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CFD SIMULATION OF SUBCOOLED BOILING

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Abstract: Subcooled boiling on heated wall under forced convection is used in many industrial sectors. The main advantage of subcooled boiling is the large heat transfer coefficient. Subcooled boiling is typically used in situations, where cooling of the walls with high heat fluxes is necessary. In pressurized water reactors the subcooled boiling occurs on fuel rod cladding. This phenomenon is also associated with reactor operation safety, because it´s closely related to the critical heat flux. Due to the complexity of experimental facilities focused on subcooled boiling, the experimental results are often unavailable. Also high costs of these facilities can sometimes lead to use of physical similarity of the water and selected freons (e.g., R12 or R113). This replacement enables to provide required measurements at lower temperatures and pressures on freons. Experiments on the DEBORA device performed in CEA Grenoble with freon R12 is an example of such measurements. In addition, recently the CFD codes reached quality level which makes it possible to solve models with evaporation and condensation including the subcooled boiling with appropriate accuracy. The goals of this work are CFD simulations of the subcooled boiling of freon R12. Research related to experiments on the DEBORA device were used for CFD calculations by ANSYS Fluent program. Computational grid of the axially symmetric V-sector of the heated tube was created in pre-processor GAMBIT. Transient cases were calculated. Behaviour of the freon respectively near the heated wall for simulated cases was described. Also steam production and diffusion processes of the subcooled boiling are compared with each other cases. Subsequently these simulations will be used for problems linked to Pb-Li eutecticum cooled by steam-water mixture within.

Keywords: CFD simulation, subcooled boiling, freon R12

1. INTRODUCTION

DEBORA project at CEA Grenoble was focused to determine character of subcooled boiling. Dichlorodifluoromethane (R12) was used as examined fluid. This experiment was able to determine the void fraction, gas velocity, temperature of the fluid and the bubble size. The main advantage of the DEBORA measuring device is possibility to use lower operating parameters than device with water-steam as fluid, due to physical similarity of selected freons and water. This leads to a much simpler and safer measurements.

Figure 1 shows the geometry of the considerate DEBORA device. It is a vertical heated tube with internal diameter of 19.2 mm. Freon is heated along a 3.5 m length part. The rest of 5 m long tube is unheated and it corresponds to 1 m long inlet section and 0.5 m long outlet section.

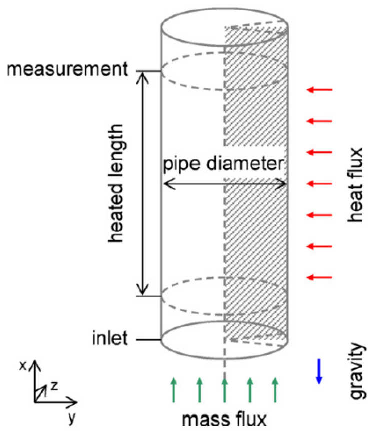

Figure 1. Sketch of the DEBORA test geometry [1]

CFD model, based on the experiment device geometry, was created. Boundary conditions and standard numerical approaches are set according to the experiment conditions. Particular study to specified setting of subcooled boiling is provided. In connection with boiling in heated tube, during subcooling occurs the radial profile of the two phase flow is changing. Up to now, only specified UDF functions defined by CFD user could be used. Newly the numerical models describing this phenomenon are implemented to the CFD ANSYS Fluent program. These models are very complicated and sensitive to use their settings. Only provided experimental data can help to understand the behaviour of the subcooled boiling and consequently enable set the suitable simulation criteria leads to convergent and physically correct results. This understanding can significantly help to successfully solve more complicated cases, where subcooled boiling occurs, such as the cooling Pb-Li eutectic cold trap by steam-water mixture, considered in CANUT project.

Main output of this work is to determine selected quantity (pressure, velocity, temperatures and so on) and their comparison to the measured and previously calculated values in the specified geometry position. In DEBORA facility a radial profile of the vapour volume fraction and its speed at the end of the heated part were measured by optical probe. Furthermore bubble size profiles were available for this area. Axial wall temperatures were measured using thermocouples, but radial temperatures were not available [1].

2. MODEL DESCRIPTION

Studied part corresponds with the geometry of the DEBORA experimental device and it is created by pre-processor GAMBIT. Only 45° V-cutout, shown by Figure 2, was considered due to the symmetry and to reduce the computational time. For first calculations slightly rough hexahedra grid was applied. Based on this first simply approximations the model was improved. Finally the hexahedral grid reach 90,000 cells with their higher concentration in the wall vicinity. Computational model is depicted on the Figure 2. Cells quality was monitored by the *Equi-size skew*, which not exceed value of 0.5 and by the *Aspect-ratio* with maximum of 10.3.

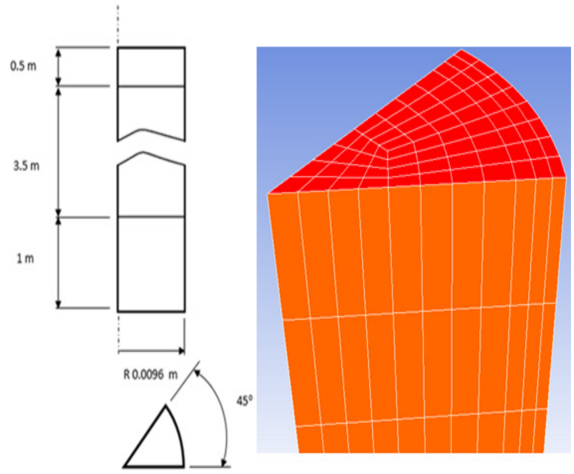

Figure 2. Computational model sketch with detail of the used grid

The physical values setting for the freon R12 liquid and vapour were based on specified conditions of the DEBORA project, table 1. Therefore linear functions depending on the temperature were used for density, specific heat capacity, viscosity and thermal conductivity. These values are shown in table 2 and were obtained from NIST database [5].

Tab.1. DEBORA experimental data [2]

Measured quantity	p [MPa]	v [m/s]	q_w [W/m^2]	T_{in} [°C]	T_{sat} [°C]
Measured values	3.008	0.86	58260	67.89	94.24

Tab.2. Freon R12 physical data setting for sat. pressure at 3.008 MPa

Temperature [°C]	Pressure [MPa]	Density [kg/m^3]	c_p [kJ/kg.K]	Viscosity [Pa.s]	Therm. Cond. [W/m.K]	Phase
65	3.008	1162.3	1111	0.00012705	0.055010	liquid
94.242	3.008	958.81	1646.2	7.8443e-05	0.043012	liquid
94.242	3.008	211.48	1631.9	1.6967e-05	0.020194	vapor
130	3.008	145.58	897.74	1.7505e-05	0.017367	vapor

At the input part of the model the *Velocity inlet* boundary condition with same speed for both phases was applied. The *Volume fraction* of steam at the inlet was set to 0 and *Turbulence intensity* estimated at 3%. Boundary condition of *Pressure outlet* at the end of the model was set. For heated wall section the heat flux with 58 260 W/m2 value was assigned. At the end of the heated section 11 radially distributed tracked points were created to monitoring calculated data. Their distribution is shown in Figure 3.

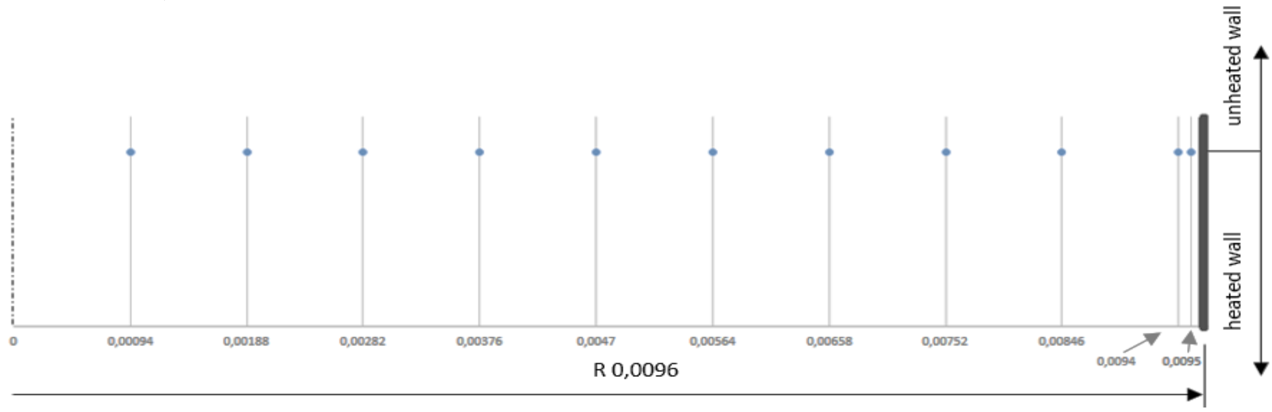

Figure 3. Distribution of the tracked points

3. SOLVER SETTING

The solver setting is mainly supported by the documentation [2], [3] and [4]. Because of iteration process instability the stationary solution with pseudo transient formula must have been replaced by time dependent solution. The Realizable k-ε turbulence model with the Standard wall function was chosen. For the sequential solution velocity and pressure fields was used the Multiphase coupled model and for gradients the *Least square Cell-based method* were set. All discretization schemes were set to 1st order, because of high sensitivity to void fraction and bubbly formation near the wall.

Calculations are carrying out on the eight AMD Opteron processors (each of 2.4 GHz). The whole final calculation take 48 hours of computer time.

Setting for subcooled boiling in ANSYS Fluent (release 15) are:

- Drag (resistance force) - Ishi correlation
- Lift (hydrodynamic lifting force) - Tomiyama correlation
- Turbulent dispersion - Lopez-de-Bertodano correlation
- Turbulence interaction - Troshko-Hassan correlation
- Heat (heat transfer between phases) - Ranz-Marshall correlation
- Mass (mass transfer between phases) - Constant saturation temperature
- Bubble size modeling - Yao-Morel correlation

Wall lubrication (effect of virtual mass) are neglected in the calculation, because brings a big solution impact to the fineness grid. For bubble departure diameter where bubbles breaking away from the wall the Unal correlation was used. Other parameters were left at the default settings.

4. CALCULATION RESULTS

Simulation results are compared with data which are given from [2] and contain calculations of ÚJV Řež and measured values from the DEOBRA experiment. Results from the Calculation were determined as an average value of eleven measurement points described above. Because of very long and inner tube the contours of selected parameters for the computational area are displayed in dispositional views. In the following sections particular physical quantities are described.

4.1. Liquid temperature

Radial temperature profile was not measured, so comparison is only with results by ÚJV Řež. Character of the radial profile, in Figure 4 is similar, but apparent differences up to 3.8 °C between the temperature values are seen. The reason is probably caused by different quality of a grid and by some differences in numerical approach. Slight decrease in the curve near the wall can be caused by unapplied Two-phase wall function. Figure 5 depicts mixture temperature along the whole calculated area. Contours show that the highest temperature values are reached at the upper part of the heated wall. These contours highly correspond to the temperature curve of the Calculation at the Figure 4.

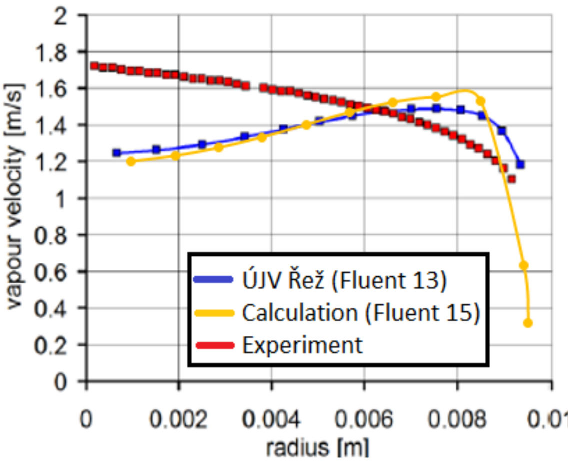

Figure 8. Vapour velocity radial profile

4.2. Bubble diameter

Bubble diameter monitored along the tube is very important parameter suitable to descript the subcooled boiling phenomenon. As shown in Figure 9, the bubble diameter along the radius has similar size and character as measured data. It means that the bubbles near the wall are breaking up and in the centre of the stream increase their diameter. Higher difference between Calculation and the rest data correspond to the differences noticeable in above listed diagrams.

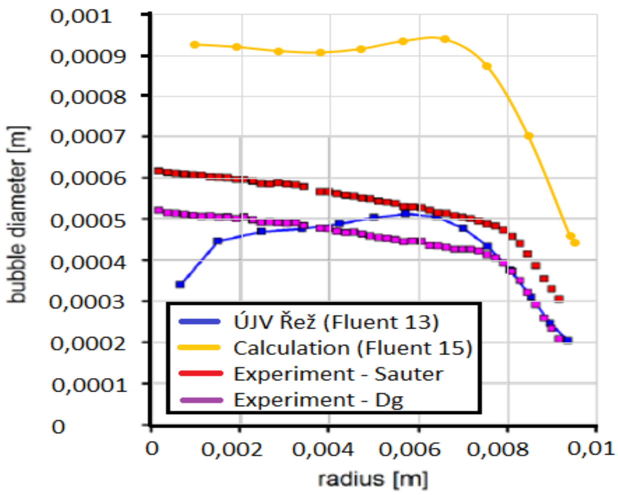

Figure 9. Bubble diameter radial profile

5. CONCLUSION

The main goal of this work was to test potentialities newly occurred for subcooled boiling simulations in Release 15 of the CFD program ANSYS Fluent. Comparison of performed simulation were based on calculation already performed by ÚJV Řež and measured data from DEBORA experiments. While the comparison between measured data and calculations from ÚJV Řež are in high level of agreement, results of this work show slightly different values of interest. This disagreement of both calculations can be primary caused due to different numerical approach. For calculation form ÚJV Řež own specific UDF functions had to be implemented, while for the calculation performed in this work were used standard models newly implemented in the applied CFD program. Due to very complicated and sensitive numerical model used for describing this boiling phenomenon there are at the model settings many degree of freedom which leads to time-consuming study. It can subsequently product some hidden discrepancy between particular settings.

In the future works further simulations leading to calculated model improvement have to be performed, especially in view of calculation settings and computational grid specification. Other consequent work will fixate to simulate the subcooled boiling of water, which occurs for example in Pb-Li cold trap cooling system.

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