U. P. B. Sci. Bull., Series C, Vol. 69, No.4, 2007 ISSN 1454-234x

MODELLING OF A CORIUM PROGRESSION IN REACTOR VESSEL AND CONTAINMENT DURING SEVERE ACCIDENT AT NPP

Sejed ASLKHADEMI[1], Ali MOGADDAM[2], Ivan KAZACHKOV[3]

Nuclear power safety problems are recognized as the most important in further development of the nuclear power industry in the world and present operation of the nuclear power plants (NPPs), which are still considered by many countries as the highest priority energy source. The paper is devoted to the problems of corium retention inside the containment during severe accidents at the NPPs and their modeling, which have a great importance for guaranteeing the safe operation of the stations.

In the nuclear reactors of the third generation, which be necessary at the change to the operable reactors of the second generation, the presence of a passive systems (they are capable for work even under the conditions of the complete de-energizing of station) is required for NPPs protection from the severe accidents, to localize emergency and to prevent leakage of the radioactive materials outside the containment. As far as the containment is the last safety barrier of NPP, the problem considered is of paramount importance for nuclear power safety.

For a successful construction and an operation of the passive safety systems it is necessary to carry out modeling and simulation of the different thermal hydraulic processes with the "hypothetical severe accidents" scenario, in order to be acquainted with the processes taking place and to build the correct and effective protective system on the basis of the obtained in such simulation knowledge.

Keywords: nuclear power, safety, passive, protection, modelling, simulation.

1. Introduction

During postulated severe accidents at NPPs the high temperature molten core material is expected to encounter water. The melt-water interaction would then involve film boiling, intensive evaporation up to a steam explosion, melt fragmentation and solidification, etc. If a vapor film around discrete melt fragments collapse, the interaction with the water can result in steam explosions. Such events are of potential safety concern, partly due to the dynamic loading on reactor and/or containment structures, and partly due to the generation of fine debris particles, which could have a negative impact on the long-term coolability of the core material.

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[1] Aspirant, National Technical University of Ukraine "KPI", Kyiv, Ukraine
[2] Aspirant, National Technical University of Ukraine "KPI", Kyiv
[3] Prof., National Technical University of Ukraine "KPI", Kyiv

Many problems were studied concerning the basic features of the severe accidents' progression during the past two decades analytically and experimentally [1-25]. Ex-vessel melt (debris) coolability revealed as a critical safety issue for the current and for the future water reactor plants with respect to stabilization and termination of the postulated severe accidents with a core melt down [3,4,6,12,14,15]. Late phases of a severe accident progression are associated with a corium melt discharge from the reactor vessel and further spreading of it on the concrete basemat in the current NPPs of the second generation or in a core-catcher in future plants of the third generation.

The accident would be considered terminated when the coolability (quenching and solidification) of the melt/debris bed is achieved in the long term. The most convenient accident management measure to cool the debris is to establish a water layer on a top of the melt pool. This coolability scheme has been investigated extensively in the MACE experiments (Sehgal *et al.* 1992 and Merilo *et al*. 1997) where it was found that a tough crust is formed on the upper surface of the melt pool, which severely limits the access of the water overlayer to the melt pool.

Tromm *et al.* (1993), Alsmeyer and Tromm (1995), Alsmeyer *et al.* (1998) achieved coolability by injecting coolant water from the bottom of the core melt pool. This has been investigated in the COMET experiments performed in Germany by FZK. In the experiments the melt was found to quench in a relatively short time to porous, easily penetrable debris, with continued access of water to the regions of the solidified debris.

The understanding of the peculiarities of a film-boiling phenomenon under such circumstances, spreading of the corium on the basemat of the containment, corium jet penetration into the water pool [23], cooling the particles of corium after their solidification [21,22,24,25], cooling of the corium melt layer by injection of water jets [14,15], etc. These and other phenomena are of significant importance for understanding the features of the severe accident scenario at NPPs.

In this paper, the conditions governing the behaviors of a corium retention and coolability inside the containment during severe accidents at the NPPs and their modeling are analyzed and the basic approaches for such modeling and simulation are studied.

2. To the modelling of a corium melts cooling by injected water jets

The problem belongs to a multiphase multicomponent flow dynamics with intensive heat transfer and phase changes (vaporization of the water due to contact with hot melt, melts cooling down and solidification, etc.). The experimental visualization of the coolant jet injection into the melt pool performed at the RIT/NPS [14,15] is shown in Figure 1 to the left. The schematic representation of the jet divided into the three parts (in Fig. 1 to the right): an initial part where injected water evaporated at the outlet from a nozzle is mixing with a surrounding corium melt to be cooled down, transient part and fully developed turbulent flow.

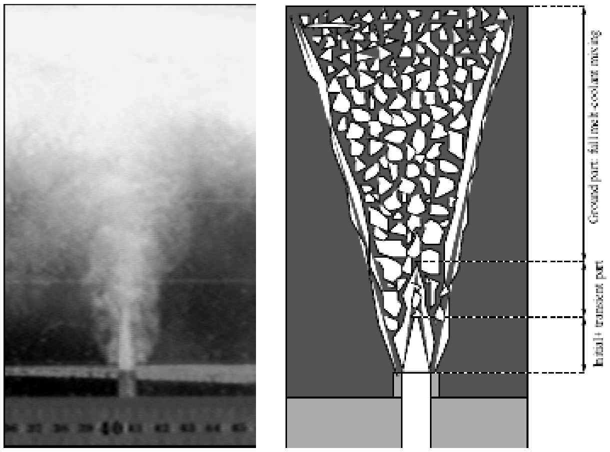

Fig. 1. Experimental visualization and model scheme (right) for melt cooling with injected jets.

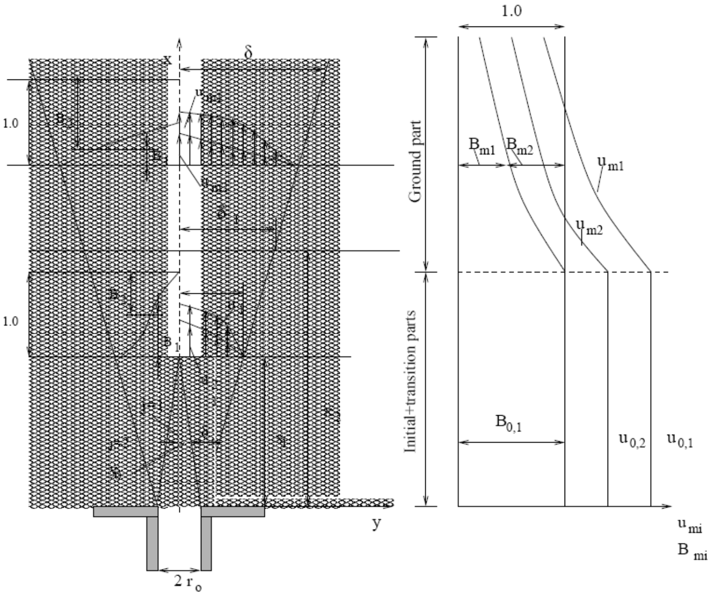

Fig. 2. Velocity and phase indicator profiles for two-phase jet model scheme.

Figure 1 to the left shows very well the close correspondence of the schematic model applied (right in Fig. 1) to the real experimental data. Dr. Palladino has got clear pictures of a jet flow where even potential core of the vapor is sharply seen. The end of an initial part of the jet is located where the vapor is totally mixed with the melt. Transient part is intermediate between the initial part and the fully developed turbulent mixing layer (ground part). The ground part is the longest one, where all components of the two-phase flow are well mixed (vapor, melt, and solidified corium particles in some locations).

3. Formulation of the equations for the model of two-phase jet

Basic parameters of the turbulent two-phase jet are the initial velocity u_{10} of the vapor flow at the outlet from the nozzle with the radius r_0. Viscosities and densities of the vapor and melt are, respectively, μ_1, μ_2 and ρ_1, ρ_2. The maximal velocities of the phases are at the jet axis u_{m1}, u_{m2}, and their function-indicators according to the method of Prof. A.I. Nakorchevskii [26, 27] are B_{m1}, B_{m2}. If the phase is present at the moment at the point considered, the function-indicator for that phase is equal 1, otherwise it is 0. Thus, $B_1 + B_2 = 1$ is satisfied at each point.

The equation array for axisymmetrical ($\partial / \partial \varphi = 0$) two-phase turbulent jet in cylindrical coordinates (x, φ, y) according to [26] is presented as follows

$$\frac{\partial}{\partial x}\left(y\rho_i B_i u_i\right)+\frac{\partial}{\partial y}\left(y\rho_i B_i v_i\right)=0,\ \rho_i B_i\left(u_i\frac{\partial u_i}{\partial x}+v_i\frac{\partial u_i}{\partial y}\right)=\frac{1}{y}\frac{\partial}{\partial y}\left(yB_i\tau_i\right)-\frac{\partial}{\partial x}\left(B_i p\right),\quad (1)$$

$i, j=1, 2$, $\tau_i = \rho_i \kappa_i \delta u_{mi} \partial u_i / \partial y$ - turbulent shear by the "new" Prandtl formula, where κ_i is the constant for i phase, δ is the width of the mixing layer, u, v, p are velocity components by coordinates x and y and pressure, respectively. Gravitational forces are neglected, and by index i the sum in the equations (1) is taken so that the equation array is presented for the phase mixture.

Now the boundary condition for the initial part of the jet is stated as

$$\eta=0,\ u_i=u_{io},\ \frac{\partial u_1}{\partial \eta}=\frac{\partial u_2}{\partial \eta},\ \frac{\partial^2 u_1}{\partial \eta^2}=0,\ B_1=1,\ \frac{\partial B_1}{\partial \eta}=0,\ \frac{\partial^2 B_1}{\partial \eta^2}=h(\zeta), \quad (2)$$

$$\eta=1,\ u_1=u_2=0,\ \frac{\partial u_1}{\partial \eta}=\frac{\partial u_2}{\partial \eta}=0,\ \frac{\partial^2 u_2}{\partial \eta^2}=0,\ B_1=0. \quad (3)$$

Accounting the boundary conditions (2), (3), polynomial approximations for the dimensionless velocity profiles are got in the form

$$u_1=1-4\eta^3+3\eta^4,\ u_2=1-6\eta^2+8\eta^3-3\eta^4,\ B_1=1-\eta^3+0.5\eta^2(1-\eta)h(\zeta), \quad (4)$$

where the dimensionless velocities are obtained with respect to the scale velocities u_{10}, u_{20}.

Another dimensionless coordinates and parameters are as follows:

$$\zeta = \kappa_1 \frac{x}{r_0},\ \eta = \frac{y - y_0(x)}{\delta},\ s_0 = \frac{u_{20}}{u_{10}},\ n = \frac{\rho_2}{\rho_1},\ \overline{y}_0 = \frac{y_0(x)}{r_0},\ \overline{\delta} = \frac{\delta(x)}{r_0},\ i_0 = ns_0^2 .$$

Here $\kappa_{21} = \kappa_2 / \kappa_1$, the function $h(\zeta)$ is determined according to the value of parameter i_0, e.g. for $n \geq 3$ it is $h(\zeta) \in [-6, 0]$.

Then substitution of polynomial approximations (4) into the equations (1) and further integration of them across the mixing layer yields for the initial part

$$\overline{y}_0^2 + 2\overline{y}_0\overline{\delta} a_1 + 2\overline{\delta}^2 a_2 = 1, \qquad \overline{y}_0^2 + 2\overline{y}_0\overline{\delta}\left(a_3 + i_0 b_3\right) + 2\overline{\delta}^2 (a_4 + i_0 b_4) = 1,$$

$$\left(1 - \overline{u}_1^*\right)\overline{y}_0 \frac{d\overline{y}_0}{d\zeta} + \frac{d}{d\zeta}\left[\overline{y}_0\overline{\delta}\left(a_3^* + i_0 b_3^*\right) + \overline{\delta}^2\left(a_4^* + i_0 b_4^*\right)\right] - \overline{u}_1^* \frac{d}{d\zeta}\left(\overline{y}_0\overline{\delta} a_1^* + \overline{\delta}^2 a_2^*\right) -$$

$$i_0 \overline{u}_2^* \frac{d}{d\zeta}\left(\overline{y}_0\overline{\delta} b_1^* + \overline{\delta}^2 b_2^*\right) = \left(\overline{y}_0 + \overline{\delta}\eta^*\right)\left[B_1^*\left(\frac{d\overline{u}_1}{d\eta}\right)^* + i_0\kappa_{21}\left(1 - B_1^*\right)\left(\frac{d\overline{u}_2}{d\eta}\right)^*\right]. \quad (5)$$

The values signed with a star * are computed at the middle section of the mixing layer ($\eta^* = 0.5$). In general, the value η^* can be chosen arbitrary. Here the next integrals were computed in the equations (5):

$$a_1 = a_{11} + a_{12}h = \int_0^1 B_1\overline{u}_1 d\eta, \qquad a_2 = a_{21} + a_{22}h = \int_0^1 B_1\overline{u}_1 \eta d\eta,$$

$$a_3 = a_{31} + a_{32}h = \int_0^1 B_1\overline{u}_1^2 d\eta, \qquad a_4 = a_{41} + a_{42}h = \int_0^1 B_1\overline{u}_1^2 \eta d\eta,$$

$$b_1 = b_{11} + b_{12}h = \int_0^1 B_2\overline{u}_2 d\eta, \qquad b_2 = b_{21} + b_{22}h = \int_0^1 B_2\overline{u}_2 \eta d\eta,$$

and so on, similarly for b_3, b_4. Computation of the integrals is a simple routine procedure. Then equation array (5) is solved with the boundary conditions:

$$\zeta = 0,\quad \overline{y}_0 = 1,\quad \overline{\delta} = 0; \qquad \zeta = \zeta_1,\quad \overline{y}_0 = 0,\quad \overline{\delta} = \overline{\delta}_1. \quad (6)$$

Similar equation array is got for the ground part of the jet flow

$$2B_{m1}\overline{u}_{m1}\overline{\delta}^2 = \frac{1}{\alpha_{11} + \alpha_{12}h}, \qquad 2B_{m1}\overline{u}_{m1}^2\overline{\delta}^2 = \alpha_{21} + \alpha_{22}h + i\left(\frac{\beta_{20}}{B_{m1}} + \beta_{21} + \beta_{22}h\right),$$

$$\frac{d}{d\zeta}B_{m1}\overline{u}_{m1}^2\overline{\delta}^2\left[\alpha_{21}^* + \alpha_{22}^* hi\left(\frac{\beta_{20}^*}{B_{m1}} + \beta_{21}^* + \beta_{22}^* h\right)\right] - \overline{u}_{m1}\frac{d}{d\zeta}B_{m1}\overline{u}_{m1}\overline{\delta}^2\left[\overline{u}_1^*(\alpha_{11}^* + \alpha_{12}^* h) + \right.$$

$$\left. + i\overline{u}_2^*\left(\frac{\beta_{10}^*}{B_{m1}} + \beta_{11}^* + \beta_{12}^* h\right)\right] = \eta^* B_{m1}\overline{u}_{m1}^2\overline{\delta}\left(\frac{\partial\overline{u}_1}{\partial\eta}\right)^*\left[\gamma_1^* + \gamma_2^* h + i\kappa_{21}\left(\frac{\partial\overline{u}_2/\partial\eta}{\partial\overline{u}_1/\partial\eta}\right)^*\left(\frac{1}{B_{m1}} - \gamma_1^* - \gamma_2^* h\right)\right], \quad (7)$$

$$\left[1 + i\left(\frac{1}{B_{m1}} - 1\right)\right]\frac{d\overline{u}_{m1}}{d\zeta} = 2\frac{\overline{u}_{m1}}{\overline{\delta}}\left(\frac{\partial\overline{u}_1}{\partial\eta}\right)_m\left[1 + i_0\kappa_{21}\left(\frac{1}{B_{m1}} - 1\right)\left(\frac{\partial^2\overline{u}_2/\partial\eta^2}{\partial^2\overline{u}_1/\partial\eta^2}\right)_m\right].$$

Boundary conditions for the equation array (7) are stated as follows

$$x = x_t, \quad \overline{u}_{m1} = 1, \quad B_{m1} = 1. \tag{8}$$

4. Numerical simulation of the corium cooling with vapour jets

Numerical solution of the boundary problems (5), (6) and (7), (8) was performed on computer. Some results of computations and experimental data [14,15] are shown in Figure 3. Based on the flow parameters computed the temperature in the melt pool and vapour flow rate were also estimated. The correlation between numerical results and experimental data [14,15] is good.

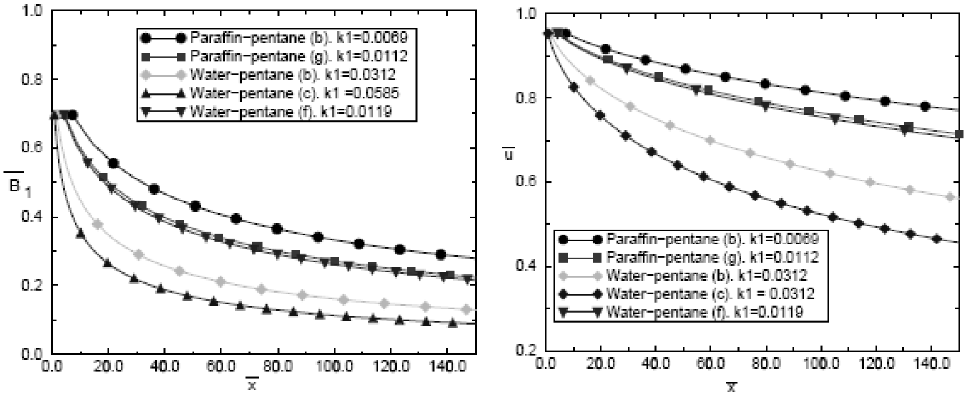

Fig. 3. Velocity and phase-indicator profiles for the two-phase melt-coolant jet.

The results obtained allowed performing the experiments with the different modelling melts: $CaO\text{-}WO_3$, $MnO+TiO_2$, etc. [14,15]. An example of a porous material obtained by this cooling scenario for $MnO+TiO_2$ is shown below.

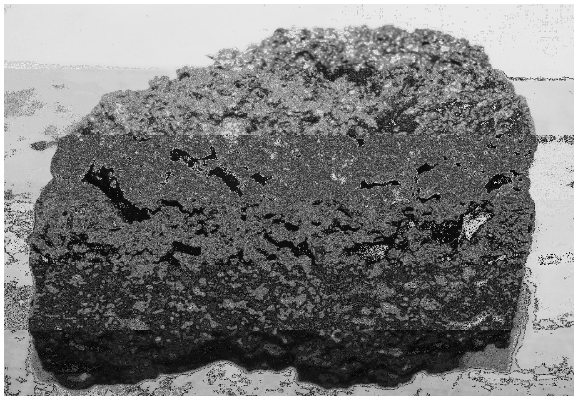

Fig. 4. $MnO\text{-}TiO_2$ debris of ceramic type (simular to UO_2+ZrO_2) structure.

The obtained structure has porosity in the debris interconnected and uniformly distributed. Therefore it may be cooled down uniformly by the water ingression so that such severe accident scenario allows controlled debris bed cooling.

5. Conclusions

The proposed two-phase model has been proven successful for modelling and simulation of the corium melt cooling down by water jets' injected from below into the melt pool. It allows computing the velocity and phase distribution (vapour, melt) in a space occupied, as well as estimating the required water (vapour) flow rate and obtained temperature distribution.

REFERENCES

[1]. *T.G. Theofanous, et al.,* In-vessel coolability and retention of core melt/ DOE/ID-10460.-1995.

[2]. *B.R. Sehgal,* Accomplishments and challenges of the severe accident research// Nuclear Engineering and Design, **vol. 210**, 2001, pp. 79-94.

[3]. *O. Kymalainen, et al.*, In-vessel retention of corium at the Loviisa Plant// Nuclear Engineering and Design, **vol. 169**, 1997, pp. 109-130.

[4]. *V.V. Asmolov,* Latest findings of RASPLAV Project/ Proc. OECD/CSNI workshop on in-vessel core debris retention and coolability, 1998.

[5]. *L.A. Bolshov, et al.*, Numerical models of molten core spreading processes in nuclear reactor safety problems/ Proc. 4th Int. Topical Meeting on Nuclear Thermal Hydraulics.- Operations and Safety, April, Taipei, Taiwan, 1994.

[6]. *N.I. Kolev*, Verification of IVA5 computer code for melt-water interaction analysis, Proc. NURETH-9, 1999.

[7]. *M.L. Carboneau, V.T. Berta, M.S. Modro*, Experiment analysis and summary report for OECD LOFT Project Fission Product Experiment LP-FP-2/ OECD LOFT-T-3806, 1989.

[8]. *V.E. Denny, B.R. Sehgal,* Analytical prediction of core heat up/liquefaction/slumping, Proc. Int. meeting on LWR severe accidents evaluation.- Cambridge Mass, 1983.

[9]. *M.M. Pilch, et al.*, The probability of containment failure by direct containment heating in Zion/ NUREG/ CR-6075, Sand93-1535, 1993.

[10]. *K. Takumi, et al.*, Results of recent NUPEC hydrogen related tests, Water Reactor Safety Information Meeting, Washington D.C., 1993.

[11]. *S. Dorofeev, et al.*, Flame acceleration limits for nuclear safety applications, CSARP Meeting, New Mexico, 1999.

[12]. *D. Magallon, et al.*, Corium melt quenching tests at low pressure and subcooled water in FARO/ Proc. NURETH-9, 1999.

[13]. *K. Froment, J.M. Seiler,* Importance of a strong coupling between phys-chemistry and thermal hydraulics for modeling late phases of severe accidents in EWRs, Proc. NURETH-9, 1999.

[14]. *D. Paladino, I.V. Kazachkov, B.R. Sehgal, A. Theerthan,* DECOBI Experiments at RIT/NPS, 2nd Half-Yearly Progress Meet. ECOSTAR Pr. REZ-Czech Rep., Jan.-Feb. 2001.

[15]. *I.V. Kazachkov, D. Paladino, B.R. Sehgal*, Ex-vessel coolability of a molten pool by coolant injection from submerged nozzles, 9th Int. Conf. Nucl. Energy Devel. Nice, France, 2001.

[16]. *B.R. Sehgal,* et al., MACE project overview, Proceedings of the OECD Meeting on Core Debris Concrete Interaction.- Karlsruhe.- Germany, 1992.

[17]. *H. Alsmeyer, B. Spencer, W. Tromm*, The COMET-concept for cooling of ex-vessel corium melts, Proc. of ICONE-6.- May 10-15.- San Diego, 1998.

[18]. *W. Tromm, H. Alsmeyer and H. Schneider*, Fragmentation of Melts by Water Inlet From Below. NURETH-6 Grenoble, France, 1993.

[19]. *H. Alsmeyer* and *W. Tromm,* "The COMET Concept for Cooling Core Melts: Evaluation of the Experimental Studies and Use in the EPR", Wissenschaftliche Berichte FZKA 6186/EXV-CSC(99)-D036, Karlsruhe, Germany, Oktober 1999.

[20]. *A.K. Stubos and J.-M. Buchlin,* "Analysis and Numerical Simulation of the Thermohydraulic Behavior of a Heat Dissipating Debris Bed During Power Transients", in Int. J. Heat Mass Transfer, **vol. 36**, no. 5, 1993, pp. 1391-1401.

[21]. *I.V. Kazachkov and M.J. Konovalikhin*, "A Model of a Steam Flow through the Volumetrically Heated Particle Bed", in Int. J. Thermal Sciences, **vol. 41**, 2002, pp. 1077-1087.

[22]. *I.V. Kazachkov, M.J. Konovalikhin and B.R. Sehgal,* Dryout Location in a Low-porosity Volumetrically Heated Particle Bed, J. Enhanced Heat Transfer, **vol.8**, no.6, 2001, 397-410.

[23]. *H.S. Park, I.V. Kazachkov, B.R. Sehgal, Y. Maruyama and J. Sugimoto*, Analysis of Plunging Jet Penetration into Liquid Pool in Isothermal Conditions, ICMF 2001: Fourth International Conference on Multiphase Flow, New Orleans, Louisiana, U.S.A., May 27 - June 1, 2001.

[24]. *M.J. Konovalikhin, I.V. Kazachkov, and B.R. Sehgal,* A model of the steam flow through the volumetrically heated saturated particle bed, ICMF 2001: Fourth International Conference on Multiphase Flow, New Orleans, Louisiana, U.S.A., May 27 - June 1, 2001.

[25]. *I.V. Kazachkov, M.J. Konovalikhin and B.R. Sehgal,* Coolability of melt pools and debris beds with bottom injection, 2^{nd} Jap.-EU Two-Phase Flow Group Meeting, Tsukuba, Japan, 2000.

[26]. *A.I. Nakorchevskii*, Heterogeneous turbulent jets, Kiev: Naukova Dumka, 1980.

[27]. *A.I. Nakorchevskii*, Turbulence as a regular viscous flow of the basic laminar modes, Turbulenzmodelle und ihre Anwendung in der Technik, Berlin, 1982, pp. 197-207.