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NUMERICAL STUDY OF SADDLE-SHAPED VOID FRACTION PROFILES EFFECT ON THERMAL HYDRAULIC PARAMETERS OF THE CHANNEL WITH TWO-PHASE FLOW USING OPENFOAM AND COMPARISON WITH EXPERIMENTS

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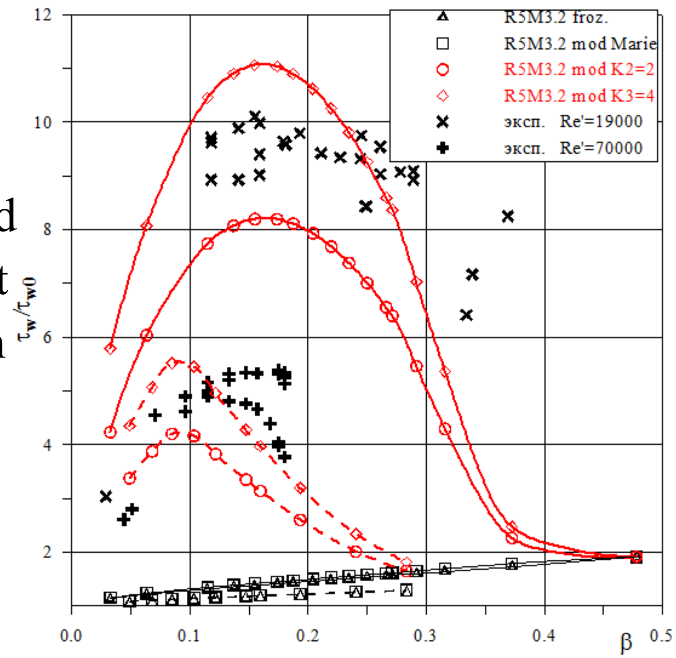
Introduction

- Two- and *multiphase flows* with bubble structure is widely presented in traditional and *nuclear power industry*, in chemical and technological production, pipeline transport of hydrocarbons, metallurgical and other equipment. Regimes of normal operation for such systems are justified by experimental and numerical methods based on regulatory and reference data
- The models presented in the majority of the *one-dimensional codes not always adequately enough describe gas distribution* via radius of the channel and don't take into account abnormal growth of friction at the wall of the channel, and for this reason they are in the process of active verification.
- Implementation of CFD codes for multiphase flow simulation with "Euler-Euler" approach allows to overcome shortcoming of the one-dimensional semi-empirical codes.



Re´ = 19000 –сплошные линии, Re´ = 70000 – пунктир

- Kornienko Yu.N. Generalization of analytical integral forms of friction, heat and mass transfer coefficients for non-equilibrium two-phase flows. Annular channels and fuel assemblies. // Issues of atomic energy. Physics of nuclear reactors series, 2013. Issue.4. – P. 61-76. (in Russian)

Purpose of the work

- The present work is dedicated to *verification of numerical model in standard solver of open-source CFD code OpenFOAM* for two-phase flow simulation – *twoPhaseEulerFoam*, and to determination of the “baseline” model parameters. The investigation of heterogeneous distributions of non-equilibrium coolant flow, which leads to abnormal friction increase of the channel in two-phase adiabatic “water-gas” flows with low void fractions, presented

- There are a significant number of works in open literature, dedicated to two-phase flow modeling with CFD codes have the following distinctive features:
  - authors use *modified* solvers with two-phase models;
  - for verification they use *international experimental data* for void fraction distribution;
  - authors basically don’t consider effects of *abnormal friction increase*

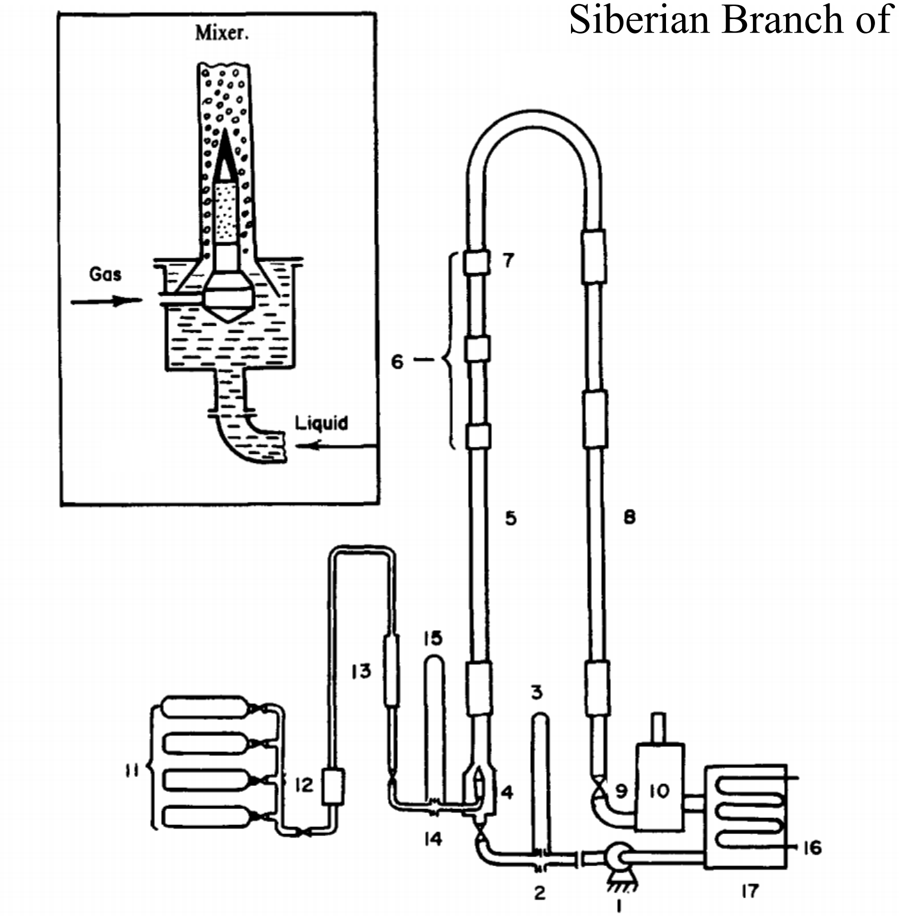
- On contrary, during this work authors used *default OpenFOAM solver* for velocities and void-fraction profiles calculation; the results of simulation were compared against *Russian experimental data* including comparison of friction at the wall. As a result the *friction coefficient* of channels walls were obtained in the wide range of gas flow ratio β.

Development of *twoPhaseEulerFoam*

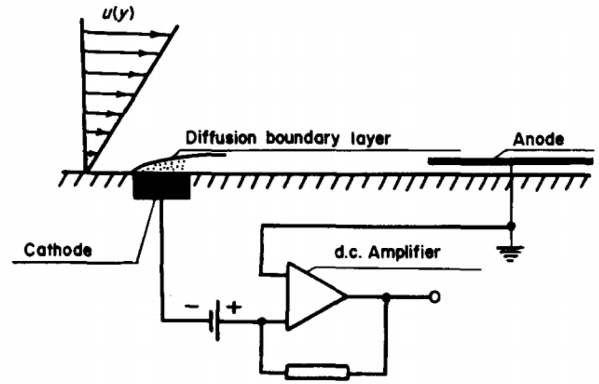
- OpenFOAM 1.7.x (2010) twoPhaseEulerFoam
  - Euler-Euler solver for turbulent two-phase flows
  - Constant material properties
  - Constant dispersed phase diameter
  - No bubble specific drag models, turbulent dispersion or wall lubrication force
  - No heat or mass transfer
  - Hard coded k-eps turbulence model
- 2.1.0 (2011)
  - Temperature base heat transfer solution, compressibility, non-unifrom diameter
- 2.1.1 (2012)
  - Improved void fraction solution algorithm (MULES)
- 2.2.0 (2013)
  - Support for multiphase thermodynamics, enthalpy based energy solution
- 2.3.0 & 2.3.1 (2014)
  - Consolidation, new runtime selectable interfacial and turbulence models. Large selection of closure models
- 3.0 & 3.0.1 (2015)
  - Boundary condition with heat flux
- 4.0 (2016)
  - Simplification of sub-models use

Information on experiment

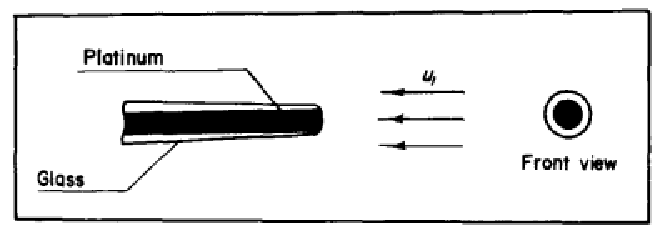
Siberian Branch of Russian Academy of Sciences



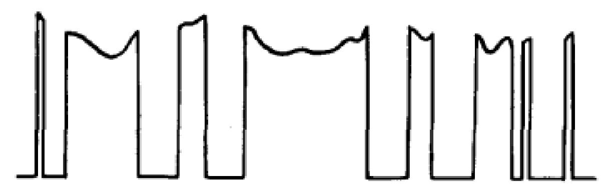
Schematic diagram of experimental set-up: 1—pump, 2, 14—orifice meters, 3, 15—differential manometers, 4—mixer, 5—upward channel, 6—regions of visualization, 7—test section, 8—downward channel, 9—adjusting valve, 10—separator, 11—compressed air vessels, 12—filter, 13—heater, 16—heat exchanger, 17—storage tank.



Schematic representation of electrochemical method of wall shear stress measurements.



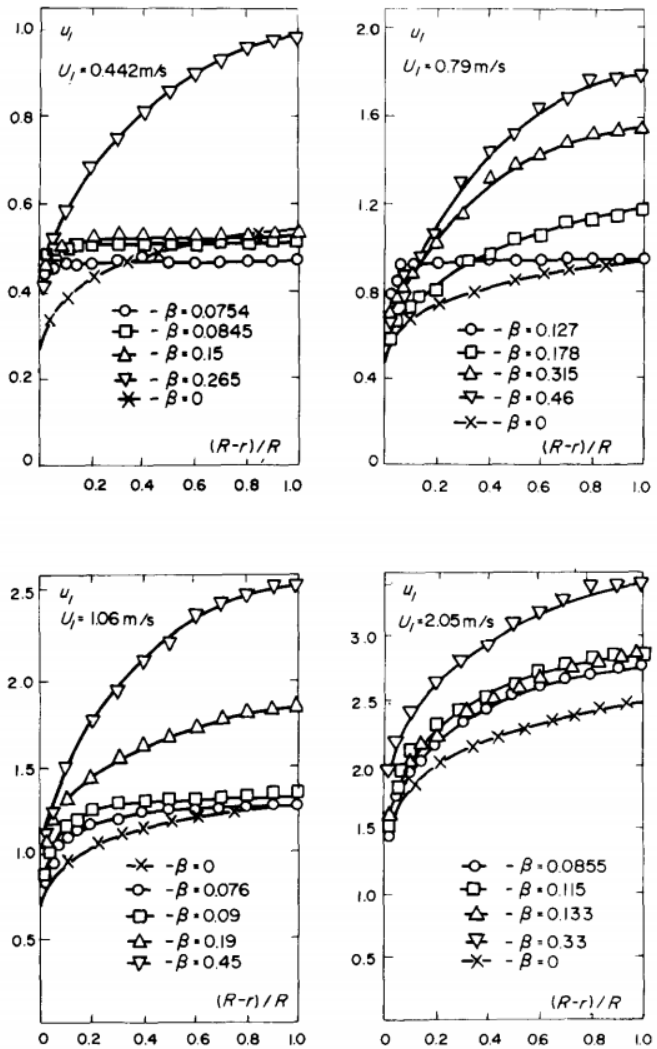
Electrochemical "blant nose" velocity probe.



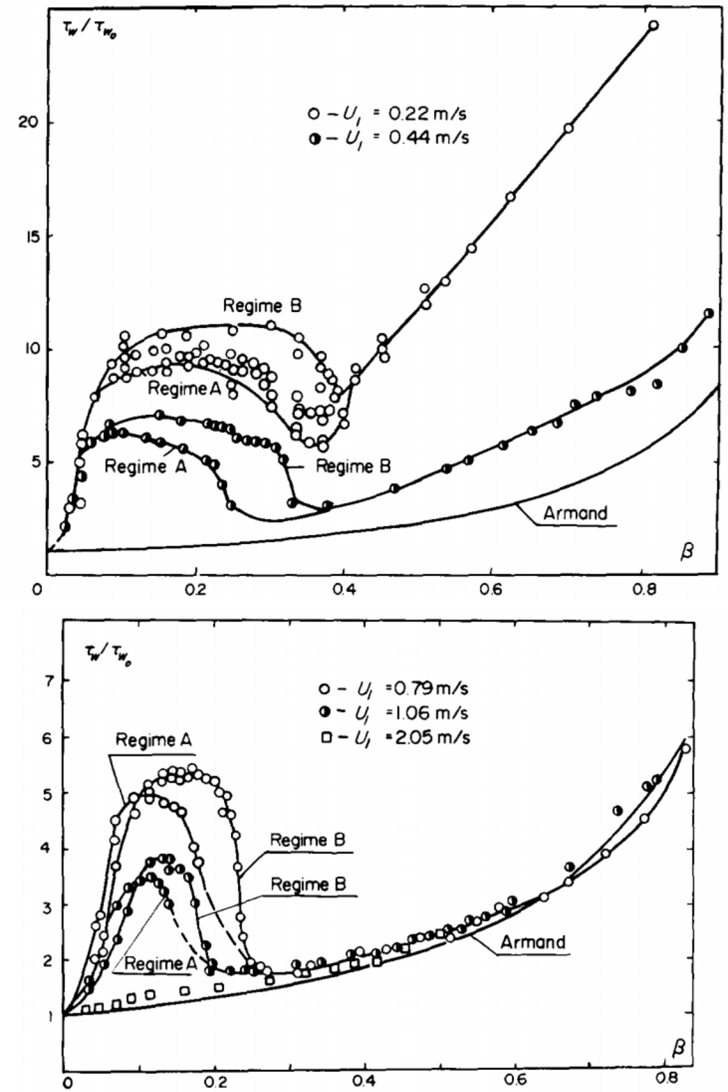
Signal of velocity probe in two-phase flow

- Nakoryakov V.E. et al. Local Characteristics of Upward Gas-Liquid Flows // Int. J. Multiphase Flow – 1981. – V. 7. – P. 63-81.

Experimental data

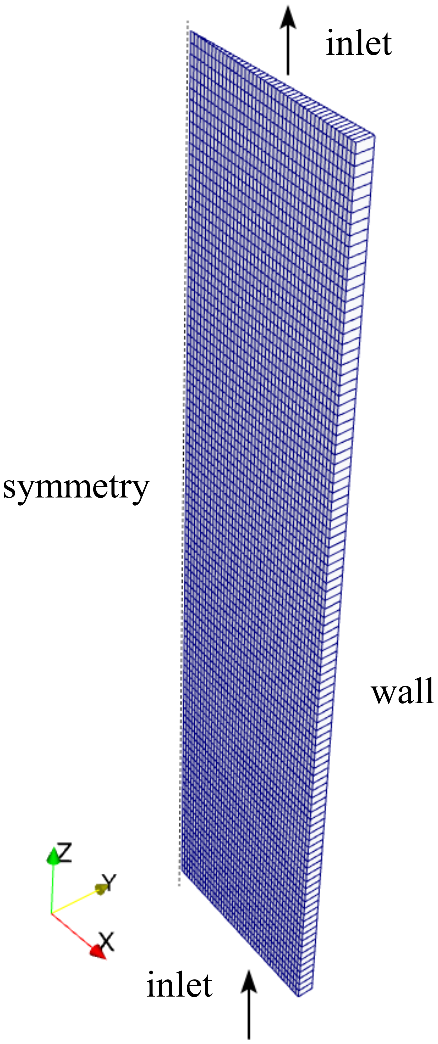


Liquid velocity profiles in two-phase flow.



Wall shear stress vs gas flow rate.

Case set-up



- ***inlet:***
  - Uniform velocity profile for liquid and gas phases (U_g, U_l)
  - Uniform void fraction profile (α)
- ***wall:***
  - No-slip BC for liquid phase
  - Slip BC for gas phase
  - Standard wall-function for turbulence parameters
- ***outlet:***
  - *zeroGradient* for velocity and turbulence parameters,
  - fixed pressure value

Interfacial interaction models

$$\vec{M}_{ki} = -\vec{M}_{ik} = \vec{M}_D + \vec{M}_L + \vec{M}_{TD} + \vec{M}_W$$

drag, lift, turbulent dispersion and wall forces

- Interfacial interaction models in OpenFOAM 2.3.0 (2012):

Drag, C_d:
- Hosokawa & Tomiyama (2009)
- Tomiyama (2002)
- Tomiyama (1995)
- Schiller-Nauman (1935)
- Constant C_d

Virtual Mass, C_{vm}:
- Lamb (1879)
- Constant C_{vm}

Turbulent dispersion:
- Burns (2004)
- Bertodano (RPI) (1992)
- Gosman (1992)
- None

Swarm correction for Drag:
- Tomiyama (1995)
- None

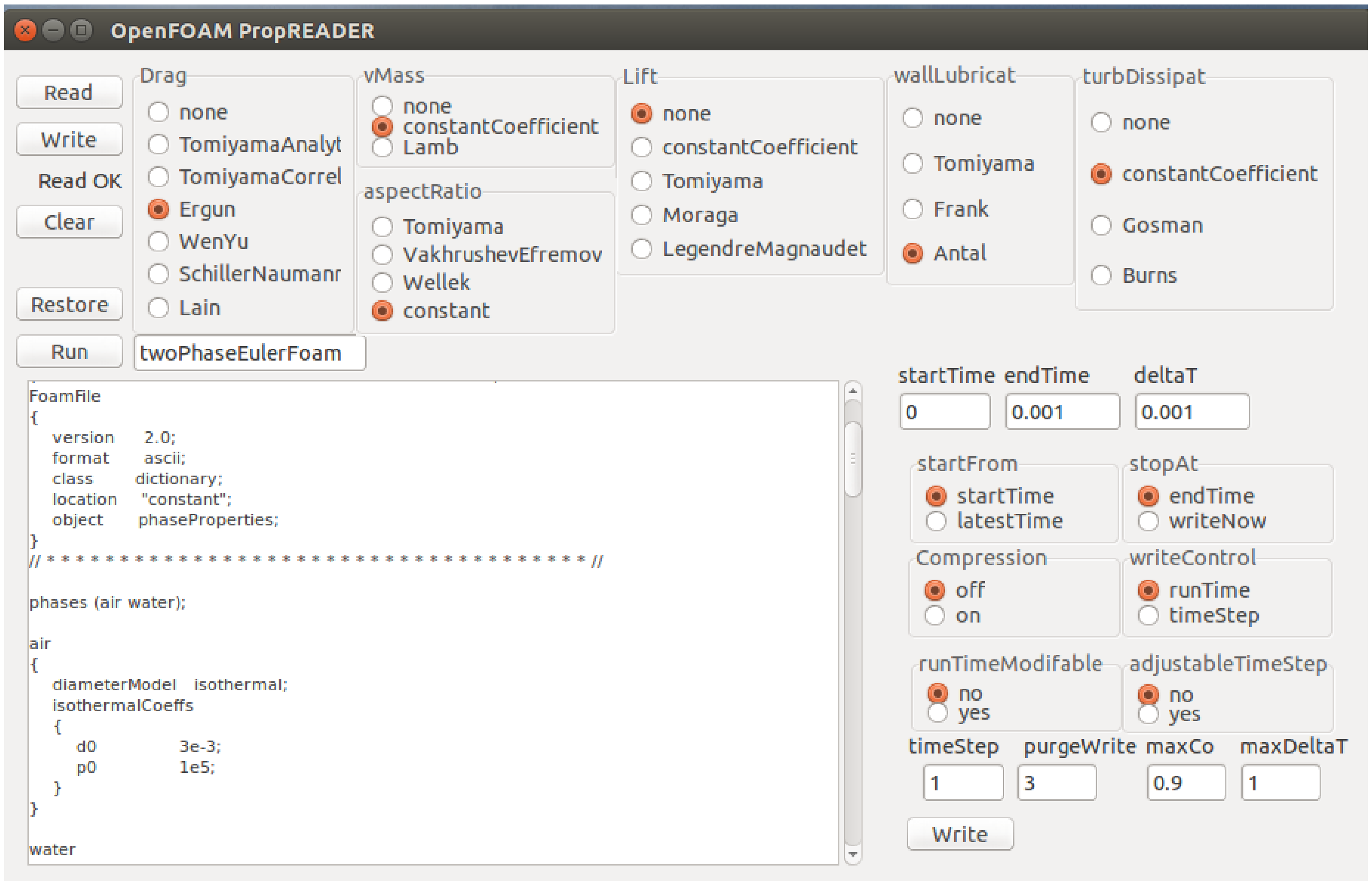
Bubble aspect ratio:
- Hosokawa & Tomiyama (2009)
- Vakrushev & Effremov (1970)
- Wellek (1966)
- Constant

Wall lubrication force:
- Frank (2004)
- Generalized Tomiyama (2003)
- Antal (1991)
- none

Lift, C_l:
- Tomiyama (2002)
- Constant C_l

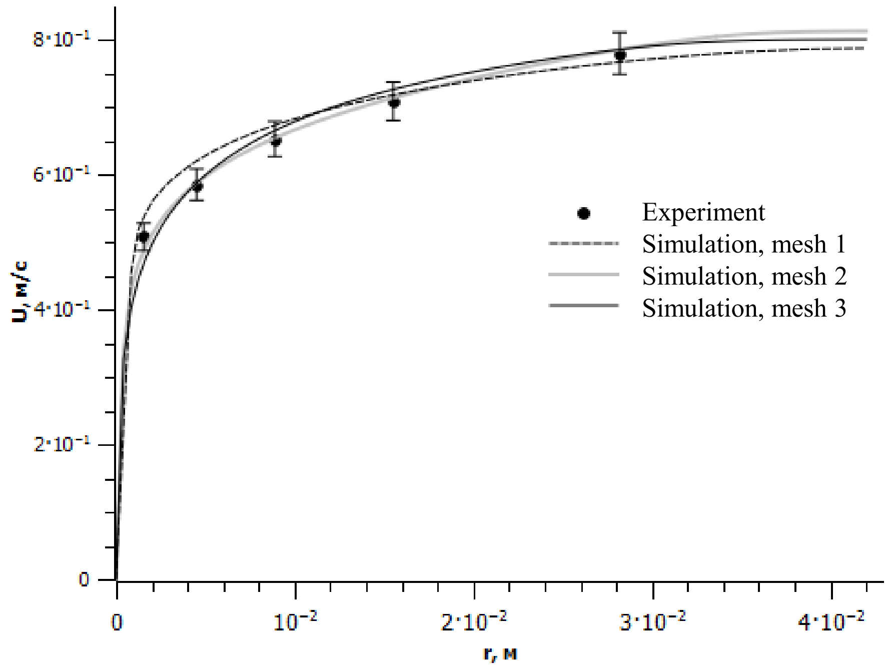
twoPhaseEulerFoam Properties Reader

- Utility to simplify *phaseProperties* file input

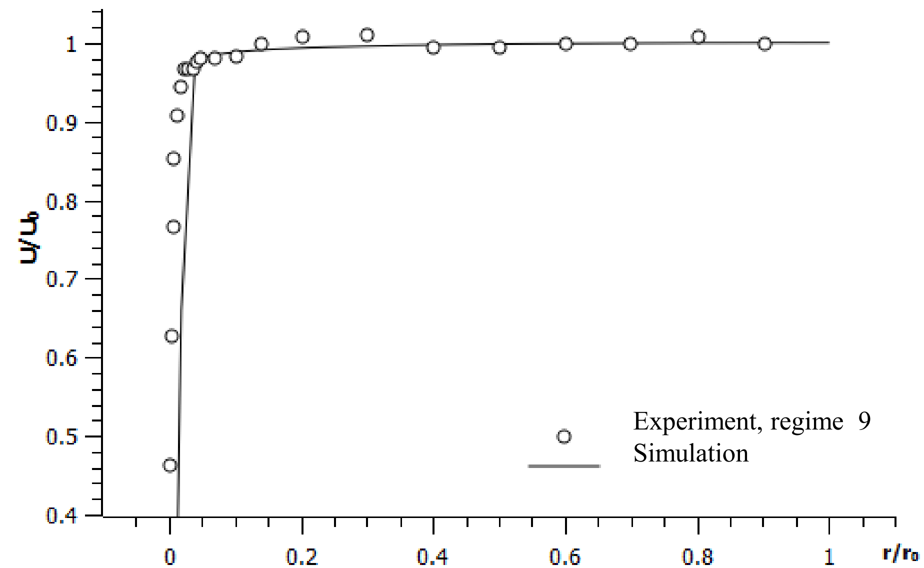


Determining optimal mesh size

❑ α = 0



❑ α = 0,05



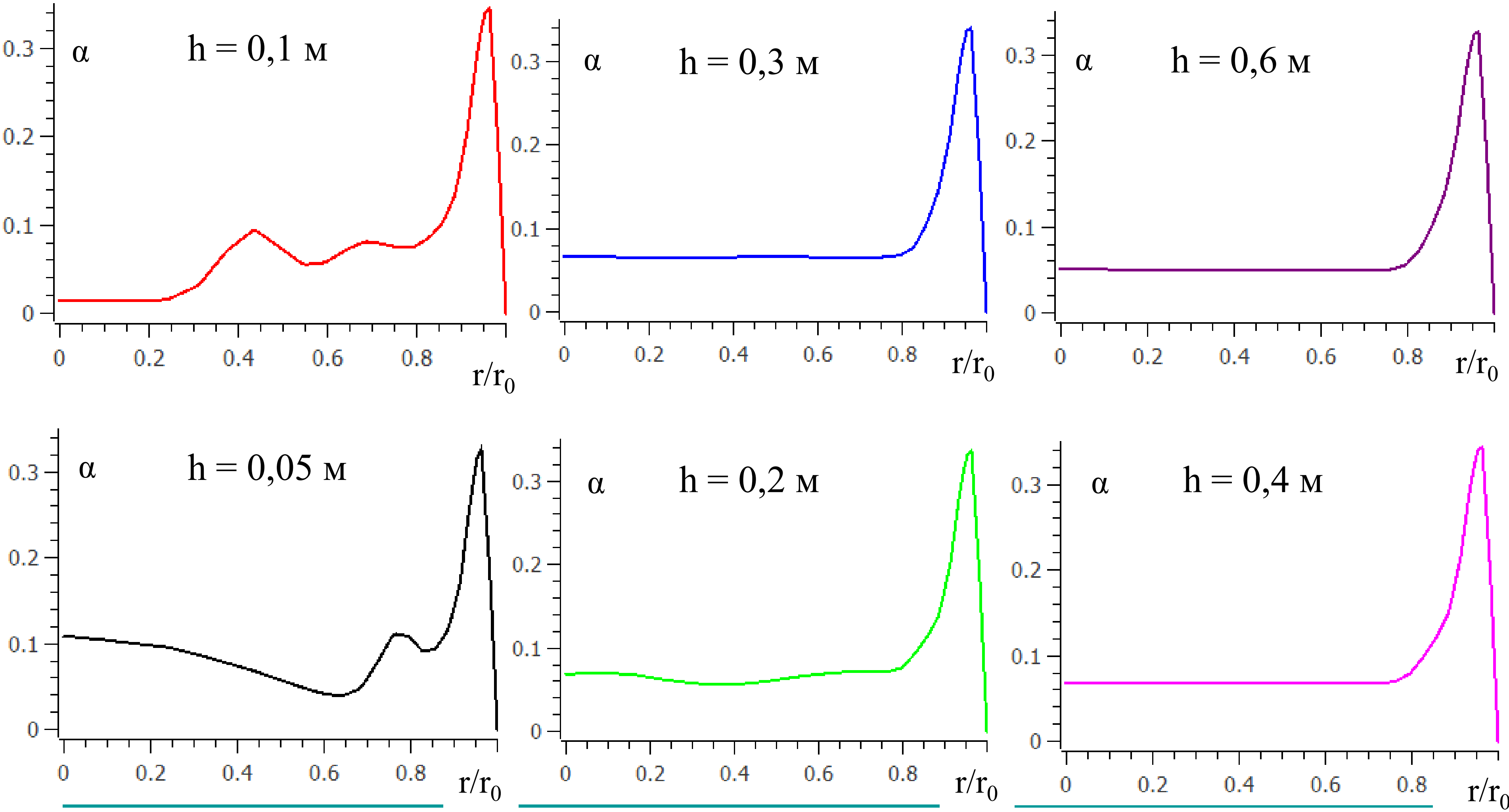
• – Data [Nakoryankov], mesh 1 – 1000 cells, mesh 2 – 4000 cells, mesh 3 – 10 000 cells

Comparison of simulation results and experimental data for single-phase simulation

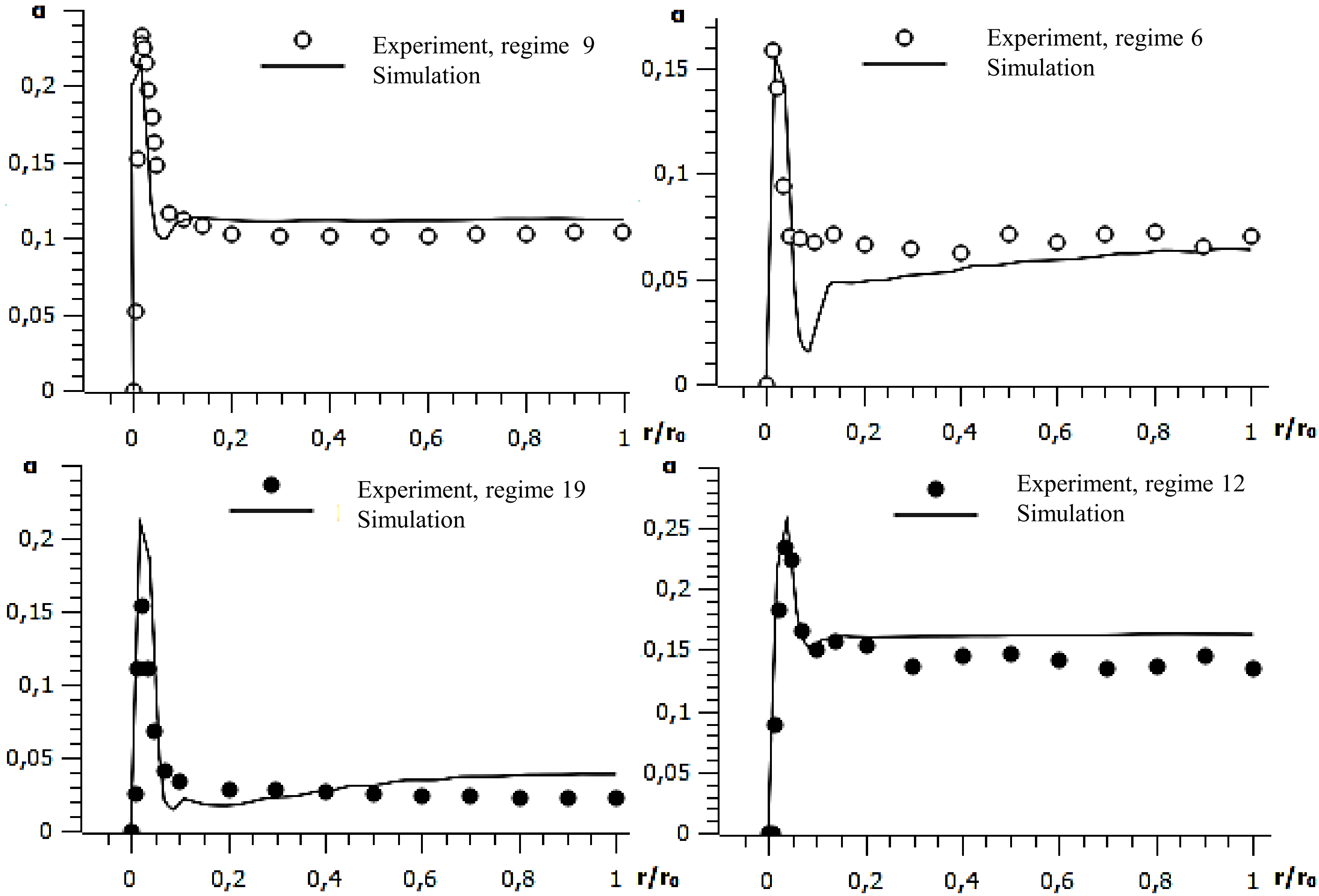
❑ Nakoryakov V.E. et al. Local Characteristics of Upward Gas-Liquid Flows // Int. J. Multiphase Flow – 1981. – V. 7. – P. 63-81.

Simulation results (1)

Void fraction distribution via radius and height of the channel



Simulation results (2)

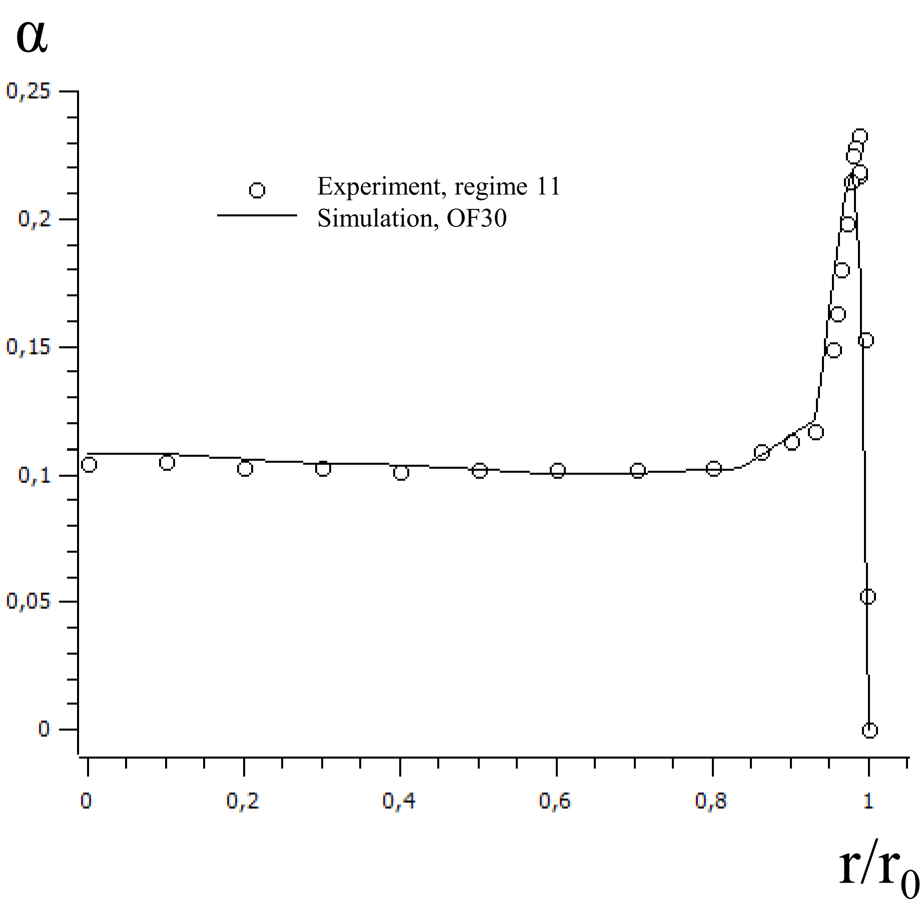


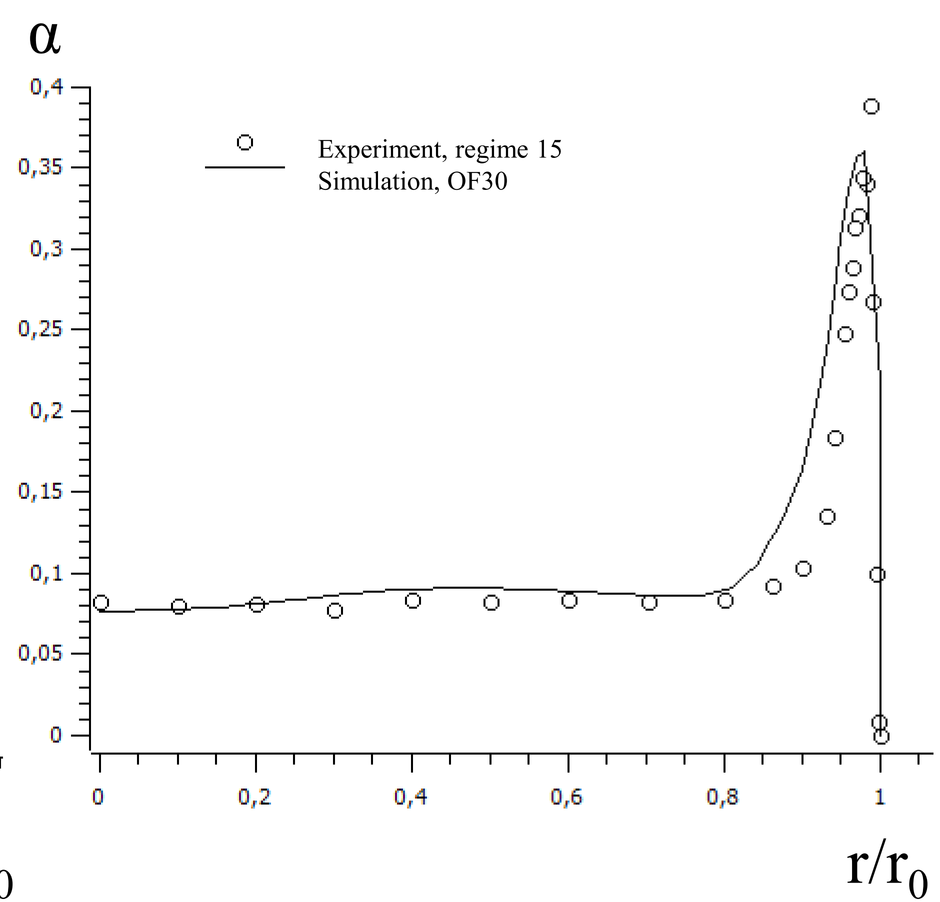
Void fraction distribution via radius

- OpenFOAM 2.3
  - «Baseline» model
  - d_b= const (1 mm)
  - T9: α=0,05; β=0,07
    Re = 44 000
  - T6: α=0,07; β=0,15
    Re = 22 000
  - T19: α=0,03; β=0,04
    Re = 110 000
  - T12: α=0,15; β=0,2
    Re = 44000

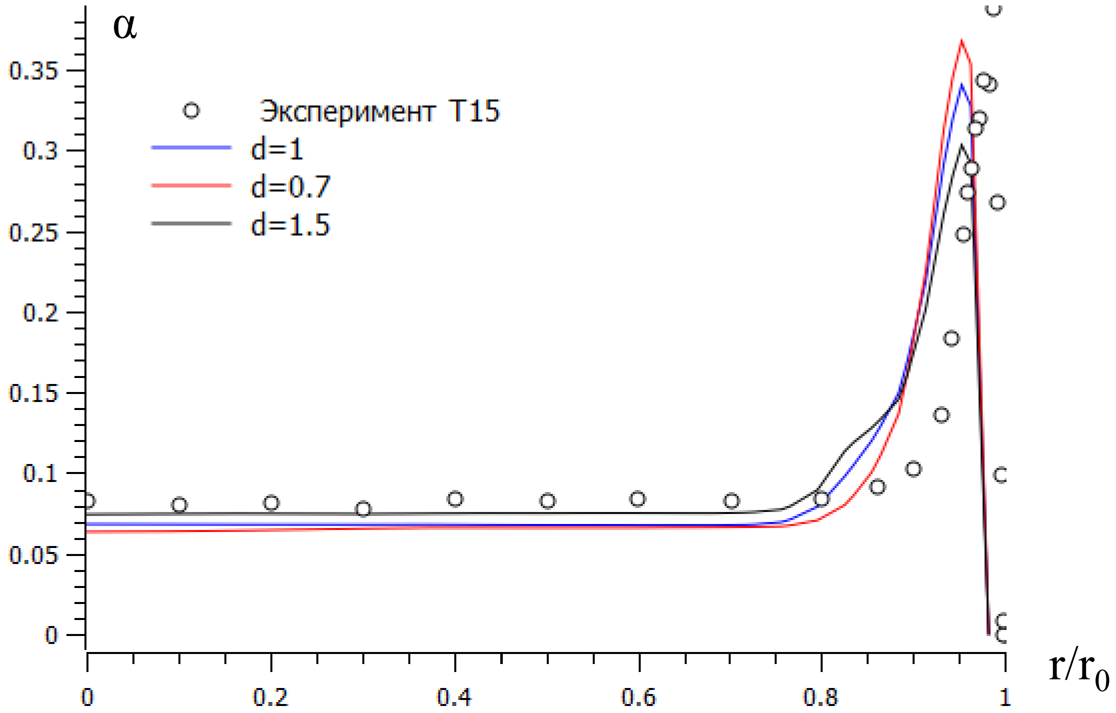
Simulation results (3)

- OpenFOAM 3.0 | «baseline model» + d_b – IATE (0,5 – 1,5 мм) + *turbulentBreakUp* + kOmegaSST-Sato + *randomCoalescence*



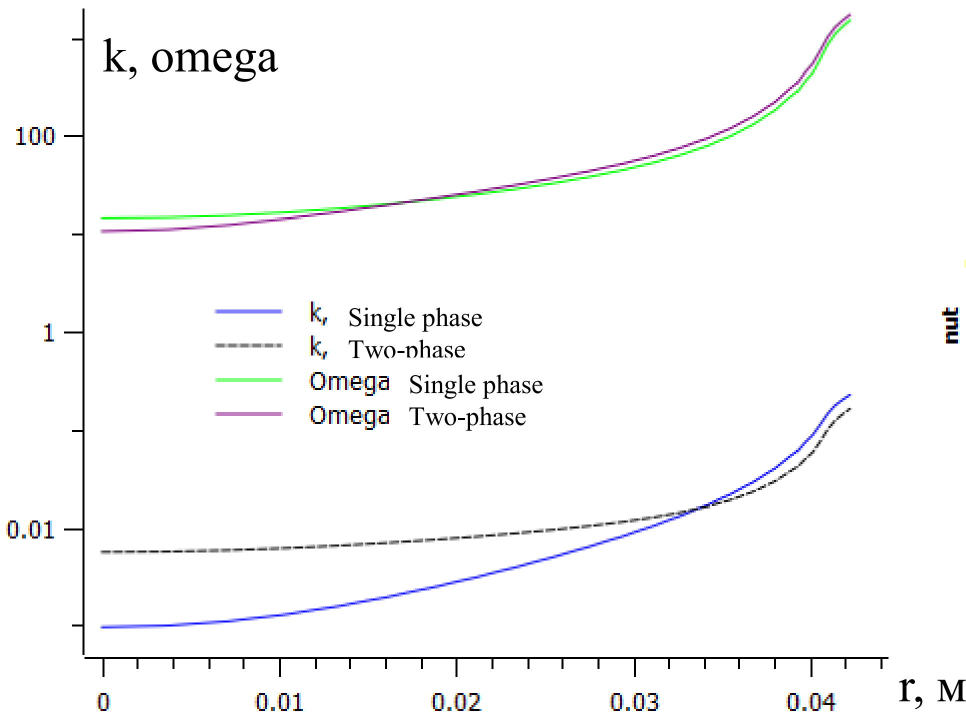


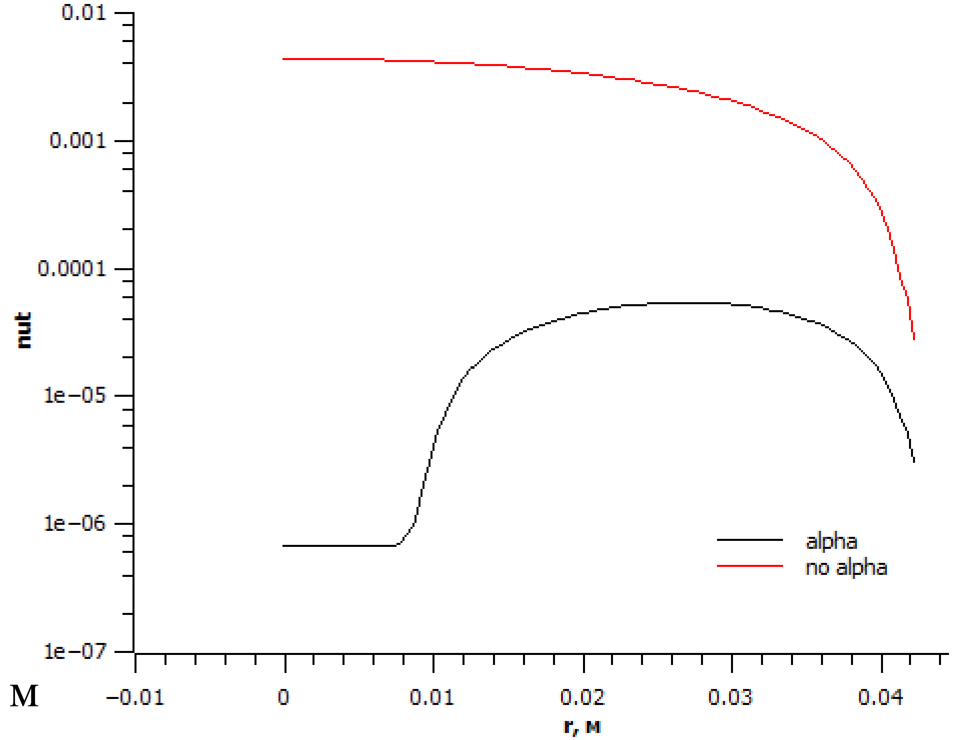
Simulation results (4)



Зависимость от размера пузырька, d [мм]

Simulation results (5)

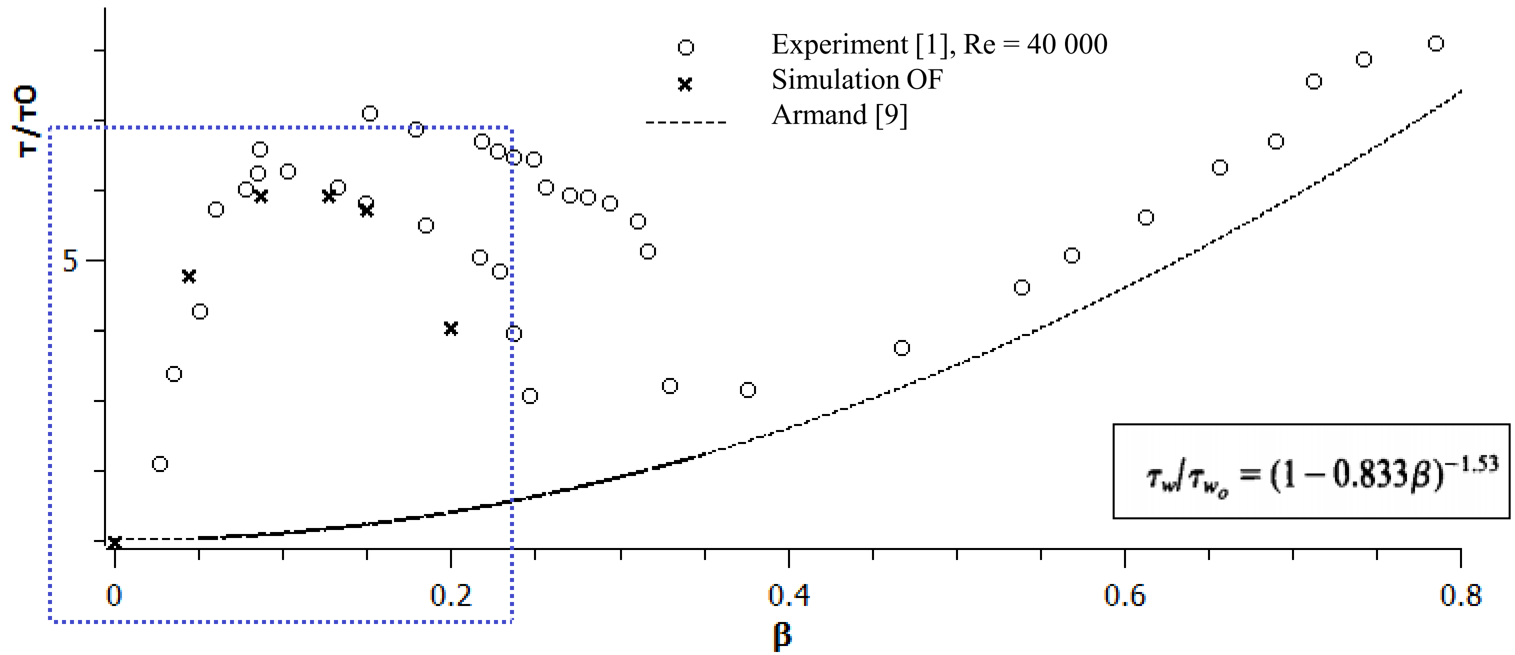




Turbulence suppression in two-phase flow

Simulation results (6)

- Dependence of shear stress at the wall τ on gas flow ratio β



- 1. Nakoryakov V.E. et al. Local Characteristics of Upward Gas-Liquid Flows // Int. J. Multiphase Flow – 1981. – V. 7. – P. 63-81.
- 9. Armand A.A., Nevstryaeva E.I. Investigation of mechanism of two-phase flow in vertical tube. // Izv. VTI Vol. 2, P. 1-8. 1950

Conclusion

- In the work the result of numerical simulation of void fraction distribution via radius of the channel with two-phase flow with low (β = 0.05…0,2) gas flow ratios are presented

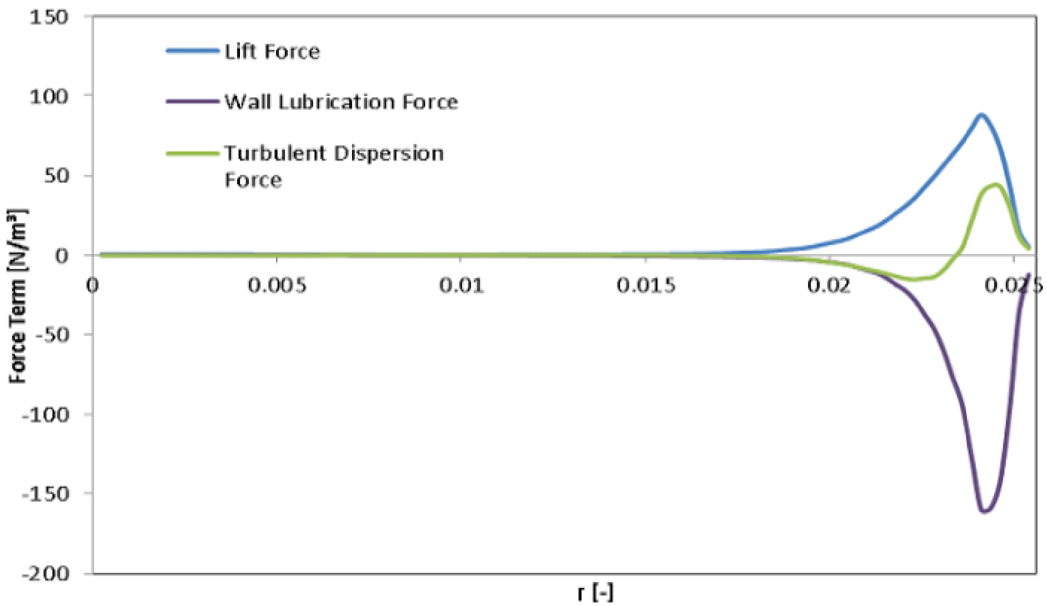
- In the area of the low void-fractions simulation results demonstrate abnormal increase (six times increase in the maximum) of shear stress in the round channel, which was observed experimentally

- Based on simulation results the decision was made that OpenFOAM code is *adequately simulates* saddle-shaped void-fraction profile, which is believed to be the reason of abnormal increase of shear stress in channel at **$0 < \beta < 0,2$**

Thank you for attention!

$$\mu = \mu^{mol} + \mu^{turb} + \mu^{bub}$$

$$\mu^{bub} = C_B \rho_L \alpha_G d_B \left| \mathbf{u}_G - \mathbf{u}_L \right|$$



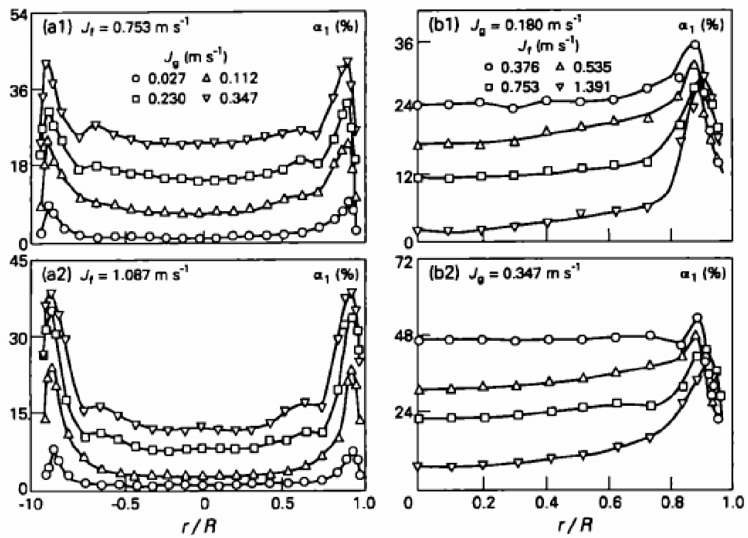


FIG. 3. Void fraction distributions (a) at constant J_f, (b) at constant J_g.

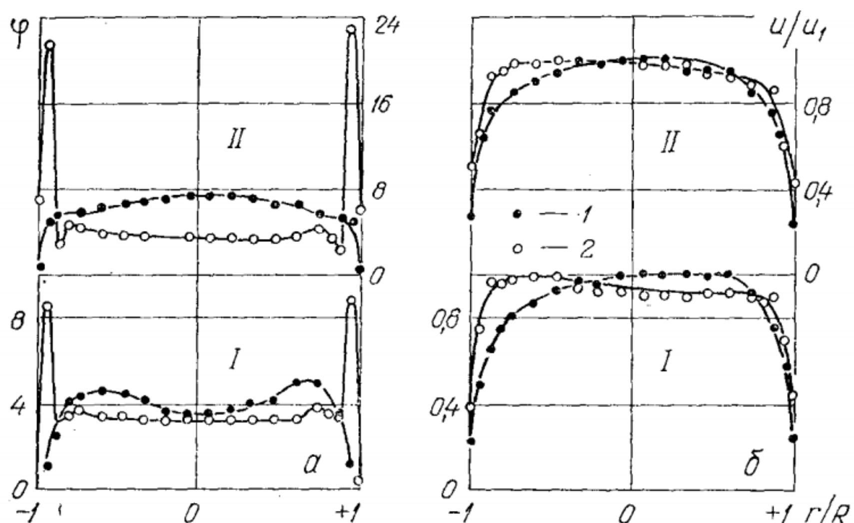


Рис. 4. Профили локального газосодержания (*а*) и скорости жидкости (*б*) при $\beta = 10\%$: *I* — Re=990; *II* — Re=2280; *1* — d=1 мм; *2* — 0,5; r, R, м; u, u_1, м/с; φ, %

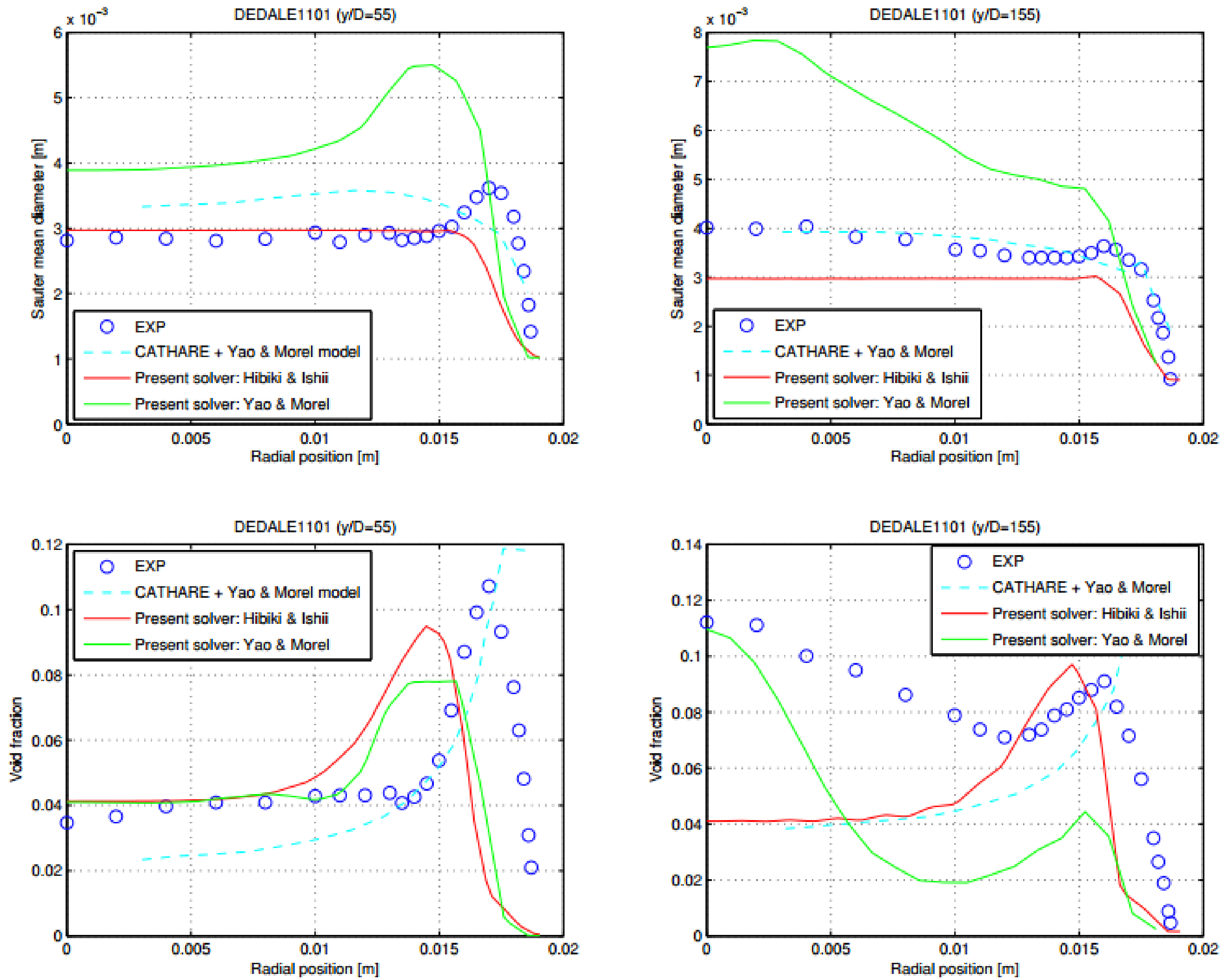


Figure 5.20. experimental and predicted flow variables profiles for bubbly-to-slug transition case

F03G03

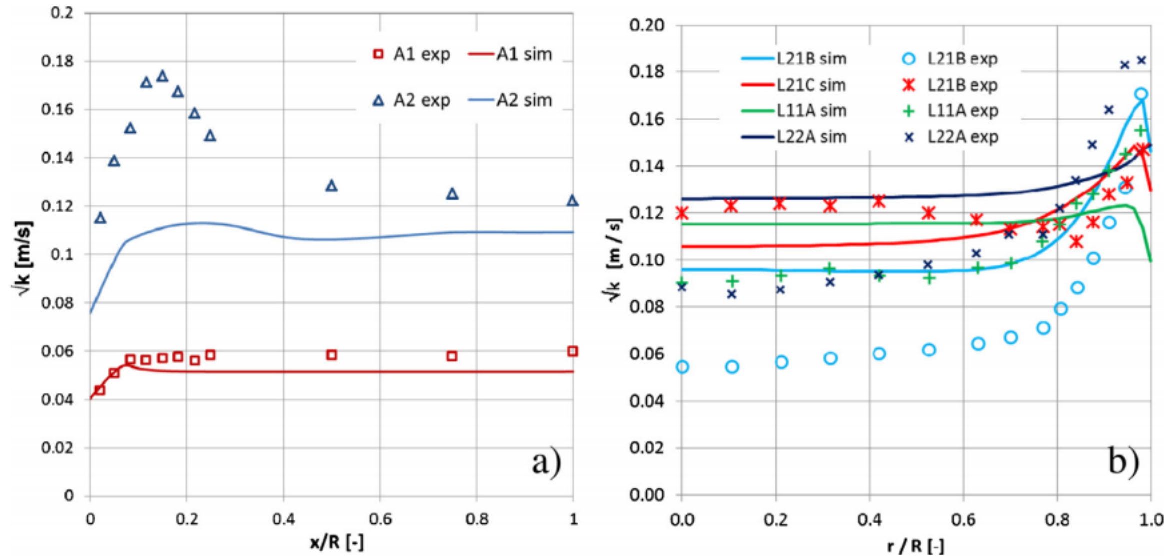


Fig. 6. Comparison of baseline model simulation results for the profiles of the turbulent kinetic energy with experimental data for different experimental runs from (a) Mohd Akbar et al. (2012), time averaged result from a transient simulation, (b) Liu (1998), steady state simulation (all figures are taken from Rzehak et al. (2014) were also the details

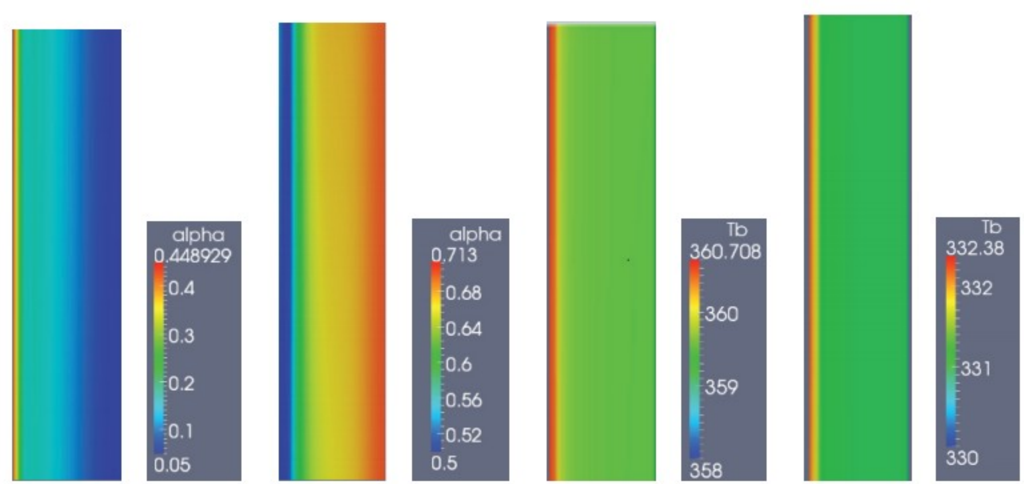


Fig. 1. Snapshots of simulated instantaneous vapor volume fraction (a & b) and liquid temperature (c & d) for DEBORA5 and DEBORA7, respectively (r = 0 m to r = 0.0096 m and z = 3.0 m to z = 3.5 m)

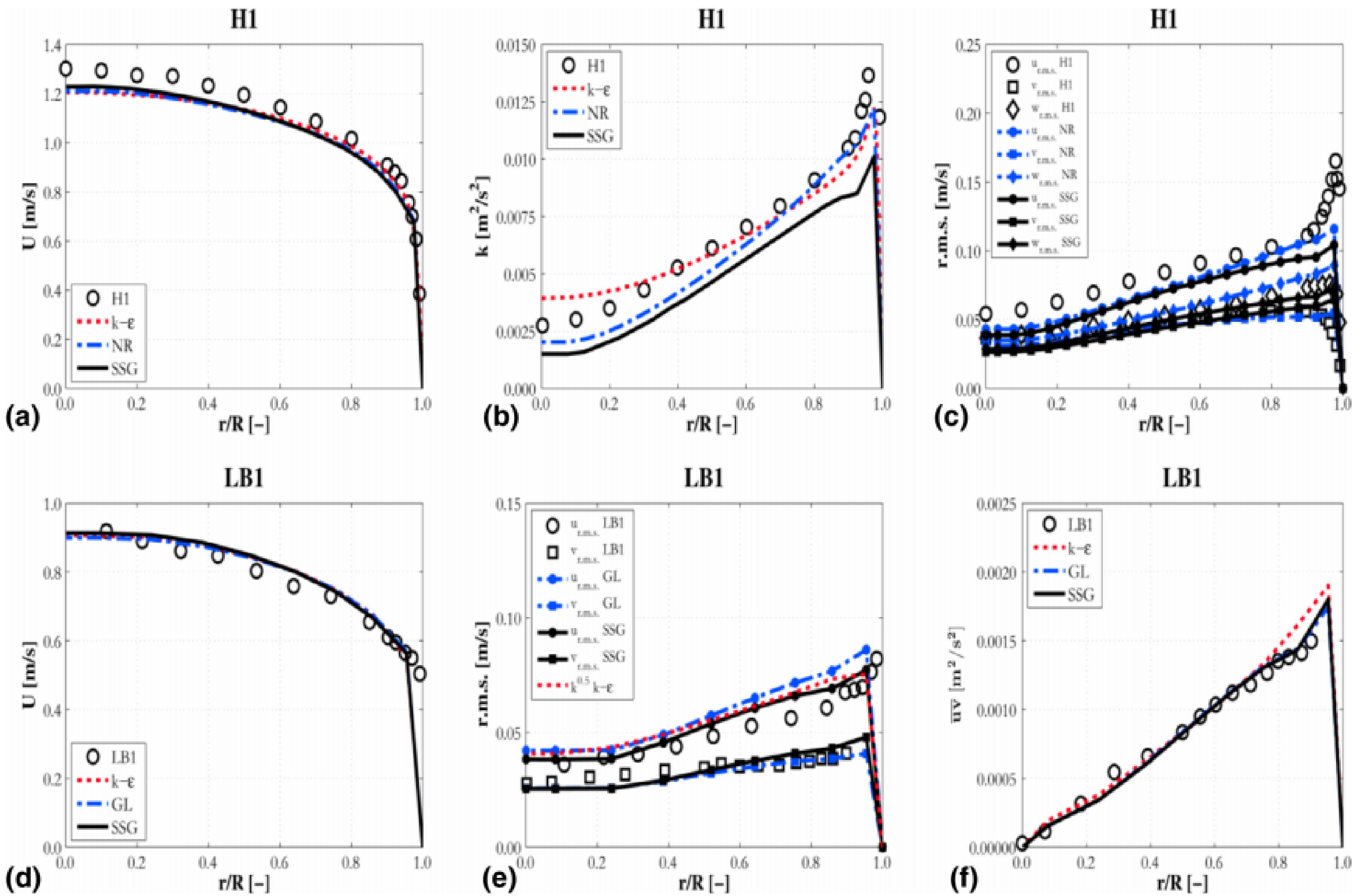


Fig. 2. Radial profiles of predicted velocity, turbulence kinetic energy and velocity fluctuations from different turbulence models compared against single-phase data from experiments H1 and LB1. GL: Gibson and Launder (1978); NR: Naot and Rodi (1982); SSG: Speziale et al. (1991).