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ASTEC V1.3 Code Assessment on the STORM Aerosols Mechanical Resuspension Tests

A Fission Product Transport Study

A. Bujan, B. Toth and R. Zeyen

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Contact information
Address: P.O. BOX 2, 1755 ZG Petten, The Netherlands
E-mail: arunas.bieliauskas@ec.europa.eu
Tel.: +31 224 56 5387

http://ie.jrc.ec.europa.eu/
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Executive Summary

In order to validate the mechanistic fission product transport module SOPHAEROS of the ASTEC V1.3 integral code all available STORM resuspension test results were analyzed. We focused on the assessment of two aerosol resuspension models implemented in SOPHAEROS: (1) on the semi-empirical Force-Balance (FB) model; (2) and the more mechanistic Rock'n Roll (RnR) model. The calculated resuspended mass fractions were compared with the measured or estimated ones obtained in the STORM SR09, SR10, SR11, SR12 and SR13 tests. As a result, some tests were satisfactorily reproduced, however discrepancies were identified in the examined aerosol resuspension models.

Complying with the test conduct, each ASTEC calculation consisted of two parts. Firstly, the aerosol deposition process was calculated to create the initial deposited aerosol mass distribution on the inner surface of the actual test pipe. The main parameter is the total deposited mass in the pipe. Secondly, the resuspension process was calculated; it is the only process, which has an effect in the pipe this period. In addition, parametric studies were done to assess the influence of resuspension during the aerosol deposition.

It was shown that the FB model over-estimates (up to a factor of 6) the final resuspended aerosol mass fraction for the analyzed STORM tests if the default value of the cohesive force coefficient ($1.0 \cdot 10^{-6}$ N/m) is used in the calculations. However, if the cohesive force coefficient was increased ten times to a value of $1.0 \cdot 10^{-5}$ N/m, for most of the analysed tests, the FB model gives substantially better agreement with the measured final resuspended mass fractions and the overestimation becomes less (by a factor of 2.5). It should also be pointed out that, according to FB model, the resuspension is a continuous process, i.e., the resuspended mass depends significantly not only on the applied, constant carrier gas velocities during resuspesion phase, but also on the duration of this phase. However, this fact is in contradiction with the data measured in the STORM resuspension tests, which showed that the majority (>99 %) of the deposited mass is resuspended not continuously but within a relatively short time (5 s to 25 s) just after an abrupt increase of the mass flow rate (or velocity) of the carrier gas.

For the RnR model, the calculations showed that it significantly underestimates (up to a factor of 3) the final resuspended aerosol mass fraction for the SR09 and SR10 tests. Furthermore, in the SR11 and SR12 test analyses it was revealed that the resuspended mass calculated by the RnR model is sensitive to the time step. In these tests, the final velocity of the carrier gas during resuspension phase reached values higher than 90 m/s. When the FB model was used, no influence of time step on the calculated results was detected.

Using the RnR model, the sensitivity studies showed that the final resuspended mass fraction is remarkably sensitive to the maximum time step. Moreover, for high fluid velocities (> 90 m/s), some discrepancies occurred in the calculated partial fractions related to a given deposition mechanism. Therefore, the maximum time step of 1.0 s was imposed in the calculations. The peculiarity of RnR model is that the resuspension happens during a single time step, just after a stepwise increase in gas flow velocity. Nevertheless, by limiting the maximum time step to 1.0 s we could have coherent and physically sound calculation results.

For the SR11 and SR12 tests, the calculations with RnR model over-estimate the resuspended fraction during the first (SR12) and the first two resuspension steps (SR11), whereas the situation becomes opposite during the subsequent resuspension steps; this has a compensating effect on the final value of resuspended mass.

In general, it can be concluded that concerning the final resuspended mass fraction and mainly the kinetics of aerosol resuspension in turbulent pipe flow conditions there is a need for further code assessment and for improvement of resuspension models implemented in the current version of SOPHAEROS/ASTEC module. This is under way in the Source Term Topic of the SARNET project.

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1 Introduction

Under severe accident conditions, the deposition and resuspension of aerosols in the primary circuit of a nuclear power plant influences mainly the release of radioactive materials (fission products, activated structural materials) into the containment. The aerosol resuspension may be an important source of radioactivity to the environment in the late stages of a severe accident when highly turbulent gas flows pass over the aerosols deposited on the wall and structures of the reactor vessel and primary circuit. The powerful gas flow is a consequence of degradation phenomena occurring in the reactor core and the coolant system, for example, the relocation of the molten core materials to lower plenum of reactor vessel is followed by strong evaporation of the water being there.

Due to the high importance of the thermophoretic deposition and mechanical resuspension in the primary circuit, both processes were examined in the STORM (Simplified Test Of Resuspension Mechanism) test facility at the Joint Research Centre, Ispra. In the STORM SD test series the thermophoretic deposition, whereas in the SR test series the gas-flow-induced resuspension of deposited aerosols was studied.

The validation results of the previous version of the fission product transport code SOPHAEROS/ASTECV1.0 on selected STORM tests (SD04, SD05, SD07, SD08, SR09 and SR11) have been described in detail in [1]. The objective of the present work is to explore the capability of the new SOPHAEROS module[2] implemented in the latest version of the European Integral Code ASTEC V1.3 (Accident Source Term Evaluation Code) to reproduce the experimental results of the STORM resuspension tests SR09 [4], SR10 [5], SR11 [6], SR12 [7] and SR13 [9].

In the SOPHAEROS module of ASTEC V1.3 [2], there are two models available for the calculation of resuspension of deposited aerosols: the semi-empirical Force-balance model (FB) as a default option and the alternative Rock'n Roll (RnR) model based on the approach of Biasi [10]. For the analyses described in this report both the FB and RnR models were used. As it has been already mentioned in [1], for the SR09 and SR11 tests the FB model provided acceptable calculation results only by increasing the cohesive force coefficient (coeff_Hc) as user input 10 times. It should be noted that this force coefficient is not used in the RnR model, i.e., it has is no influence on the calculated results when the RnR model is selected. Therefore, all the before-mentioned STORM tests were analyzed by using the FB model both with the default value ($1.0 \cdot 10^{-6}$ N/m) and the increased value ($1.0 \cdot 10^{-5}$ N/m) of force coefficient. These analyses also showed that the maximum time step has no influence on the results calculated by the FB model.

Using the RnR model for analyses it has been found that the calculated resuspended fraction is highly sensitive to the maximum time step allowed in the calculations. Therefore, besides the default time step settings, when the maximum time step can vary in a wide range up to 30 s, the RnR model was also used with an imposed time step of 1.0 s. It should be pointed out that the influence of maximum time step has been considerable only in the analyses of SR12 and mainly SR11 tests in which the applied velocity of the carrier gas during resuspension phase was higher than 90 m/s.

2 STORM Test Facility and Tests Conduct

The STORM (Simplified Test Of Resuspension Mechanism) facility was operated by EC/JRC at Ispra, Varese, Italy. The test section is located downstream of the mixing vessel; it consists of four steel pipes connected in series and/or parallel (see Figure 1). The first pipe between the mixing vessel exit and the test pipe inlet (total lengths is ≈4 m) was thermally insulated in order to reduce thermophoretic deposition and heat losses as well as to avoid steam condensation. The 63-mm inner diameter test pipe was 5 m long and it was surrounded by an oven to keep the pipe wall temperature at the requested levels during the deposition and resuspension phases.

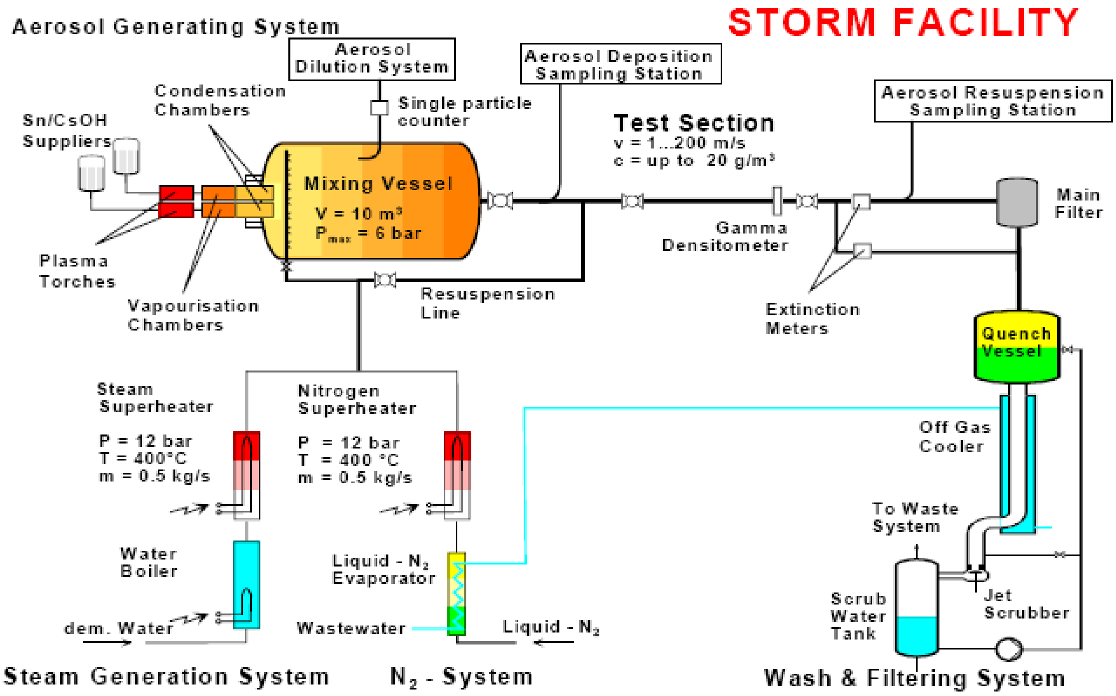


Figure 1: Scheme of the STORM test facility

The gas flow temperatures at the vessel outlet and in the test section (see Figure 2) were stabilized within one hour. Figure 2 shows that thirteen thermocouples are located on the outer wall surface (TETP1, TETP2…TETP10, TETPVin1, TETPVin2 and TETPVout). At the test pipe exit, along the inner radius of pipe, the gas temperatures were measured in three locations: in the centerline of the pipe (TGTP1); at a distance of ≈10 mm (about one third of the pipe radius) from the inner wall surface (TGTP2); and on the inner wall (TGTP3). It should be noted, that - as described in the following - the inlet centreline temperature of fluid was measured during the resuspension phase by thermocouple TGRLU1, whereas during the deposition phase by the thermocouple TGDLU1.In each test, the absolute fluid pressure was set to 0.1 MPa.

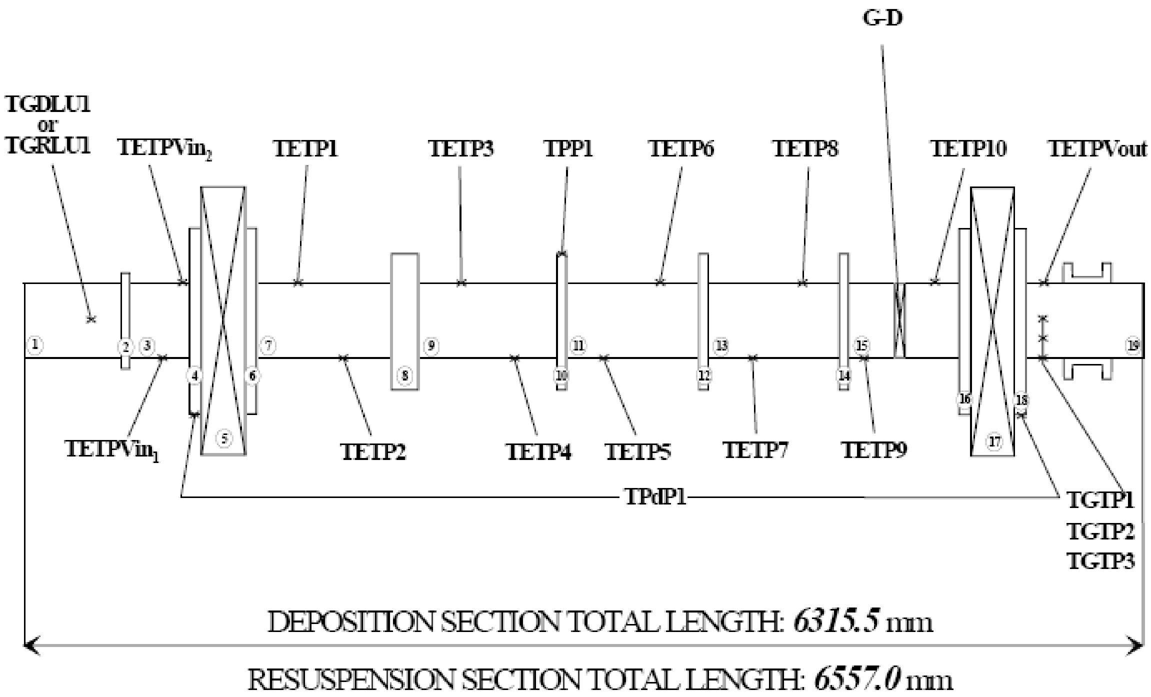


Figure 2: Test pipe configuration and position of thermocouples

The STORM tests SR09, SR10, SR11, SR12 and SR13 can be subdivided into four phases: (1) heat-up phase, (2) temperature stabilization phase, (3) aerosol deposition phase, (4) and aerosol resuspension phase. These phases are shortly described in the following sections for each test.

2.1 Test SR09

In the SR09 test [4], the heat-up phase of about 4 hours was carried out by applying a nitrogen flow of 180 kg/h at 385 ºC injected into the vaporisation chamber. Then this nitrogen flow was reduced and finally replaced with a cold N_2 flow of 20 kg/h as quenching gas during the deposition phase. At the same time, steam with mass flow rate of 37.5 kg/h at 365 ºC was injected as carrier gas directly into the mixing vessel. The gas flow temperatures at the vessel outlet and in the test section stabilised within two hours.

The SnO_2 aerosol particles were produced by means of a plasma torch operating during the 9000-s-long deposition phase and with a constant tin powder feed rate of 32 g/min on average. Helium flow (40 Nl/min) and argon flow (242 Nl/min) were used as plasma gases. The airflow rate for the oxidation of Sn to SnO2 was set to 266 Nl/min.

Before initiating the resuspension phase, the test pipe was closed with valves at both ends (see Figure 1). At the end of the deposition period, the test pipe was detached from the facility and connected to the by-pass and resuspension line including the downstream aerosol sampling station and the main aerosol filter. This was done by changing the tubes connected with the test pipe inlet and outlet valve. The N_2 carrier gas flow through the by-pass line was set to 314 kg/h (0.08722 kg/s) at 385 ºC and after reaching stable flow and temperature conditions it was switched to the open test pipe for the initiation of the resuspension phase. The main test conditions during the deposition and resuspension phase are summarized in the Table 1.

2.2 Test SR10

In SR10 [5], after a heat-up phase of about 6 hours, with a nitrogen flow rate of 200 kg/h at 340 ºC, the N_2 flow injected around the vaporisation chamber was reduced and finally replaced with a cold N_2 flow of 20 kg/h as quenching gas during the deposition phase. At the same time, steam with mass flow rate of 40 kg/h at 360 ºC was injected as carrier gas directly into the mixing vessel. The flow temperatures at the vessel outlet and in the test section stabilised within 2 hours.

The SnO_2 aerosol was produced during deposition phase by the same way as in the SR09 test with a constant tin powder feed rate of 32.08 g/min on average. The applied helium, argon and air mass flow rates were the same as in SR09 test.

Before initiating the resuspension phase, the pipe section was closed at both ends as in SR09 test. The carrier gas flow was switched via a second vessel exit to the by-pass line. Here the flow rate was increased and – after reaching stable flow and temperature values – switched back to the opened pipe section for the resuspension phase. The N_2 flow used for resuspension was set to 503 kg/h (0.1397 kg/s) at 358 ºC. The main test conditions during the deposition and resuspension phases are summarized in the Table 2.

2.3 Test SR11

A heat-up phase of about 4 hours, with an inlet nitrogen flow rate of 250 kg/h at 380 ºC was used in SR11 [6] test to avoid steam condensation. Following that initial phase, the N_2 mass flow rate injected around the vaporisation chamber was reduced and finally replaced with a cold N_2 flow of 20 kg/h as quenching gas during the deposition phase. At the same time, steam with the mass flow rate of 40 kg/h at 355 ºC was injected as carrier gas directly into the mixing vessel. The flow temperatures at the vessel outlet and in the test section stabilised within 2 hours.

The SnO_2 aerosol was produced during deposition phase in the same way as in the SR09 and SR10 tests with a constant tin powder feed rate of 31.3 g/min on average. The helium, argon and air mass flow rates were the same as in SR09 and SR10 test.

The resuspension flow was stabilised in a by-pass line and when stable flow and temperature conditions were reached, the N_2 flow was switched to the test pipe for the initiation of the resuspension phase. This phase was subdivided in 6 periods, with stepwise increase of the N_2 carrier gas flow from 450 to 805 kg/h at 370 ºC. The main test conditions during the deposition and resuspension phases are summarized in the Table 3.

2.4 Test SR12

After a heat-up phase of about 4 hours with an inlet nitrogen flow rate of 275 kg/h at 385 ºC, the N_2 flow injected around the vaporisation chamber was replaced with a cold N2 flow of 20 kg/h as quenching gas in SR12 [7] test during the deposition phase. At the same time, steam with the mass flow rate of 40 kg/h at 365 ºC was injected as carrier gas directly into the mixing vessel. The flow temperatures at the vessel outlet and in the test section stabilised within 2 hours.

The SnO_2 aerosol was produced during deposition phase by the same way as in SR11 test with the constant tin powder feed rate with a mean value 33 g/min. Helium, argon and air mass flow rates were also the same as in SR11 test.

The resuspension flow rate was stabilised in a by-pass line and when stable flow and temperature conditions were reached, the N2 flow was switched to the test pipe for the initiation of the resuspension phase. The resuspension phase was subdivided in 3 periods. The N_2 flow used for resuspension was set stepwise to 520, 570 and 630 kg/h at 385 ºC. The main test conditions during the deposition and resuspension phases are summarized in the Table 4.

2.5 Test SR13

After a heat-up phase of about 5 hours with an inlet nitrogen flow rate of 185 kg/h at 385 ºC, the N_2 flow injected around the vaporisation chamber was replaced with a cold N_2 flow of 20 kg/h as quenching gas in SR13 [9] test during the deposition phase. At the same time, steam with the mass flow rate of 40 kg/h at 380 ºC was injected as carrier gas directly into the mixing vessel. The flow temperatures at the vessel outlet and in the test section stabilised within 2 hours.

The SnO_2 aerosol was produced during deposition phase by the same way as it has been described for previous tests with the constant tin powder feed rate with a mean value 33 g/min. Helium, argon and air mass flow rates were also the same as in previous tests.

The resuspension flow rate was stabilised in a by-pass line and when stable flow and temperature conditions were reached, the N_2 flow was switched to the test pipe for the initiation of the resuspension phase. The N_2 flow used for resuspension was set stepwise to 82, 164, 250 and 340 kg/h at 385 ºC. Note that the measurement of the N_2 flow was interrupted before initiating of the fifth resuspension step with the N_2 flow of 450 kg/h [9]. The main test conditions during the deposition and resuspension phases are summarized in Table 5.

3 SOPHAEROS Analyses of the STORM Tests

In the analyzed tests, the averaged aerosol flow at the inlet of the test pipe was practically constant during the whole deposition phase. It was calculated as a difference between the total mass of aerosols generated and the mass of aerosols deposited before the test pipe inlet and divided by the duration of the deposition phase (9000 s in all analyzed tests); the calculated values are given in Tables 1 to 5. The applied effective aerosols density (4000 kg/m3) corresponds to that of the SnO2 particles with a relatively small porosity. The aerosols heat conductivity was set to 11 W/m/K; this value was taken from the ISP-40 report [8].

The two parameters of the lognormal particle size distribution – the 0.434 µm geometric mean diameter (G.M.D.) and the 1.7 geometric standard deviation – were estimated from the measurements obtained with impactors located upstream of the test pipe [8]. These values were used for the calculation of each analyzed STORM tests. Due to the small fraction of aerosols that deposit in the test pipe, it can be considered that this distribution remains valid practically along the pipe. In all described analyses the particle size distribution was discretised into twenty size bins (default option), covering a particle size range 0.01 µm to 100 µm.

The test pipe was divided into 10 control volumes of the same length. The distribution of the gas and wall temperatures along the test pipe for the SR09 and SR11 tests were taken from former computational analyses [1]; for the other STORM tests they were estimated from the available measured data (see Figure 2 and Tables 2, 4 and 5).

The current SOPHAEROS module has a tendency to overestimate the aerosol deposition due to thermophoretic deposition [1], when there is a very high temperature difference between the gas bulk and the near-wall area (as, for example, in the case of Phébus steam generator tube, [11]). In the modeling, the thermophoretic deposition velocity is determined by the Talbot equation [2, 12] and it is proportional to the calculated local Nusselt number (Nu). Therefore, in all STORM test described in this report, the TRAPMELT option [2] (Nusselt number is calculated from Dittus-Boelter correlation: $Nu = Max\ [0.023\ Re^{0.8}\ Pr^{0.4};\ 3.66]$) was applied instead of the default CATHARE option, which assumes a Prandtl number (Pr) equal to 1.0. In analyzes, the calculated Pr number was ~0.75, i.e., it is nearly constant during the entire deposition phase. The calculated in this way deposited mass at the end of deposition phase was less by ~11% compared to the CATHARE option. For all other physical phenomena the default modelling options were used (e.g. Liu-Agarwal correlation for aerosol deposition due to eddy impaction, [2]).

All SOPHAEROS/ASTEC V1.3 calculations included the simulation of deposition phase followed by resuspension phase. The main goal of this report is to assess the resuspension models available in the current version of SOPHAEROS module. Therefore, mainly the calculated resuspended mass fraction is compared against the measured data instead of resuspended mass. In this way, the influence of the over-estimation of the calculated deposited mass at the end of deposition phase (especially in the SR11 test, see chapter 3.3) on the total calculated resuspended mass is eliminated.

For each above-mentioned STORM test, computational analyses were done by using four different resuspension modelling options:

● Force-balance model with the cohesive force coefficient $coeff\_Hc = 1.0 \cdot 10^{-6}$ N/m (this calculation is denoted in the tables and figures as **FB1**)

● Force-balance model with value of the $coeff\_Hc = 1.0 \cdot 10^{-5}$ N/m (denoted as **FB2**)

● Rock'n Roll model with an imposed maximum time step of 1.0 s (denoted as **RnR1**)

● <u>Rock'n Roll</u> model with the imposed maximum time step of 30 s (denoted as **RnR2**)

3.1 Test SR09 results

The main results of the SR09 test analyses at the end of deposition phase (at 9000 s) and at the end of resuspension phase (at 17220 s) are summarized and compared with the available measured data in the Table 6 and Figure 3.

It was found in each calculation that the dominant deposition process is thermophoresis (≈90 percents of the total deposited mass); it is due to remarkable gas–to–wall temperature difference, which was in the range of 70 to 90 K depending on the time and position in the test pipe during the deposition phase.

The calculated deposited mass is in good agreement with the estimated from test data mass of ~166 g; it is even under-estimated in the "FB1" analysis (see Table 6), because considerable resuspension is predicted already during the deposition phase in this calculation (see Figure 3). Indeed, the calculation without activation of resuspension during the deposition phase predicts a total deposited mass of 171.4 g, i.e. the calculated resuspension during deposition phase is negligible (< 1 % of the deposited mass) in the "FB2", "RnR1" and "RnR2" analyses.

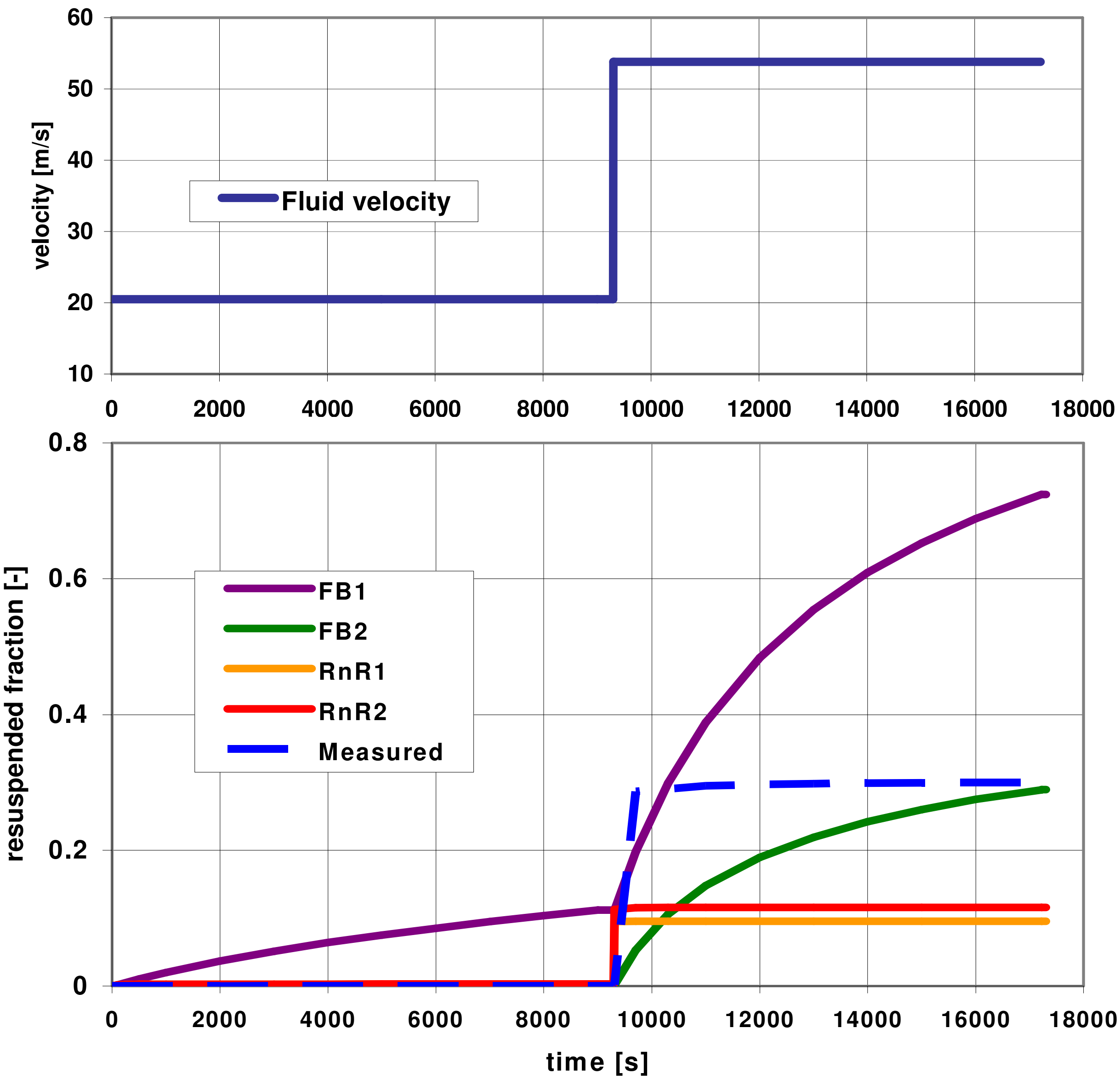


Figure 3: Resuspended fraction (bottom) and carrier gas velocity in the SR09 test (top)

The calculated resuspended mass fraction during the resuspension phase (9300 - 17220 s) in the "FB1" analysis is ~69 % (Table 6), it is strongly over-estimated in comparison with estimated from the measured value of ~30 %. Increasing of the adhesion coefficient by a factor of 10 in the FB2 analysis leads to very good agreement with the estimated value. However, it should be pointed out that according to the Force-balance model the calculated resuspended fraction continuously increases during the entire resuspension phase. This is because it strongly depends on the whole duration of the resuspension. However in the experiment, the majority of the resuspension occurred only during the first ~25 s after the beginning of resuspension phase [4], see Figure 3. On the other hand both calculations with the Rock'n Roll model predict that the majority (>99%) of the resuspended fraction occurred during the first second after increasing of the N_2 mass flow rate (i.e. after increasing the fluid velocity from ~20 m/s to ~54 m/s). Both calculations with the Rock'n Roll model underestimate the total resuspended fraction; the influence of the maximum time step" is practically negligible (see Table 6 and Figure 3).

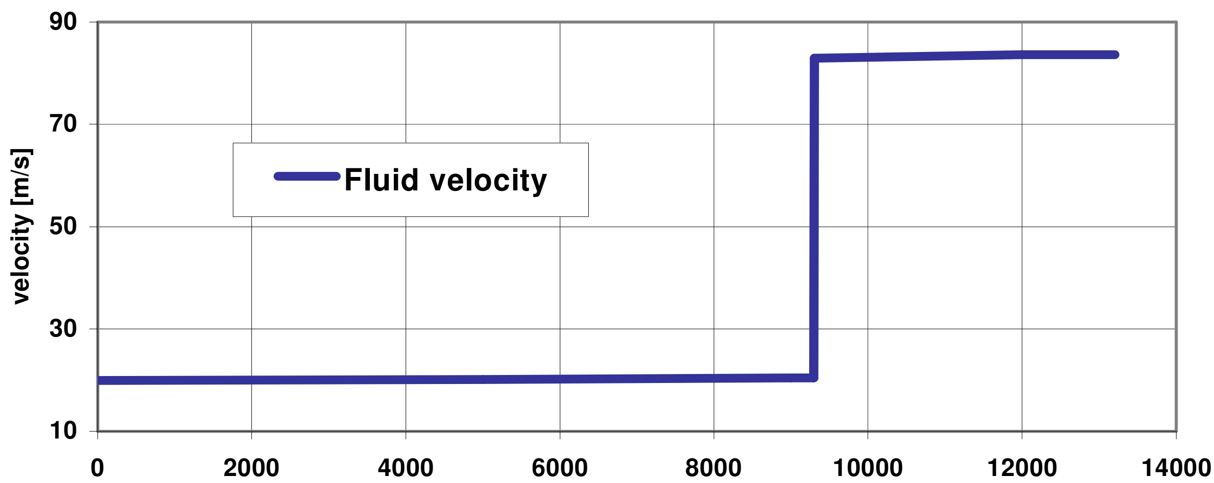
3.2 Test SR10 results

The main results of the SR10 test analyses at the end of deposition phase (at 9000 s) and at the end of resuspension phase (at 13200 s) are summarized and compared with the available measured data in the Table 7 and on the Figure 4.

In all compared calculations, the dominant deposition processes are the thermophoresis (~90 % from total deposited mass) and the eddy (turbulent) impaction (~10 %). The thermophoretic deposition in the SR10 test is not as much as it was predicted for the other tests. The reason is evidently the lower fluid–to–wall temperature difference, which in the SR10 test was in the range of 10 to 30 K depending on the time and position in the test pipe during the deposition phase.

The deposited mass at the end of deposition phase (9000 s) was not measured and not estimated in the report [5]. Therefore, as a workaround, the final deposited mass was calculated by ASTEC (without the activation of the resuspension model) and the obtained value of ~33 g was used for the estimation of the measured resuspended fraction (~70 %, see Table 7).

As in the SR09 test, a relatively large resuspension is predicted already during the deposition phase in the "FB1" analysis (see Table 7 and Figure 4), whereas the calculated resuspension during the deposition phase is negligible in the "FB2", "RnR1" and "RnR2" calculations.



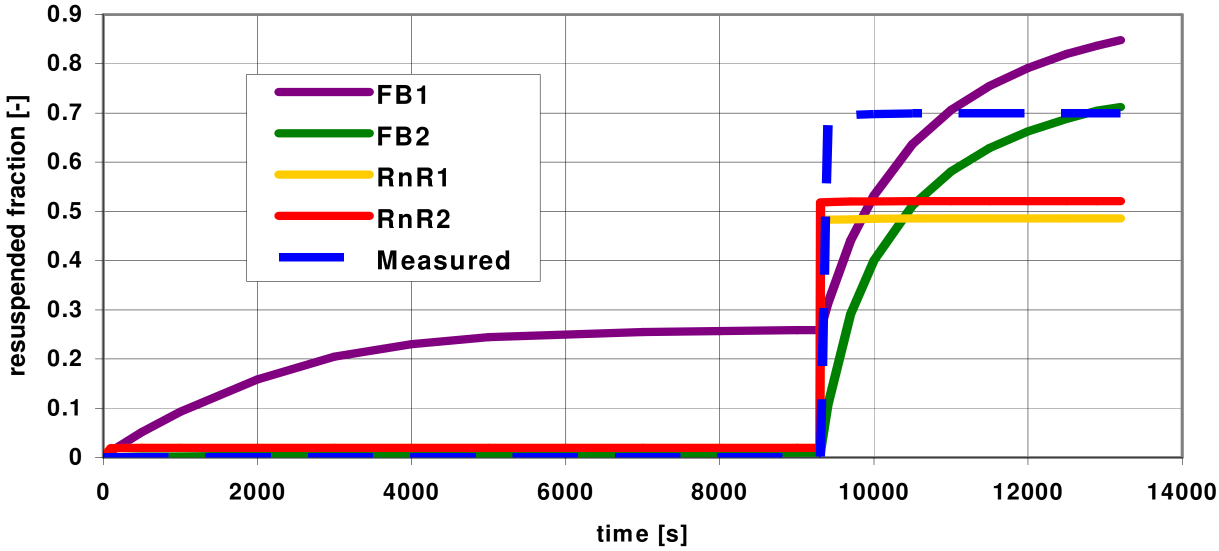


Figure 4: Resuspended fraction (bottom) and carrier gas velocity in the SR10 test (top)

The calculated resuspended mass fraction during resuspension phase (9300 - 13200 s) in the "FB1" analysis is ~80 % (Table 7), it is over-estimated in comparison with estimated from measured value of ~70 %. Increasing of the adhesion coefficient by a factor of 10 in the "FB2" analysis leads to very good agreement with estimated value. However, as it was already mentioned for the SR09 test, according to the Force-balance model the calculated resuspended fraction continuously increases during the entire resuspension phase (i.e. strongly depends on the duration of the resuspension phase). At the same time, in the experiment (see Figure 4) the majority of the resuspension occurred in about ~15 s after the beginning of the resuspension phase [5]. On the other hand, both calculations with the Rock'n Roll model predict that the majority (>99%) of the resuspension occurred during the first second just after increasing of the N2 mass flow rate (i.e. fluid velocity from ~21 m/s to ~83 m/s). Both calculations with Rock'n Roll model underestimate the total resuspended fraction (see Table 7 and Figure 4). The influence of the maximum time step is not significant.

3.3 Test SR11 results

The main results of the SR11 test analyses at the end of deposition phase (at 9000 s) and at the end of resuspension phase (at 14820 s) are summarized and compared with available measured data in the Table 8 and on the Figure 5.

In all compared calculations the dominant deposition process is thermophoresis (~94 % of the total deposited mass) mainly due to the relatively large fluid–to–wall temperature difference, which was almost constant (120 K to – 125 K) along the test pipe during the entire deposition phase.

The calculated deposited mass is overestimated in all analyzed cases (Table 8) by a factor of ~1.5, i.e. as it was already predicted in the former SOPHAEROS analysis with corrected temperature and/or mass flow rate used [1]. Only in the "FB1" analysis, considerable resuspension is predicted already during deposition phase (see also Figure 5). Indeed the calculation without activation of resuspension predicts a total deposited mass of 272.5 g, i.e. the calculated resuspension during deposition phase is negligible (< 1 percent of the deposited mass) in the "FB2", "RnR1" and "RnR2" analyses.

The final calculated resuspended mass fraction after the end of the sixth resuspension step (i.e., at 14820 s) in the "FB1" analysis is ~81 % (see Table 8 and Figure 5); it is slightly over-estimated in comparison with estimated from measured value of ~76 %.

Increasing of the adhesion coefficient by a factor of 10 in the “FB2” analysis leads to slight underestimation of the resuspended fraction (the calculated resuspended fraction is ~69 %). But, as it was already mentioned for the SR09 and SR10 tests, according to the Force-balance model the calculated resuspended fraction continuously increases as a function of time after each step of resuspension, while in the experiment (see Figure 5) the majority of the resuspension occurred in about ~25 s just after the beginning of each resuspension step (i.e. in six consecutive measurements of the aerosol mass concentration) [6].

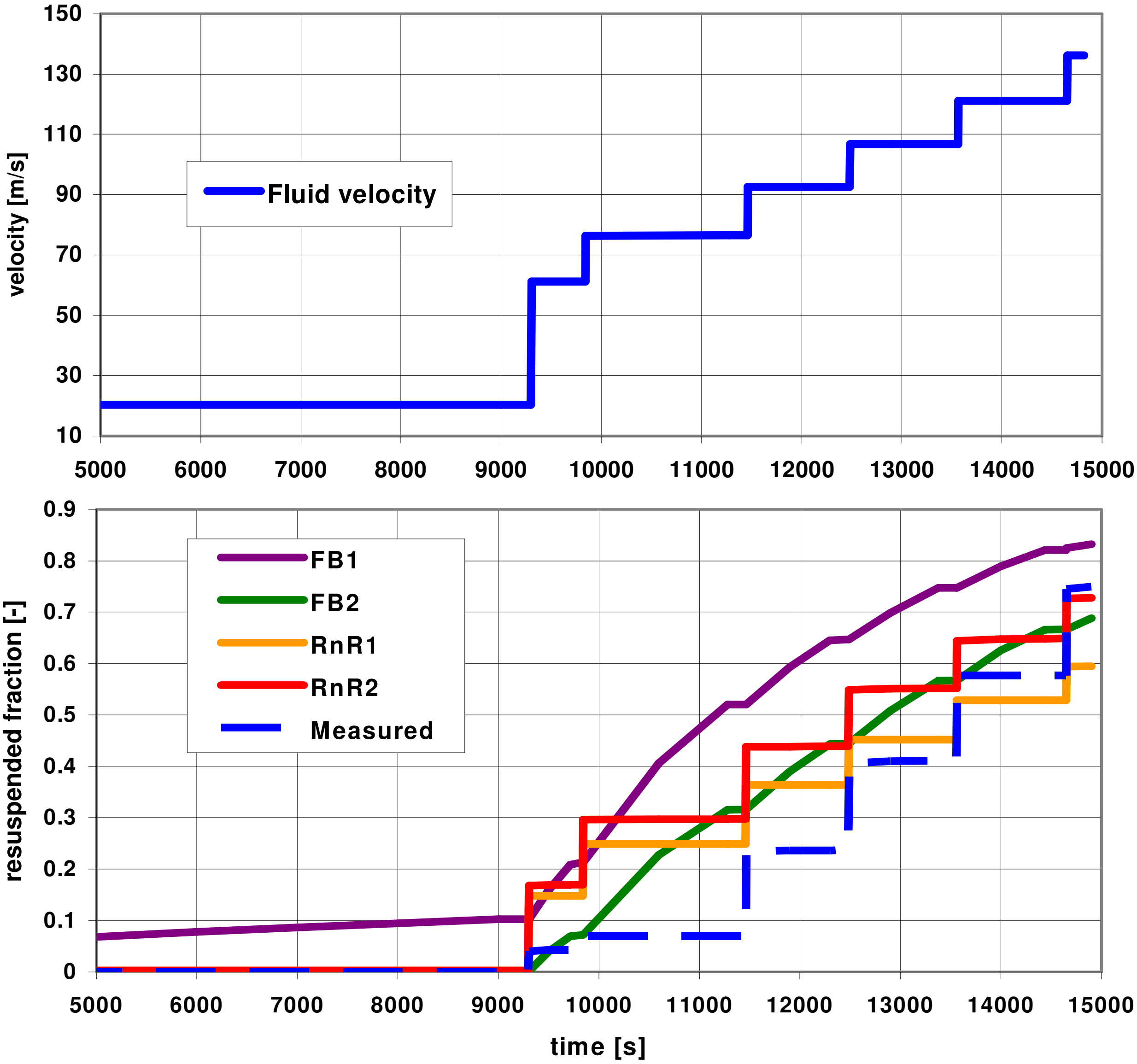


Figure 5: Resuspended fraction (bottom) and carrier gas velocity in the SR11 test (top)

On the other hand, both calculations with Rock’n Roll model predict that the majority (>99%) of the resuspended fraction occurred during one second just after increasing of the N2 mass flow rate in each resuspension step (see also fluid velocity in Figure 5). Using the maximum time step of 30 s in the “RnR2” calculation leads to a nearly perfect prediction of the final calculated resuspended fraction (~73 %), but detailed analysis of the printed results indicates some “anomaly” after ~12000 s when the fluid velocity at pipe inlet exceeds ~90 m/s (Figure 5). Decreasing of the time step to 1.0 s in the “RnR1” analysis eliminates this anomaly but the predicted final resuspended fraction decreases to ~59 % (see Table 8). More details about this anomaly are described in the Appendix.

The experimental measurements of all STORM resuspension tests [4, 5, 6, 7 and 9] showed, that the majority (>99 %) of the deposited mass is resuspended in a very short time interval (5 s to 25 s) after increasing of the carrier fluid mass flow rate (fluid velocity), i.e. the resuspended mass (fraction) depends only partially on the duration of resuspension step. The Rock ‘n Roll model even predicts that this time is less than one second1. The comparison of the different calculations with the Rock 'n Roll model and that of the STORM SR11 test results, in terms of resuspended fractions as a function of the gas velocity, is shown in Figure 6.

The results of the SOPHAEROS Force-balance model are not shown in this figure, because they strongly depend on the duration of the resuspension gas flow. In Figure 6, for comparison, some other calculation results are also included: the results of stand-alone Rock'n Roll model calculation taken from article [10] (marked as Biasi), the results of a SOPHAEROS analysis [13] denoted as "Alpy". The latter analysis was performed with a modified source code, where the particle diameter was used instead of particle radius in the correlations for the calculation of the geometric mean and spread of the normalized adhesive force [10]. The results obtained by the current version of SOPHAEROS / ASTEC v1.3 (calculations "RnR1" and "RnR2" in Figure 6) confirmed the conclusion of Alpy [13], that Biasi's result can be reproduced only by introduction of the above-mentioned changes into the source code.

[1] As described in [10], it is a common feature of resuspension from rough surfaces that if a fraction of the particles resuspends, then most of that fraction is resuspended in a very short time (< 1 s), and the remaining paricles resuspend over many hours (long term resuspension). So, as long as the time for resuspension in the calculation includes this initial phase then there will be little error in the value of the resuspension calculated and what is observed unless the actual time is very small (less than 1 ms) which is never the case in the experiments. So the value chosen for the resuspension time will have little effect on the results. For convenience the value for resuspension time was set to 1 s in the Rock 'n Roll model [10], which is used also in the SOPHAEROS module [2].

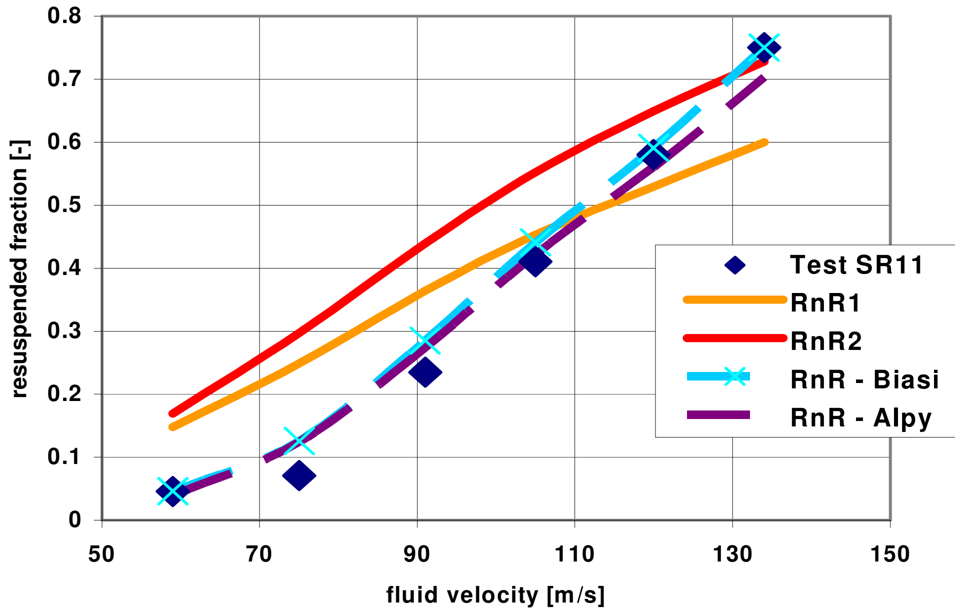


Figure 6: Comparison between the various model predictions and the STORM SR11 test results

As it is illustrated in the Figures 5 and 6, for the SR11 test, both Rock'n Roll (RnR1 and RnR2) and the Force-balance models over-estimate the resuspended fraction during the first two resuspension steps (rapid increasing of fluid velocity, see Figure 5), whereas the situation becomes the opposite during the last four resuspension steps. The reason may be that these models take into account the resuspension of a monolayer deposit in which all particles are initially exposed to the increased flow, i.e., the model does not simulate the in-depth progression of particle entrainment through the thickness of multi-layer deposit. But it should be also noted that in case of FB calculations this is also partly a consequence of the long duration of the second resuspension step, see Figure 5. Concerning the "RnR1" and "RnR2" calculations it seems that the discrepancy is mainly a consequence of the fact that in the present algorithm of Rock'n Roll model of the SOPHAEROS/ASTEC v1.3 module the particle radius and diameter are used not consistently.

3.4 Test SR12 results

The main results of the SR12 test analyses at the end of deposition phase (at 9000 s) and resuspension phase (at 17540 s) are summarized and compared with the available measured data in Table 9 and Figure 7.

In all compared calculations the dominant deposition process is thermophoresis (~90 % of the total deposited mass); it is mainly due to the relatively large fluid–to–wall temperature difference, which was about 50 to 110 K depending on the position inside the test pipe and on the time during the deposition phase.

The calculated deposited mass at the end of deposition phase (9000 s) is only slightly over-estimated (factor of 1.12) in comparison with the measured mass of ~164 g, even predicted perfectly in FB1 analysis (see Table 9), because considerable resuspension is predicted already during the deposition phase (see Figure 7). Indeed the calculation without activation of resuspension predicts total deposited mass 183.3 g, i.e. the calculated resuspension during deposition phase is negligible (< 1 % of the deposited mass) in the "FB2", "RnR1" and "RnR2" calculations.

The final resuspended mass fraction ~91 % calculated with FB model by using the default value of the cohesive force coefficient (FB1) is significantly overestimated (Table 9, Figure 7) compared to measured value ~51 %, even remains considerably over-estimated also in the "FB2" calculation (~78 %), where this coefficient was increased 10 times. The main reason is the relatively long duration of all three resuspension periods in comparison, e.g., with the SR11 test because the FB model calculates a continuous resuspension of the deposited particles during the entire period of resuspension phase. The measurement in the SR12 test showed [7] that majority of resuspension occurred in ~5 s after the start of each resuspension step.

Both calculations with the Rock'n Roll model ("RnR1" and "RnR2") predict better agreement with the measured total resuspended fraction (see Table 9 and Figure 7) in comparison with FB model.

It should be noted that the same anomaly (negative mass fraction of deposited particles due to eddy impaction is compensated by a mass fraction of >100 % due to thermophoretic deposition) was observed in the RnR2 calculation as in RnR2 calculation of SR11 test (see the appendix) already after the start of the first resuspension step (~10000 s, Figure 7) due to the very rapid increase of carrier fluid velocity near to ~90 m/s. This was not observed in the RnR1 calculation of the SR12 test.

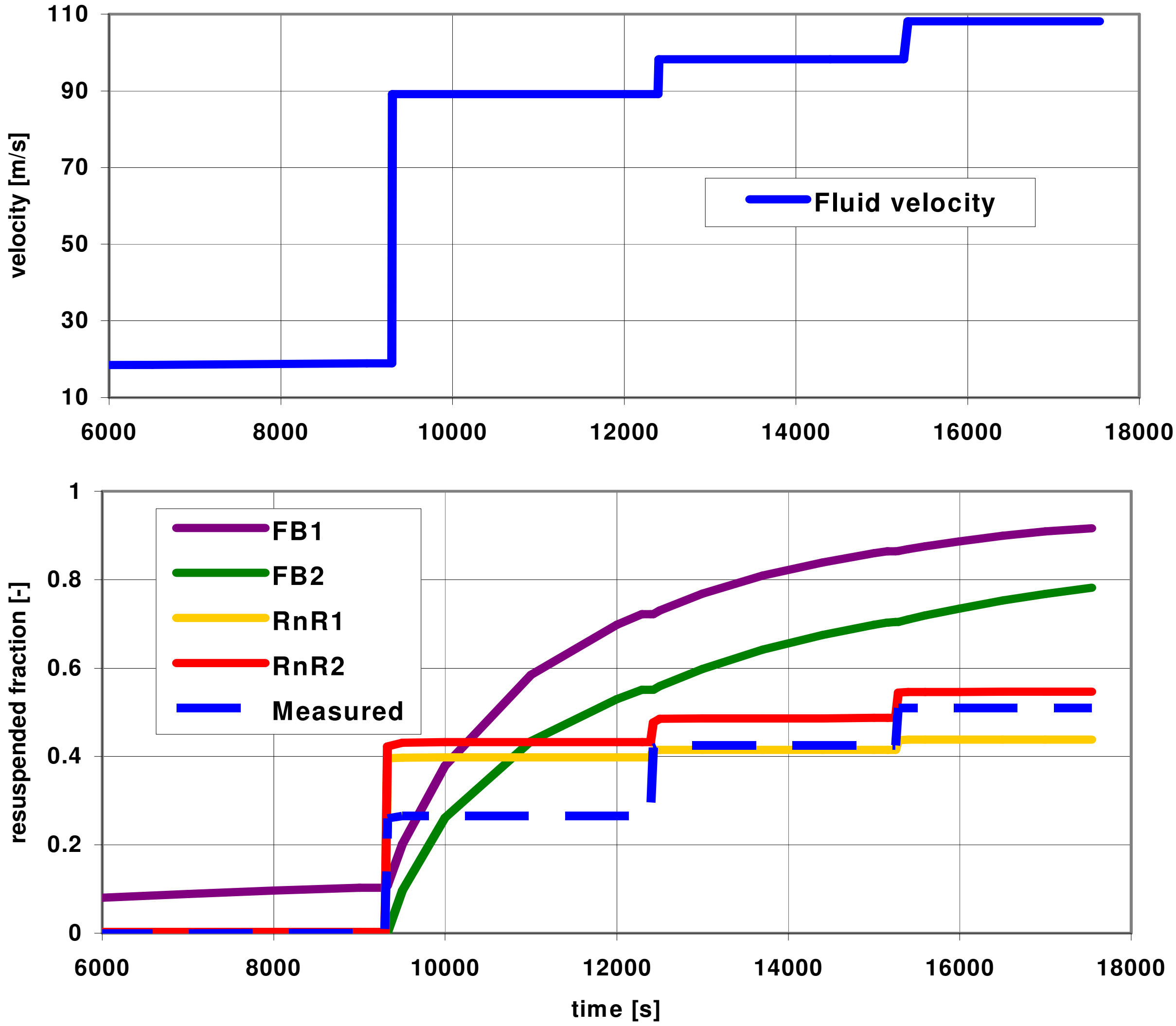


Figure 7: Resuspended fraction (bottom) and carrier gas velocity in the SR12 test (top)

As it is illustrated in Figure 8 (also in Figure 7), the both Rock'n Roll ("RnR1" and "RnR2") calculations strongly over-estimate the resuspended mass fraction during the first resuspension step, while the situation becomes opposite during the last two resuspension steps. The result of stand-alone Rock'n Roll model calculation taken from [10] and denoted as Biasi is also included in Figure 8. The results of both SOPHAEROS / ASTEC v1.3 analyses in principle confirmed the results predicted in previous analyses of the SR11 test, i.e., that it is not possible to reproduce Biasi's result without correction of the source code of Rock'n Roll model.

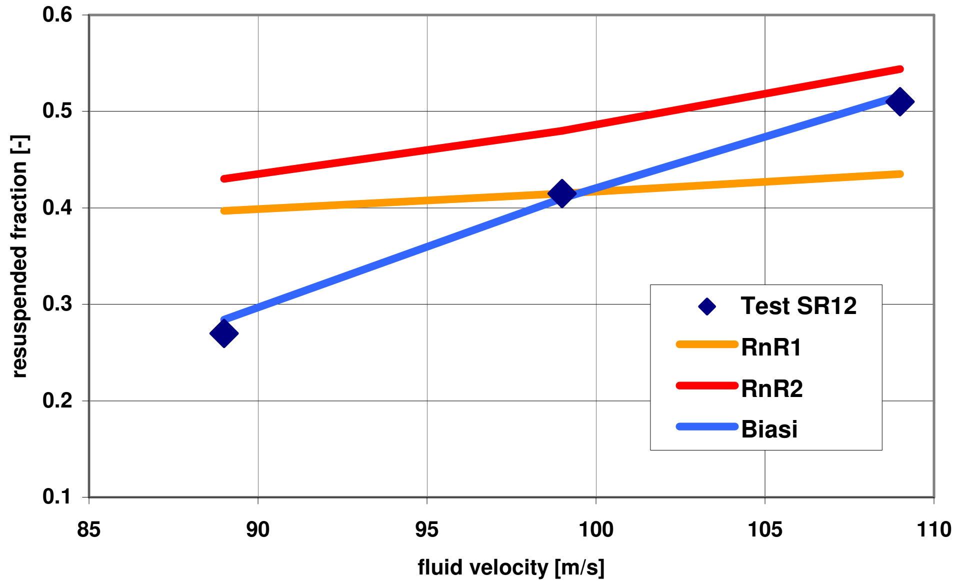


Figure 8: Comparison between the various model predictions and the STORM SR12 test results

3.5 Test SR13 results

The main results of the SR13 test analyses at the end of deposition phase (at 9000 s) and at the end of resuspension phase (at 15180 s) are summarized and compared with the available measured data in Table 10 and Figure 9.

In all compared calculations, the dominant deposition process is thermophoresis (~90 % of total deposited mass); this is mainly due to the relatively large fluid–to–wall temperature difference, which varies between 50 and 110 K depending on the position inside the test pipe and on time during deposition phase.

The calculated deposited mass at the end of deposition phase (9000 s) is over-estimated by a factor of ~1.3 in comparison with the measured mass of ~167.8 g. This overestimation is lower (factor ~1.1) in the "FB1" analysis (see Table 10), because considerable resuspension is predicted already during deposition phase (see Figure 9). Indeed, the calculation without activation of resuspension predicts the total deposited is mass 214.2 g, i.e., the calculated resuspension during deposition phase is negligible (<1 % of the deposited mass) in the "FB2", "RnR1" and "RnR2" analyses.

The final resuspended mass fraction is ~49 %, it was calculated with FB model by using the default value of the cohesive coefficient (FB1) and it is significantly higher (Table 10, Figure 9) compared to measured value of ~8.5 %. The final resuspended fraction still remains considerably over-estimated also in the "FB2" calculation (~21 %) using a 10 times increased value of this coefficient. The main reason is the same as it was found in the analyses of the SR12 test (see previous chapter 3.4), i.e., the relatively long duration of the last 2nd, 3rd and 4th resuspension steps (Figure 9) in comparison, e.g. with SR11 test (as was already mentioned the FB calculates continuous resuspension of the deposited particles during entire period of the resuspension phase).

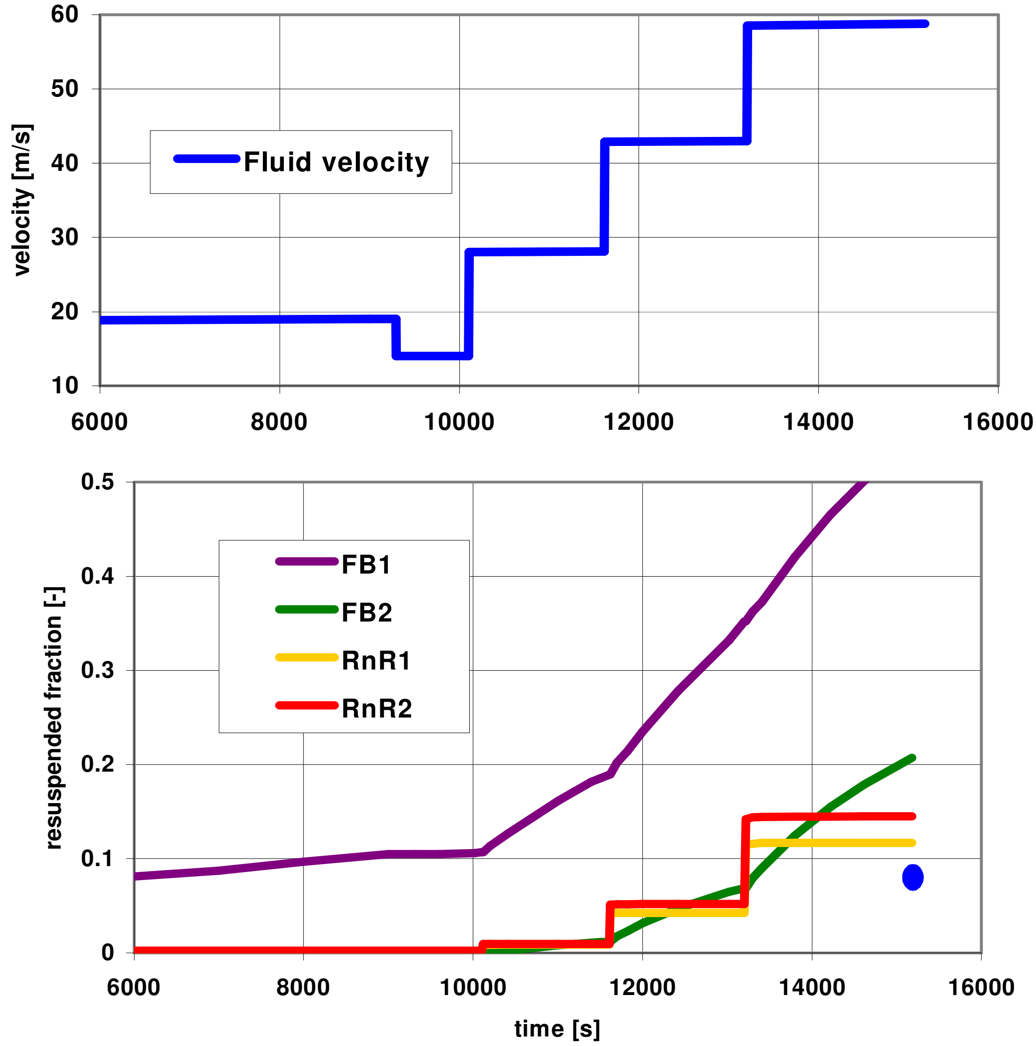


Figure 9: Resuspended fraction (bottom) and carrier gas velocity in the SR13 test (blue point shows the measured value)

Both calculations with the Rock'n Roll model ("RnR1" and "RnR2") predict better agreement with measured total resuspended fraction, ~8.5 %, (see Table 9 and Figure 9) in comparison with FB model. According to the data given in [9] the N2 mass flow rate during the first resuspension step (9300 – 10120 s) was 82 kg/h (0.0228 kg/s) – see also Table 5 in section 2.5) and the corresponding calculated carrier fluid velocity (~13.5 m/s, Figure 9) was still lower than during the deposition phase (~19 m/s). Therefore no resuspension was predicted in the calculations during this first resuspension step. Moreover, only the final (total) value of the measured resuspended mass fraction (~8.5 % - blue point in Figure 9) can be derived from the data given in [9].

4 Summary of the results

Four computational analyses were carried out for each considered STORM test such as SR09, SR10, SR11, SR12 and SR13 by using the SOPHAEROS module of the ASTEC V1.3rev.0 [2] code in stand-alone mode. The modelling options used in a given calculation are as follows:

- Force-balance (FB) model with the default value of cohesive force coefficient (1.0·10-6 N/m); this calculation is denoted as “FB1”
- Force-balance model with a value 10 times higher then the default (1.0·10-5 N/m); this calculation is denoted as “FB2”
- Rock’n Roll (RnR) model with maximum time step set to 1.0; this calculation is denoted as “RnR1”.
- Rock’n Roll model with maximum time step 30 s; this calculation is denoted as “RnR2”

As Figure 10 shows, the FB model of mechanical resuspension with the default value of the cohesive coefficient (FB1) over-estimates the final resuspended fraction for all the analyzed STORM tests. The FB model gives substantially better agreement with the measured (estimated) final resuspended fractions if the value of the default cohesive coefficient is increased by a factor of 10 (FB2); however, remarkable over-estimation for SR12 and SR13 still remains. It should be pointed out that according to the FB model the resuspension is a continuous process and therefore the calculated resuspended mass significantly depends not only on the carrier fluid velocity during resuspesion phase, but also on the duration of these phase (one or several steps). This is in contradiction with the experimental measurements.

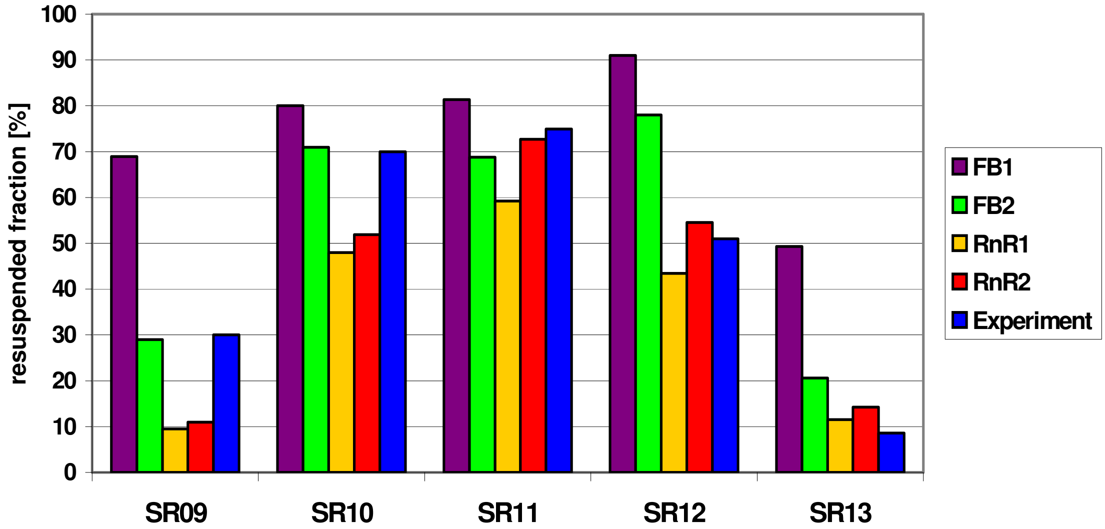


Figure 10: Comparison of the calculated and measured total resuspended fractions

The STORM SR09 to SR12 resuspension tests [4, 5, 6, 7] showed, that the majority (>99 %) of the deposited mass is resuspended in a very short time interval (5 s to 25 s) just after increasing of the carrier fluid mass flow rate, i.e., in reality, the resuspended mass (fraction) depends only partly or negligibly on the duration of resuspension step, during which the gas flow velocity is kept at a constant value.

The RnR model significantly underestimates the final resuspended fraction for the SR09 and SR10 tests (see Figure 10), in which the resuspension phase was simulated in one step by increasing carrier fluid velocity from ~20 m/s to ~54 m/s (SR09) and to ~83 m/s (SR10). On the other hand this underestimation of the final (total) resuspended fraction is small or negligible (even slightly over-estimated for SR13), in dependence on the value of maximum time step. Also, in the Rock’n Rock model, 99 % of the fraction is resuspended in a very short time (≤ 1 s). It should be noted that the influence of maximum time step as input parameter is remarkable only in the SR11 and SR12 test analyses (see Figure 10) in which the final velocity of the carrier gas during resuspension phase reached values >90 m/s.

For SR11 and SR12 tests, both SOPHAEROS Rock'n Roll calculations ("RnR1" and "RnR2") over-estimate the resuspended fraction during the first (SR12) and the first two resuspension steps (SR11) whereas the situation become opposite during the later steps, and this has a compensating effect on the final resuspended fraction.

5 Conclusions

The calculated results showed that the dominant deposition process during the deposition phase in all analyzed STORM tests (SR09 – SR13) is the thermophoresis and that there is trend to overestimate the retained mass. However, this over-estimation was found to be significant (factor ~1.5) only in the SR11 test, where the highest fluid–to–wall temperature difference was applied (120 – 125 K). In all other SR tests, except the short inlet part (<1 m) of the test pipe in SR12 and SR13 tests, this temperature difference was <100 K and the factor of overestimation of total deposited mass became did not exceed 1.3. Therefore, further examinations of the uncertainties in the thermal hydraulic conditions are required. The main reasons are that the gas temperature profile as well as the inlet gas temperature inside the test pipe could not be directly measured. Therefore, it can be recommended to perform in the future a comprehensive analysis of all STORM tests by using the SOPHAEROS and the CESAR module of ASTEC [14] in coupled mode. This will provide consistent thermal-hydraulic boundary conditions for the simulations. Such coupled analyses of the STORM tests are still not possible due to limitations of the CESAR [15] module implemented in ASTEC V1.3 Rev0 [14], namely, that the current module can take into account only one type of a non-condensable gas, i.e., the handling of several types of non-condensables is not foreseen in this module. Finally, it is also recommended to check the influence of reference temperature for calculation of fluid properties entering the Talbot formula, used in the code to calculate the velocity of thermophoretic deposition as this was indicated in [16].

The results of the analyses of the STORM re-suspension tests SR09, SR10, SR11, SR12 and SR13 showed that with the semi-empirical Force-balance (FB) model acceptable results were obtained only by increasing the default value of the cohesive force coefficient. These results confirmed the results obtained with the previous version of SOPHAEROS V2.1 [1]. It should be also mentioned that the main feature of the FB model is that the resuspension is modelled as a continuous process and therefore the resuspended mass significantly depends not only on the magnitude of the carrier fluid velocity during resuspesion phase, but also on the duration of these phase, what is not in agreement with the measurements. The STORM SR tests indicate that 5 s to 25 s is the characteristic time interval of strong resuspension, after which the resuspended mass is small or negligible.

The Rock'n Roll (RnR) model was originally established by Reeks et al. [17] and its adaptation is described in [10]. The model uses a lognormal distribution of adhesive forces. The correlations used for the "geometric mean" and "spread" of the adhesive force are derived as a function of particle size ("particle radius", as is coded in the SOPHAEROS) and are based mainly on the STORM data. The results of the SR11 test confirmed the conclusion of Alpy's calculation carried out with SOPHAEROS [13], namely the results showed in [10] could be reproduced only by modifying of the above-mentioned correlations, in the source code. Moreover, the current RnR model calculates the aerosol resuspension in turbulent pipe flows because of the monolayer concept when the deposit forms a monolayer in which all the particles are initially exposed to the gas flow. However, this is not the case in the STORM experiments. The RnR model does not simulate the penetration of gas flow in multilayer deposits and the particle entrainment in the gas flow through the multi-layers. Therefore, there is a need for further improvement of aerosol mechanical resuspension; these developments are under way in the Source Term Topic of the SARNET project [18].

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Tables

Table 1: Boundary conditions of the analyzed SR09 test

Parameter	Deposition phase: 0 – 9000 s	Resuspension phase: 9300 – 17220 s
Carrier gas flow rates	N_2: 1.014E-2 kg/s H_2O: 1.042E-2 kg/s He: 1.190E-4 kg/s Ar: 7.187E-3 kg/s O_2: 1.146E-3 kg/s Total: 0.0297 kg/s	The N_2 mass flow rate was increased in one step to 0.08722 kg/s.
SnO_2 aerosol inlet flow rate [1)]	3.562E-4 kg/s	-
Inlet gas temperature (Fig.2) TGDLU1 TGRLU1	 365 – 415 ºC -	 - 384 – 390 ºC
Outlet gas temperature (Fig.2) TGTP1 (near-wall) TGTP2 (1/3 R)	 301 – 335 ºC 261 – 299 ºC	 357 – 365 ºC 277 – 295 ºC
Pipe wall temperature (Fig.2) TETP1, TETPmax, TETP10	 291, 291, 249 ºC	 338, 348, 316 ºC
Reylnods number [2)]	~20200	~57900
Carrier fluid velocity [2)]	~20.5 m/s	~54 m/s

[1)] Ratio of the total SnO_2 mass of 3.206 kg entering the test pipe and the deposition phase duration [4]. [2)] Local values averaged by code user

Table 2: Boundary conditions of the analyzed SR10 test

Parameter	Deposition phase: 0 – 9000 s	Resuspension phase: 9300 – 13200 s
Carrier gas flow rates	N_2: 1.014E-2 kg/s H_2O: 1.111E-2 kg/s He: 1.190E-4 kg/s Ar: 7.187E-3 kg/s O_2: 1.146E-3 kg/s Total: 0.0297 kg/s	**N_2** mass flow rate increased in one step: 0.1397 kg/s
SnO_2 aerosol inlet flow rate [1)]	3.45E-4 kg/s	-
Inlet gas temperature (Fig.2) TGDLU1 TGRLU1	 369 – 399 ºC -	 - 358 – 359 ºC
Outlet gas temperature (Fig.2) TGTP1 (near-wall) TGTP2 (1/3 R)	 347 – 359 ºC 317 – 327 ºC	 352 ºC 347 ºC
Pipe wall temperature (Fig.2) TETP1, TETPmax, TETP10	 348, 350, 301 ºC	 346, 355, 321 ºC
Reylnods number [2)]	~21500	~94800
Carrier fluid velocity [2)]	~21 m/s	~83 m/s

[1)] Ratio of the total SnO_2 mass of 3.105 kg entering the test pipe and the deposition phase duration [5]. [2)] Local values averaged by code user

Table 3: Boundary conditions of the analyzed SR11 test

Parameter	Deposition phase: 0 – 9000 s	Resuspension phase: 9300 – 14820 s
Carrier gas flow rates	N_2: 1.005E-2 kg/s H_2O : 1.106E-2 kg/s He: 1.199E-4 kg/s Ar: 7.194E-3 kg/s O_2: 1.146E-3 kg/s Total: 0.0297 kg/s	**N_2** mass flow rate increased stepwise to: 9300 s : 0.1017 kg/s 9840 s : 0.1258 kg/s 11460 s : 0.1522 kg/s 12480 s : 0.1753 kg/s 13560 s : 0.1989 kg/s 14650 s : 0.2236 kg/s
SnO_2 aerosol inlet flow rate [1)]	3.83E-4 kg/s	-
Inlet gas temperature (Fig.2) TGDLU1 TGRLU1	 355 – 399 ºC -	 - 368 – 370 ºC
Outlet gas temperature (Fig.2) TGTP1 (near-wall) TGTP2 (1/3 R)	 261 – 300 ºC 235 – 262 ºC	 363 ºC 361 ºC
Pipe wall temperature (Fig.2) TETP1, TETPmax, TETP10	 220, 229, 167 ºC	 335, 364, 355 ºC
Reylnods number [2)]	~21200	68000 - 150000
Carrier fluid velocity [2)]	~20.5 m/s	61 – 136 m/s

[1)] Ratio of the total SnO_2 mass of 3.447 kg entering the test pipe and the deposition phase duration [6].

Table 4: Boundary conditions of the analyzed SR12 test

Parameter	Deposition phase: 0 – 9000 s	Resuspension phase: 9300 – 17540 s
Carrier gas flow rates	N_2: 1.011E-2 kg/s H_2O : 1.110E-2 kg/s He: 1.199E-4 kg/s Ar: 7.194E-3 kg/s O_2: 1.141E-3 kg/s Total: 0.0297 kg/s	**N_2** mass flow rate increased stepwise to: 9300 s : 0.1444 kg/s 12400 s : 0.1589 kg/s 15260 s : 0.1750 kg/s
SnO_2 aerosol inlet flow rate [1)]	4.05E-4 kg/s	-
Inlet gas temperature (Fig.2) TGDLU1 TGRLU1	 356 – 396 ºC -	 - 378 – 379 ºC
Outlet gas temperature (Fig.2) TGTP1 (near-wall) TGTP2 (1/3 R)	 262 – 296 ºC 235 – 262 ºC	 373 - 375 ºC 372 - 374 ºC
Pipe wall temperature (Fig.2) TETP1, TETPmax, TETP10	 232, 239, 179 ºC	 365, 380, 370 ºC
Reylnods number [2)]	~23000	68000 - 150000
Carrier fluid velocity [2)]	~19 m/s	89 – 108 m/s

[1)] Ratio of the total SnO_2 mass of 3.645 kg entering the test pipe and the deposition phase duration [7]

Table 5: Boundary conditions of the analyzed SR13 test

Parameter	Deposition phase: 0 – 9000 s	Resuspension phase: 9300 – 15180 s
Carrier gas flow rates	N_2: 1.013E-2 kg/s H_2O : 1.111E-2 kg/s He: 1.190E-4 kg/s Ar: 7.190E-3 kg/s O_2: 1.145E-3 kg/s Total: 0.0297 kg/s	**N_2** mass flow rate increased stepwise to: 9300 s : 0.0228 kg/s 10120 s : 0.0456 kg/s 11600 s : 0.0695 kg/s 13200 s : 0.0945 kg/s
SnO_2 aerosol inlet flow rate [1)]	4.53E-4 kg/s	-
Inlet gas temperature (Fig.2) TGDLU1 TGRLU1	 366 – 389 °C -	 - 384 – 387 °C
Outlet gas temperature (Fig.2) TGTP1 (near-wall) TGTP2 (1/3 R)	 270 – 296 °C 246 – 261 °C	 375 - 382 °C 362 - 379 °C
Pipe wall temperature (Fig.2) TETP1, TETPmax, TETP10	 243, 243, 192°C	 373, 386, 366 °C
Reylnods number [2)]	~22800	30000 - 62400
Carrier fluid velocity [2)]	~19 m/s	28 – 59 m/s
Fluid pressure	0.1 MPa	0.1 MPa

[1)] Ratio of the total SnO_2 mass of 4.077 kg entering the test pipe and the deposition phase duration [7].

Table 6: Main results of the SR09 test

Parameter	Calculation				Measurement SR09
	FB1	FB2	RnR1	RnR2	
Cohesive force coeff., N/m	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$	–	–	–
Maximum time step imposed, s	not sensitive	not sensitive	1.0	30.0	–
Deposited mass at 9000 s Geometric mean diam. of deposited particles Dominant depo. mechanism Thermophoresis Eddy impaction	 152.2 g 0.424 µm 91 % 7.3 %	 171.1 g 0.428 µm 91 % 7 %	 170.8 g 0.428 µm 92 % 6.7 %	 170.8 g 0.428 µm 92 % 6.7 %	 ~166 g Particle sizes: 0.1 – 3.0 µm – –
Deposited mass at 17220 s	47.4 g	121.9 g	154.5 g	151.9 g	117 g
Re-suspended mass fraction	104.8 g 69 %	49.2 g 29 %	16.3 g 9.5 %	18.9 g 11 %	49 g ~30 %

Table7: Main results of the SR10 test

Parameter	Calculation				Measurement SR10
	FB1	FB2	RnR1	RnR2	
Cohesive force coeff., N/m	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$	–	–	–
Maximum time step imposed, s	not sensitive	not sensitive	1.0	30.0	–
Deposited mass at 9000 s	24.6 g	32.9 g	32.75 g	32.75 g	As calculated: ~33 g
Geometric mean diam. of deposited particles, μm	0.43–0.46	0.44-0.47	0.44-0.53	0.44-0.47	Particle sizes: 0.1 – 3.0 μm
Dominant depo. mechanism					
Thermophoresis	55 %	51 %	52 %	52 %	–
Eddy impaction	37 %	40 %	39 %	39 %	–
Deposited mass at 13200 s	5 g	9.5 g	16.83 g	15.72 g	Measured: 9.7 g
Re-suspended mass	19.6 g	23.4 g	15.92 g	17 g	23.3 g
fraction	80 %	71 %	48 %	51.9 %	~70 %

Table 8: Main results of the SR11 test

Parameter	Calculation				Measurement SR11
	FB1	FB2	RnR1	RnR2	
Cohesive force coeff., N/m	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$	–	–	–
Maximum time step imposed, s	not sensitive	not sensitive	1.0	30.0	–
Deposited mass at 9000 s	244.6 g	272.2 g	271.9 g	271.9 g	175.0 g [1)]
Geometric mean diam. of deposited particles	0.424 μm	0.427 μm	0.427 μm	0.427 μm	Particle sizes: 0.1 – 3.0 μm
Dominant depo. mechanism					
Thermophoresis	93 %	94 %	94 %	94 %	–
Eddy impaction	5.5 %	5.2 %	5 %	5 %	–
Deposited mass at 14820 s	45.6 g	84.8 g	110.8 g	74 g	42 g
Re-suspended mass	199 g	187.4 g	161.1 g	197.9 g	133.0 g
fraction	81 %	69 %	59 %	73 %	~76 %

[1)] There is a relatively large spread in the reported estimated values [1]: 162 g, 178 g and 185 g, therefore their average value is considered. – : not applicable

Table 9: Main results of the SR12 test

Parameter	Calculation				Measurement SR12
	FB1	FB2	RnR1	RnR2	
Cohesive force coeff., N/m	$1.0{\cdot}10^{-6}$	$1.0{\cdot}10^{-5}$	–	–	–
Maximum time step imposed, s	not sensitive	not sensitive	1.0	30.0	–
Deposited mass at 9000 s	164.1 g	183.2 g	182.8 g	182.8 g	164 g
Geometric mean diam. of deposited particles	0.435 μm	0.435 μm	0.436 μm	0.436 μm	Particle sizes: 0.1 – 3.0 μm
Dominant depo. mechanism					
Thermophoresis	89 %	89 %	89 %	89 %	–
Eddy impaction	9 %	9 %	9 %	9 %	–
Deposited mass at 17540 s	14.9 g	40.0 g	103.2 g	83.1 g	83 g
Re-suspended mass	149.2 g	143.2 g	79.6 g	99.7 g	131.5 g
fraction	91 %	78.2 %	43.5 %	54.5 %	~51 %

Table 10: Main results of the SR13 test

Parameter	Calculation				Measurement SR13
	FB1	FB2	RnR1	RnR2	
Cohesive force coeff., N/m	$1.0{\cdot}10^{-6}$	$1.0{\cdot}10^{-5}$	–	–	–
Maximum time step imposed, s	not sensitive	not sensitive	1.0	30.0	–
Deposited mass at 9000 s	191.7 g	214.1 g	213.6 g	213.6. g	167.8 g
Geometric mean diam. of deposited particles	0.435 μm	0.435 μm	0.436 μm	0.436 μm	Particle sizes: 0.1 – 3.0 μm
Dominant depo. mechanism					
Thermophoresis	89 %	90 %	90 %	90 %	–
Eddy impaction	8.7 %	8.3 %	8 %	8 %	–
Deposited mass at 15180 s	97.1 g	169.9 g	189.1 g	183.1 g	153.6 g
Re-suspended mass	94.6 g	44.2 g	24.5 g	30.5 g	14.2 g
fraction	49.3 %	20.6 %	11.5 %	14.3 %	~8.5 %

Appendix

Details on the anomalous code behavior at high carrier gas velocities in the pipe

After increasing of the fluid inlet velocity above ~90 m/s, the calculated mass fraction of the particles deposited due to the eddy impaction mechanism becomes a negative number. This is compensated by the increase of the mass fraction to an unphysical value higher than 100% due to thermophoresis. At final time of calculation (14820 s), the mass fraction of the particles deposited due to different deposition mechanisms is predicted as follows: settling: 1.26 %, turbulent diffusion: 0.13 %, Eddy impaction: -6.61 % and thermophoresis: 105.23 %. The final mass balance, i.e, the sum of all fractions is 100 %, however this is only formally correct.

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Abstract

In most of the severe accident scenarios in light water reactors the deposition and resuspension of aerosols in the primary circuit influence mainly the release of radioactive material into the containment. Due to an energetic interactions, e.g. hydrogen burning, or fluid mechanical load – high velocity jets or sudden pressure changes – the deposited aerosols can be resuspended and significantly increase the amount of radioactive material reaching the containment and finally the potential threat of the release into the environment (source term). In this report two aerosols mechanical resuspensions models implemented in the SOPHAEROS / ASTEC V1.3 Rev.0 module are validated against the STORM resuspension experiments SR09, SR10, SR11, SR12 and SR13 and the modelling weakness are identified. In spite of the fact that these models encompass the measurements, it is shown that further improvement of aerosol resuspension model in SOPHAEROS module is necessary in order to achieve a better predictability of the source term during severe accident.

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