive materials leaks to the environment).

2. Reduce degradation of the existing shelter and the Unit 4 reactor building.

3. Mitigate the consequences of a potential collapse of either the existing shelter or the Unit 4 reactor building, particularly in terms of containing the radioactive dust that would be produced by such a collapse.

4. Enable safe dismantling of unstable structures (such as the roof of the existing shelter) by providing remotely operated equipment.

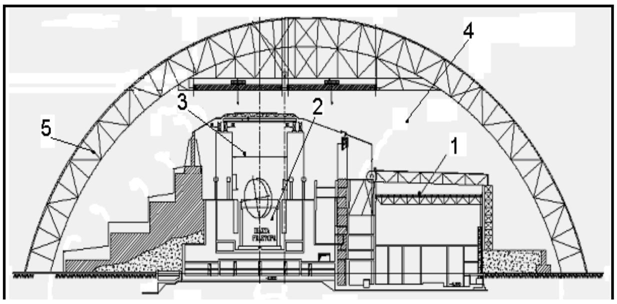


Fig. 1. The scheme of the OS and the NSC cross-section. 1- turbine hall, 2 – destroyed reactor, 3 – central hall, 4 – main volume and 5 – annular space of the NSC.

However, the construction of protective structures of the OS and the NSC does not solve all the problems associated with the operation and performance of the facility.

In particular, in the OS there are the following elements that present a threat to the environment:

1) FCM - fuel containing materials formed in the lava-like structure, which is a source of radiation and radioactive aerosols.

2) Water accumulations - radioactively contaminated water in the premises of the lower marks of the OS [2,3] (Fig. 1, pos.2), which is a source of moisture and, after drying, a potential source of RA [4-6].

3) Radioactive aerosols (RA) - aerosols that expose danger to human health and emit in the reactor zone and spread to the main volume of the NSC, where people work [7-9].

Since the main task of the New Confinement is to facilitate the transformation of the ChNPP into an environmentally safe area [10], it must provide a reliable isolation of the NSC main volume for the time it takes to dismantle the reactor structures and, in the long term, to withdraw FCM. A system of ventilation of AS was designed and it performs the following tasks under the following climatic conditions: temperature -22 to +31 ° C, relative humidity 0 to 100%, and wind speed 0 to 25 m / s:

1. Maintenance of humidity in the annular space of the Arch below 40% to reduce the corrosion of steel structures of the NSC for their 100 years operation period.

2. Maintaining the rarified pressure in the main volume of the NSC at about -5 Pa and increased pressure in the AS (Fig.1, pos. 5). It eliminates the possibility of aerosol leaks to the environment from the NSC. Pressurization and dehumidification of air in the AS is carried out by the ventilation system, which supplies treated air from the environment.

The model capable of simulating the state of such large objects as the OS and the NSC (height 110 m, width 250 m, length 160 m [1] without taking into account the zone of the environment) was developed by the authors of the work using the finite volume method, which is implemented by the Ansys Fluent software package. It is able to simulate physical processes such as mass transfer, heat exchange by convection, conductivity and radiation, multiphase flows. However, its standard functionality does not include a number of important physical processes: mass transfer through small leakages in the wall with preserving attributes of solid walls (such as conjugate heat transfer), generation of aerosols under different conditions (emission and deposition), condensation and evaporation in the NSC (the Fluent already has condensation-evaporation model, but not suitable for NSC simulation due to its high resource-cost and low optimization). To take into account all the physical processes listed above, have been introduced submodels (- custom functions that complement the existing standard Fluent model at the UDF level (user defined function) to increase the functionality or stability of the simulation).

2 Problem Formulation

2.1 Main requirements to the CFD model

For correct simulation of thermal and humidity state of the OS and the NSC the model has to consider the following properties and physical processes outside and inside of NSC and OS objects:

1. 3D and non-steady state of the NSC and OS
2. Consideration of external as well as the movement of internal air flows.
3. Accounting for the work of basic engineering equipment (ventilation, draining, climatic, etc.).
4. Evaporation and condensation inside the OS and NSC.
5. Consideration of non-tightness of NSC claddings.
6. The radioactive aerosols spread inside and outside the NSC consideration.

Schematically, the processes that occur inside and outside the OS are shown in Fig.2.

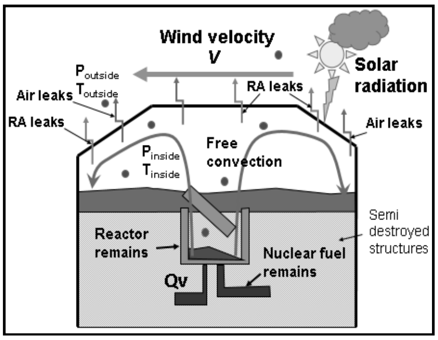


Fig. 2. Scheme of main processes inside and outside of the OS

2.2 Physical formulation of the problem

In the NSC CFD-model, the construction of the confinement is presented in full form, with all proportions and structural elements preserved, which have an effect on the flow hydrodynamics. The confinement itself is surrounded by the external volume of the environment which is 100-200 m larger than the size of the NSC. The confinement model includes a concrete foundation with a depth of 15m. Claddings of the NSC separate its internal volume from the environment and from the main volume. In the model the outer cladding has such thermal resistance and heat capacity that corresponds to the multilayer composite material covered by a stainless steel sheet. The carcase of the NSC consists of about 25 thousands tons of steel tubes which, as it was determined by the research, do not affect the hydrodynamics in the AS (occupy ~0.3 % of the total volume), however, they contribute to the AS thermal-inertia. The claddings are not air-impenetrable due to permeability of sheet connection or other defects, so the AS is not completely sealed. The problem of leakage consideration is discussed in the next paragraph. The ventilation system supplies dehumidified and heated air from the environment to the AS to maintain there overpressure and eliminate the leakage from the main volume.

Physical model corresponds to the following physical processes occurring externally and inside the NSC and OS (Fig.3)

1. Variable weather conditions outside of the NSC (changing the direction and velocity of the wind (Fig.3, b), temperature dependence from the season, solar radiation).

2. Heat generation of FCM.

3. Free convection in conjunction with the forced convection inside the NSC and OS (Fig. 3).

3. Condensation and evaporation on walls depending on the temperature of the wall and air and relative humidity.

5. Generation of aerosols in the OS as a result of air flows and human activity and the further spread of raised RA.

The main volume contains the entire structure of the OS (Fig. 4).

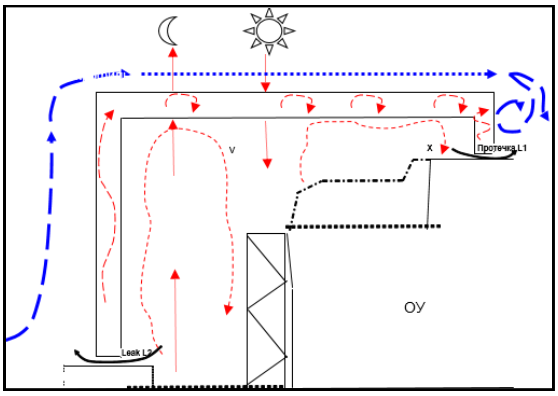


Fig.3. Longitudinal section of NSC and OS. The blue arrows on indicate the outside airflow movement due to wind and pressure difference and the red arrows inside due to thermally induced airflow movement due to temperature differences (thermal convection).

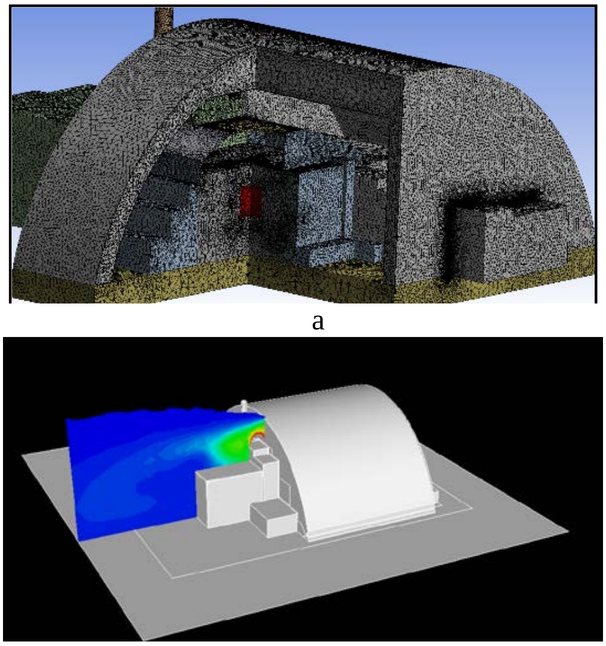


Fig. 4. Geometrical model, (a) cross-section of the model mesh and (b) velocity field for combined NSC+OS model

2.3 Mathematical formulation of the problem

The thermogasdynamic model has been developed using the Ansys Fluent software package.

Taking into account the peculiarities of the problem statement, the κ-ε standard model of turbulence has been chosen. Selected segregated (simple) pressure-based solver algorithm with first order upwind discretization for impulse, energy, turbulence and dissipation, and body force scheme discretization for pressure [11].

Species transport equation is activated for second component in air (moisture). Mixture model has been selected for a second phase (solid particles of aerosols).

The continuity equation for a multiphase flow (1):

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \overrightarrow{\upsilon_m}) = S_m, \qquad (1)$$

where $\overrightarrow{\upsilon_m}$ is the mass-averaged velocity:

$$\overrightarrow{\upsilon_m} = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \overrightarrow{\upsilon_k}}{\rho_m},$$

and ρ_m is the mixture density:

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k$$

α_k is the volume fraction of phase k.

For the *i*-component of the main phase (humidity in the air), the continuity equation will take the following form (2) and will be supplemented by the diffusion flux J of component *i* (3):

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{\upsilon} Y_i) = -\nabla \cdot \vec{J}_i + S_i, \qquad (2)$$

$$\vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\nabla Y_i - D_{T,i}\frac{\nabla T}{T}, \qquad (3)$$

Y_i is local mass fraction of each species,

$D_{i,m}$ is the mass diffusion coefficient for species *i* in the mixture, and $D_{T,i}$ is the thermal (Soret) diffusion coefficient (in model $D_{T,i} = 0$),

Sc_t is the turbulent Schmidt number (The default is 0.7).

The air density is determined from the state of the ideal incompressible gas (4), which ignores the change in density from pressure, but takes into account the change in density from temperature. This causes free convection under the influence of small temperature gradients.

$$\rho_{air} = \frac{p_{op}}{R/M_{\varpi} \cdot T}, \qquad (4)$$

Where p_{op} - operating pressure (101315 Pa),

R – universal gas constant,

M_{ϖ} - molecular mass of gas.

Impulse equation for multiphase flow (5):

$$\frac{\partial}{\partial t}(\rho_m \vec{\upsilon}_m) + \nabla \cdot (\rho_m \vec{\upsilon}_m \vec{\upsilon}_m) = -\nabla p + \nabla\left[\mu_m(\nabla \vec{\upsilon}_m + \nabla \vec{\upsilon}_m^{\,T})\right] + \rho_m \vec{g} + \vec{F} + \nabla\left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{\upsilon}_{dr,k} \vec{\upsilon}_{dr,k}\right) \qquad (5)$$

where n is the number of phases, $\vec{F}$ is a body force, and μ_m is the viscosity of the mixture:

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k ,$$

To take into account the phenomenon of aerosol deposition, the option of slip velocity activated, which takes into account the movement of aerosols (phase 2), relative to air (phase 1).

$$\vec{\upsilon}_{dr,k} = \vec{\upsilon}_k - \vec{\upsilon}_m$$

Energy equation for multiphase flow (6):

$$\frac{\partial}{\partial t}\sum_{k=1}^{n} \alpha_k \rho_k E_k + \nabla \cdot \sum_{k=1}^{n} \alpha_k \vec{\upsilon}_k (\rho_k E_k + \rho) = \nabla(k_{eff} \nabla T) + S_E \qquad (6)$$

where k_{eff} is the effective conductivity ($\sum_{k=1}^{n} \alpha_k (k_k + k_t)$), where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used. S_E includes any other volumetric heat sources. For compressible phases:

$$E_k = h_k - \frac{p}{\rho_k} + \frac{\upsilon_k^2}{2}$$

For incompressible (in this formulation of the task) $E_k = h_k$, where h_k is the sensible enthalpy for phase k.

The diffusion of energy along with the diffusion of the second component of the air phase (moisture) is taken into account by the equation $\nabla\left[\sum_{i=1}^{n} h_i \vec{J}_i\right]$.

The volume fraction equation for secondary phase k can be obtained from the continuity equation for secondary phase (7):

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \vec{\upsilon}_k) = -\nabla(\alpha_k \rho_k \vec{\upsilon}_{dr,k}) + \sum_{q=1}^{n}(\dot{m}_{qk} - \dot{m}_{kq}) \qquad (7)$$

For κ-ε standard turbulence model the k-energy turbulence equation (8):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\epsilon - Y_M + S_k, \qquad (8)$$

Equation of ϵ-energy of dissipation (9)

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\epsilon})\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon, \qquad (9)$$

In some cases, there is a need to supplement the existing standard model (for example, the need to heat the wall from solar radiation with simultaneous air leakage - the mass transfer through the wall that is not available in the Fluent package), and for this purpose submodels have been developed to complement the governing equations by determining the sources (for example, S_ϵ in (9)) and are described further.

3 Problem Solution

In order to meet the above requirements (2.1) for the 3D CFD model of the NSC, the following solutions have been developed and implemented.

3.1 3-D and non-steady state of the NSC and OS

The model should take into account all the features of the OS, including FCM in the form of local energy sources and properties of materials.

The model should be unsteady in order to take into account seasonal changes in the parameters of the environment and the thermal inertia of the massive structures of the OS and the NSC (Fig. 5). Such thermal inertia leads to the temperature lag of the individual elements of the OS (foundation, rooms) relative to the temperature of the environment up to 3 months.

Operating conditions of the object may vary with time (sealing of the NSC, AHU operating modes and heat sources, gradual dismantling of some OS parts).

With such unsteadiness of the process, measurements of physical quantities are regularly obtained from ChNPP and integrated into the model. Some data serve as input data in modeling (temperature, humidity of ambient air), and some for verifying the model and identifying its missing parameters (aerosol concentration, humidity in the premises of the OS). This allows to get adequate model parameters and ensure the reliability of the simulation results.

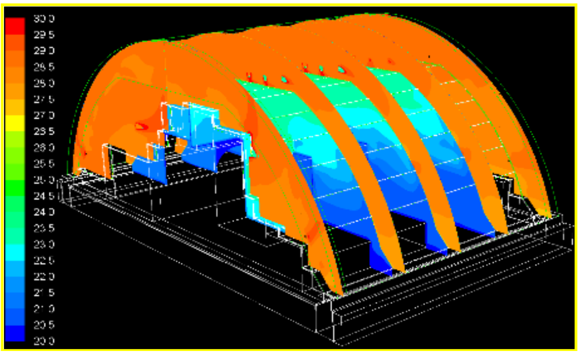


Fig. 5. temperature, °C distributions in different cross-sections of the NSC and OS.

3.3 Consideration of external and internal air flows

The distribution of pressure over the surface of the outer cladding of the NSC has a significant effect on the level of air leakeages. The hydrodynamics of the environment is calculated taking into account:

1) Rose of Wind. Consideration of changes in both the speed of air and its direction.

2) Changes in air velocity with height. The height of the building reaches 110 meters, which gives a difference in the air velocity near the ground and at an altitude of 110 meters to 2 times for the given area.

Inside the AS, there is a free convection in combination with the forced (Fig. 3), caused by air flow from the environment into the AS through the cracks and the ventilation system.

3.4 Accounting for the work of basic engineering equipment

The ventilation system (Fig. 6) has been examined and implemented into the model. In addition, this model has been used to test engineering solutions in the design of ventilation systems. The injection effect of the new NSC pipe (with a height of more than 110 m) is considered.

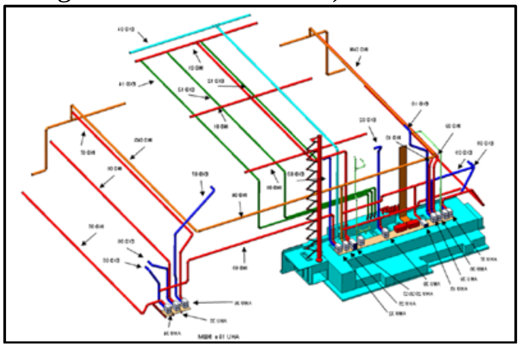


Fig.6 – The scheme of air ducts of the ventilation system of the AS and the main volume of the NSC

3.5 Evaporation and condensation inside the NSC

In the rooms of the lower levels of the OS there are significant amounts (up to 370 m^3) of standing water [3]. The amount of water is changing seasonally. Ansys Fluent allows to calculate the spread of moist air (Fig. 7) without the need for additional submodels, but condensation and evaporation in it are resource-cost processes. To fix this, the submodel of condensation and evaporation was introduced and configured. It consists of determining the sources of the second component of the air phase and energy sources in the air cells.

The OS structure (Fig1, pos. 1, 2, 3) is difficult to take into account in the model, so it was replaced by a separate homogeneous volume V_{SO}. In this volume there is evaporation / condensation and accumulation of moisture with the assumption that the wall temperature is equal to the air temperature.

A positive source for evaporation or negative for condensation is represented by the term S_i (kg / m^3s) in (2).

The evaporation-condensation flux (kg/m^{2}s) can be obtained from the Hertz-Knudsen formula [12], which based on the kinetic theory for a flat interface (10):

$$J = \beta\sqrt{\frac{M}{2\pi RT_{sat}}}(P^* - P_s), \qquad (10)$$

Where P is the pressure, T is the saturation temperature, and R is the universal gas constant. The coefficient β is the so-called accommodation coefficient that shows the portion of vapor molecules going into the liquid surface and adsorbed by this surface. P* represents the vapor partial pressure at the interface on the vapor side. The Clapeyron-Clausius equation relates the pressure to the temperature for the saturation condition.

The equation (10) consists of constant and empirical coefficients and is determined experimentally as a coefficient z:

$$z = \beta\sqrt{\frac{M}{2\pi RT_{sat}}}$$

Then the equation (10) after the multiplication on the area of the water mirror will take the form (11):

$$J = z \cdot (1 - \phi) \cdot p_s \cdot S_f \ \text{(kg/s)}, \qquad (11)$$

where z - coefficient of evaporation and condensation (found empirically), ϕ is relative humidity, S_f is the area of water surface inside the OS, approximately 1000m^2 [2], the p_s is the partial saturation pressure from the formula (12):

$$p_s = \frac{\exp(77{,}345 + 0{,}0057 \cdot \bar{T} - 7235 / \bar{T})}{\bar{T}^{8{,}2}}, \qquad (12)$$

$\bar{T}$ – average temperature in volume, K.

Finally, the source of the mass of the *i*-th component of the air phase (water) in the OS is determined from the formula (13):

$$S_i = \frac{J}{V_{SO}}, \qquad (13)$$

Moisture, condensing, may be on the surface in the form of local puddles, which may later evaporate. The amount of accumulated moisture and the rate of its evaporation are taken into account in the UDM (user defined memory) submodel, which holds the amount of accumulated moisture (water) for each cell in memory throughout the calculation, which allows to set the initial amount of moisture and track its change.

Amount of moisture accumulated (or evaporated) in the cell over the time interval Δτ by the formula (14):

$$M_\tau = M_{\tau-\Delta\tau} + \frac{J}{V_{SO}} \cdot \Delta\tau \cdot V_c, \qquad (13)$$

where V_c - cell volume.

The evaporation / condensation heat is given in the energy equation (6) as S_E, which is determined from the multiplication of the mass source on the heat of vaporization *r* (2.4 · 10^6 J / kg · K) (14).

$$S_E = J \cdot r \quad (W/m^3), \qquad (14)$$

This approach allowed to bypass the resource limitations of the Fluent software with full consideration of these effects as a dynamic change in the thermal state of the object, depending on the temperature regime of the claddings of confinement.

3.6 Consideration of non-tightness of NSC claddings and OS roof

As it was previously described, the model takes into account the heating of the outer cladding (Fig.8) of the NSC under the influence of solar radiation. This is possible by activating Discrete Ordinates radiation model that gives superficial heat sources on an impenetrable wall. In addition, an impenetrable wall allows the simulation of conjugate heat transfer that is not available under other boundary conditions (eg porous medium) and should be taken into account.

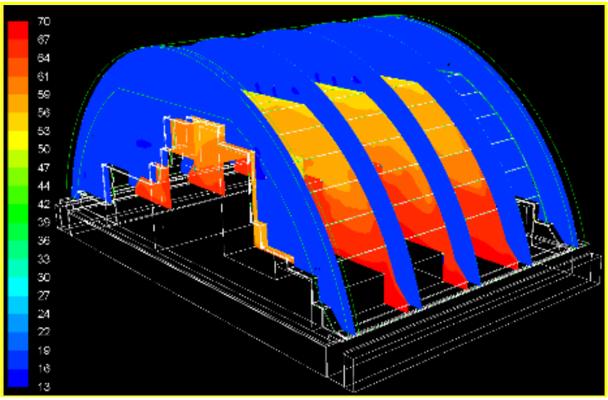


Fig. 7. Humidity, % distributions in different cross-sections of the NSC and OS.

However, the outer shell of the NSC is not tight and leakages occupy about 1,5 m^2 which should be taken into account in the model. Thus, there are several ways to model the leakages:

1) Creation of a detailed grid that would have gaps in the claddings of the AS. However, in reality, gaps are too small to be taken into account in a geometric model and can be represented as periodically enlarged gaps filled with porous medium with a certain hydraulic resistance to achieve the required mass flow. The advantage of this approach is the absence of need to create a submodel, since the approach is implemented at the geometry level. However, in the simulation of objects of such scales, the calculation speed plays an important role, which decreases proportionally with the increase in the number of grid elements. This

imposes significant restrictions on this approach. The model may lose stability and accuracy applying a coarse grid.

2) Creation of a submodel of mass transfer, thermal, kinetic and turbulent energy through an impenetrable wall. In this case, the wall remains impenetrable and able to perceive the heat of sunlight.

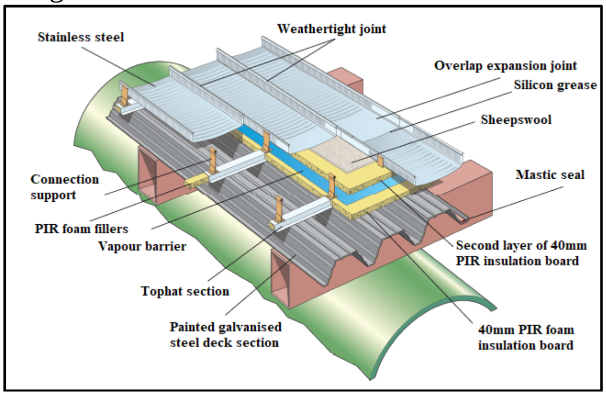


Fig.8 – Composition of Outer cladding

The cells of the air that adjoin the wall on both sides become interconnected (Fig. 9). Knowing the difference in the pressure in these cells, one can calculate the flow through the gaps and, accordingly, the energy transfer.

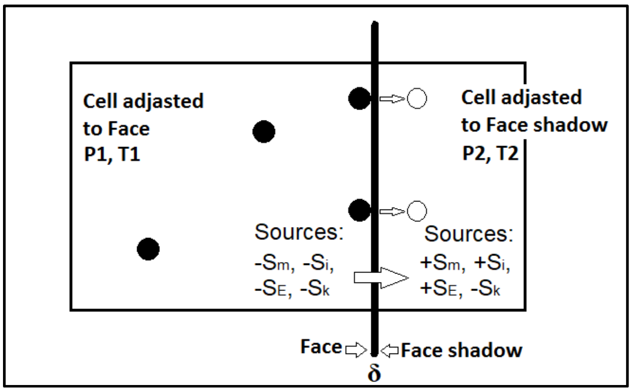


Fig.9 – Illustration of mass transfer through a solid wall

The mass transported from a cell with a high pressure in a cell with a smaller pressure from formula (15):

$$S_m = -k\frac{A}{V}\Delta p \quad (kg/m^3 \cdot s), \tag{15}$$

where A is the contact area (m^2) between adjacent cells, V is the cell volume (the volume of the receiver and the donor cell is the same due to the presence of the boundary layer in the grid), Δp - the pressure difference between the cells (Pa), *k* is the transfer coefficient (s/m) from the formula (16):

$$k = \frac{\alpha\rho}{\mu\delta} \ , \tag{16}$$

Where ρ - air density (kg/m^3), μ - dynamic viscosity (Pa·s), δ - wall thickness (m), α - the permeability of the wall (leakages) (1/s), is determined accordingly to the environment.

The pressure difference can be calculated by the formula (17):

$$\Delta p = -(\frac{\mu}{\alpha}\upsilon + C_2\frac{\rho\upsilon^2}{2})\delta \ , \tag{17}$$

Where υ - air velocity (m/s), C_2 - the coefficient of inertial losses (hydraulic resistance is considered only viscous when the speed of flow is small).

Let's express the speed through the flow rate of g (18):

$$\upsilon = \frac{g}{\rho} \ , \tag{18}$$

Let us rewrite the equation (17) in (19):

$$\Delta p = -\frac{\mu\delta}{\alpha}\upsilon = -\frac{\mu\delta}{\alpha}\cdot\frac{g}{\rho} \ , \tag{19}$$

After that, the flow rate can be expressed in (20):

$$g = -\frac{\alpha\rho}{\mu\delta}\Delta p \ , \tag{20}$$

The source of the mass in the cell in its final form (21):

$$S_m = g\frac{A}{V} \ , \tag{21}$$

Impulse to be transmitted when the mass m is transferred with a velocity υ to a cell with volume V for the time $\Delta\tau$ from formula (22):

$$I = \frac{m\cdot\upsilon}{V\cdot\Delta\tau} \ , \tag{22}$$

Let's express the mass through the mass source (23) and the velocity through the flow rate (24):

$$m = S_m \cdot V \cdot \Delta\tau \ , \tag{23}$$

$$\upsilon = \frac{S_m \cdot V}{\rho\cdot A} \ , \tag{24}$$

Substitute the (23) and (24) in (22) and finally the impulse that is transmitted when the mass of S_m is transferred to a cell with volume V, with density ρ through the contact area A, from formula (25):

$$S_i = \frac{S_m^2\cdot V}{\rho\cdot A} \ , \tag{25}$$

The idea of a source of thermal energy lies in the fact that the mass that flows from a cell with a high pressure into a cell with a smaller one has the heat energy of the donor cell, which must be inserted into the recipient cell and, accordingly, subtracted from the donor cell.

The energy source in the donor cell by the formula (26):

$$S_E = \frac{g\cdot h_c\cdot A}{V} \ , \tag{26}$$

where $h_c = C_p \cdot (T_{donor} - 298{,}15)$ - apparent energy with the zero defined at 298,15 K, J/kg [11].

Express the flow rate through the mass source:

$$g = \frac{S_m \cdot V}{A} \quad (kg/m^2 s),$$

After that, the energy source is determined by the formula (27):

$$S_E = \frac{S_m \cdot V \cdot C_p \cdot (T_{donor} - 298{,}15) \cdot A}{V \cdot A} =$$
$$= S_m \cdot C_p \cdot (T_{donor} - 298{,}15) \quad W/kg, \qquad (27)$$

For the turbulence it was assumed that the flow in the zone near the wall is laminarized, which positively affects the stability of the calculation, but causes an incorrect calculation of the heat transfer from the wall to the air , which can later be corrected by specifying the wall Prandtl number Pr_{wall}.

The laminarization of the flow is achieved at the expense of the negative source k of the turbulence energy S_k in equation (8) and it looks like (28):

$$S_k = -b \cdot k \cdot \rho \quad kg/m \cdot s^3) \qquad (28)$$

Where b - laminarization coefficient (1-5).

The negative source k of turbulent energy rejects the need for a determining the source of dissipation energy ϵ.

By setting these sources it is possible to simulate the mass transfer through an impenetrable wall, having previously linked two cells of air on different sides of the wall.

The advantage of this approach is that it does not lead to the growth in number of grid cells, with the preservation of all the features of an impenetrable wall (radiation heating).

Among the disadvantages is the need to write and test the mathematical model, as well as the potential negative impact on the stability of the model with an incorrect or incomplete assignment of sources - it is impossible to get around the task with only a few sources, for example, only mass and energy, as all the rest of the system must be specified when specifying a mass source, otherwise a divergence in functions may arise.

One of the subspecies of the 2 approach is to take into account the transfer of the second phase (humidity, aerosols).

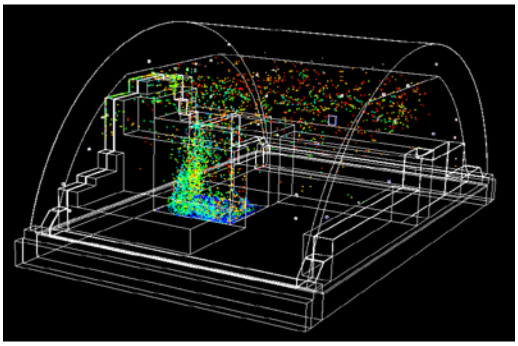
At the moment, there are 2 models in use, which represent different approaches to taking leaks into account.

3.7 The radioactive aerosols spread inside and outside the NSC consideration

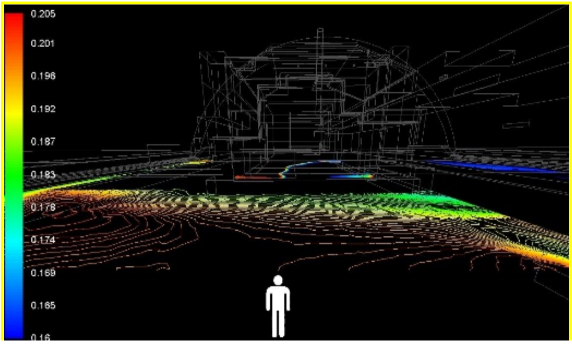
Because aerosols are the main carrier of radioactive substances, the spread of dust and aerosols in the confinement and beyond is of particular interest. The entire confinement structure was built to keep aerosols under control, not accessible to air outside the zone (Fig. 10).

Sources of aerosols in the main volume are dismantling operations of the reactor parts, free convection under small gradients of temperature and forced convection, caused by the airing of air from the environment to the main volume [4-6].

A submodel that determines the sources of resuspension from the ground due to the forced and free convection of air has been created.



a



b

Fig. 10. (a) The process of radioactive aerosol particles distribution from OS to main volume of NSC modelling, (b) isolines of RA concentrations inside the NSC at the height of 1.5m from the ground at the area of possible personnel activity

It allows to determine the distribution of aerosols on surfaces and their redistribution in space in the following processes:

1) Work of the personnel, his activity (walking, manual work).

2) Dismantling of structures of the object, as the main source of dust.

3) Emergency situations, such as collapse of the structure with further prediction of the amount of aerosols raised and the spread beyond the confinement.

The submodel is created in the form of UDF, which locally generates a source of aerosols through the sources of mass of the second phase with the specified periodicity. With the involvement of this submodel, in particular, the task of assessing the concentration of aerosols during the execution of work on the removal of FCM from the reactor hall has been resolved. The time, through which the concentration of aerosols would fall to a level safe for workers has been determined.

Aerosols sources are called as sources of the second phase at local points of the volume. Mixture model is a combined system of equations for the first phase and the second with the introduction of concentration. Therefore, the function for determining the sources of mass, energy for dust is not fundamentally different from that described in paragraph 3.6.

3.8 Results of implementing model with above-listed submodels and approaches

The listed submodels have been introduced into the model of prediction of the NSC state and have showed a good correlation with the experimental data. On the basis of this, during the construction and commissioning of the NSC, a number of recommendations have been adopted based on the simulation results.

The simulation of various scenarios of weather conditions and operating modes of heating systems contributes to better understanding of the object and the efficient performance of its functions.

Generally, the analysis shows that the NSC is not an absolute barrier for radioactive aerosols between the destroyed reactor and the environment. RA can penetrate to the environment along with air flow through the outer cladding and gaps between the western and eastern the NSC walls and building structures.

3.9 Next steps. CFD model of the NSC as a part of monitoring system

A further perspective of this model may be its introduction into the monitoring and forecasting system of the NSC state. Taking into account the peculiarities of the working conditions in the Chornobyl zone, this system can replace the working personnel who must operate the equipment in order to maintain the recommended air parameters. The model, configured for the NSC object, can monitor and predict any changes in the NSC operation conditions and react in a timely manner by automatic control of the ventilation system. Validation of the model can take place automatically when obtaining experimental data from sensors located on the NSC. Thus, the introduction of the CFD model of the NSC in the monitoring system is considered as the next step of the project.

4 Conclusion

The article describes the function of the main constitutive elements of the NSC and substantiates the need to create a 3D CFD model that takes into account the following main processes occurring in the NSC and of considerable interest:

- Free convection under the influence of small temperature gradients in conjunction with forced, caused by AHU and leakages in the claddings;
- Movement of air through the outer and inner claddings due to leakages and simultaneous consideration of conjugate and radiation heat exchange;
- Condensation and evaporation in the OS and further distribution of humidity in the NSC volume;
- Generation of aerosols in the result of external factors and their distribution / deposition.

Discussed the main assumptions that were made to take these processes into account. Presented mathematical models of the folowing submodels: evaporation / condensation, mass and energy transfer through a non-permeable wall .

As a result, the model allows reliable analysis and prediction of the NSC stateand can be included in the monitoring system.

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