Comparison of the extended rational heat transfer model with 3D simulations

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Abstract
This paper presents a first comparison between the extended rational heat transfer (eRHT) model and 3D simulations. This comparison shows a good agreement between both. However it was only compared for a limited number of cases. The main conclusion was that the Nusselt relation used over predicted the amount of heat transfer. This needs to be further substantiated in measurements and 3D simulations. Furthermore measurements are also needed to validate the 3D simulations.

1 INTRODUCTION

Surge vessels are used in many pipeline systems as a main surge protection equipment. As was shown by Zwan et al. [1] the required volume of surge vessel can be reduced significantly when the extended rational heat transfer (eRHT) model is used instead of the ideal gas model. However it was also discussed that further validation of the eRHT model was required. To validate the model detailed measurements and 3D CFD simulation of the thermodynamics of the surge vessel are required. This combination will give a good insight into the physical thermodynamic processes which take place during the filling and draining of a surge vessel. 3D CFD in general will result in a lot of detailed information on among others the temperature variation inside the surge vessel. However this is still a simulation model and real measurements are required to validate the 3D CFD model. However measurements can only provide limited insight into the temperature variation in the surge vessel due to the limited number of measurement points which can be installed and the relatively slow response time of temperature transmitters. This paper describes 3D CFD simulations which are used to make a first step in validating the eRHT model as described in [1].

2 SETUP

2.1 The surge vessel

The 23 m^3 surge vessel as installed in the alpha loop facility of Deltares has been used for the validation. Table 1 shows an overview of the dimensions of the surge vessel. Figure 1 shows both a picture and a technical drawing of the surge vessel. Figure 2 shows a schematic overview of the entire system. Draining of the surge vessel is performed via the bottom connection of the surge vessel. The flow rate is controlled with the valve installed in the draining pipeline the water is flowing into a reservoir via a submerged inlet.

Table 1 properties of the surge vessel

Property	Value
Total volume	22.7 m^3
Inner diameter	2.5 m
Height	4.63 m
Material	Stainless steel
Wall thickness	16 mm

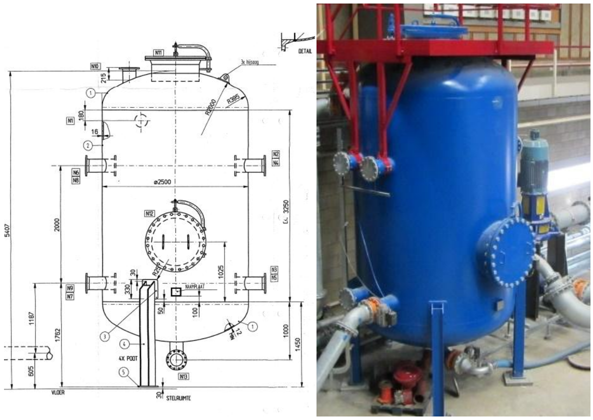

Figure 1 Technical drawing and picture of the surge vessel

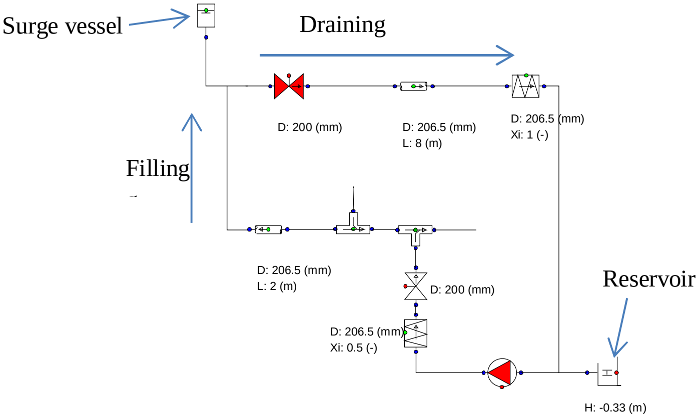

Figure 2 Schematic overview from Wanda of the setup

2.2 3D CFD features

2.2.1General features

The 3d CFD/thermal simulations have been performed with the commercial CFD code Star CCM+ [2]. Only a wedge of 5° from the surge vessel has been modelled, see Figure 3, which is a valid approach if it is assumed that the vessel is axisymmetric. Both the water and air phase are included inside the vessel, using a Volume of Fluid (VOF) method as implemented in Star CCM+ [2]. Turbulence is modelled in all fluid phases using an unsteady Reynolds average Navier stokes equations (RANS) approach with realizable k-epsilon model. The stainless steel vessel itself is modelled with a wall thickness 16 mm.

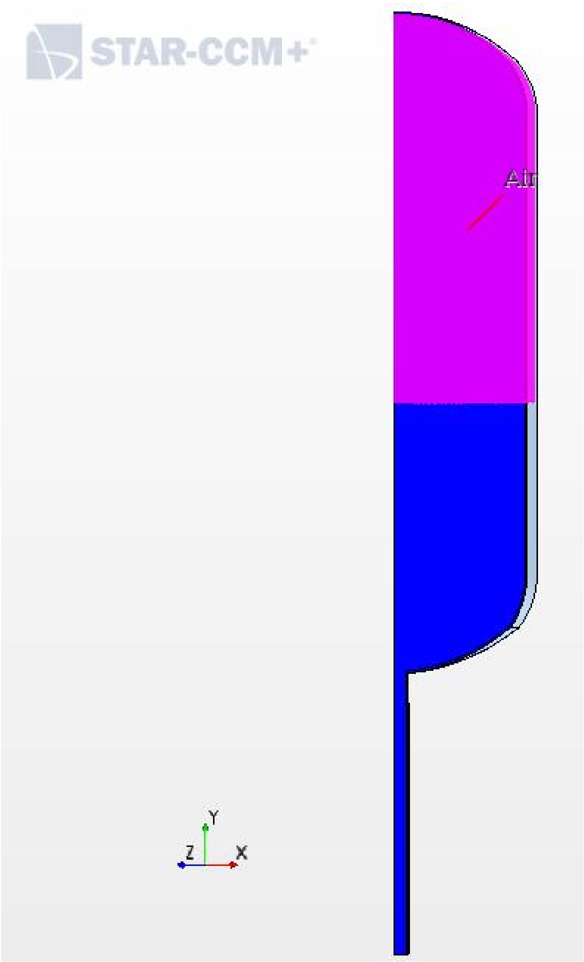

Figure 3 Wedge of the surge vessel modelled for the 3D simulations

The air phase is modeled as a multicomponent gas, consisting of air and vapour.. A mass outflow boundary condition is placed at the end of an outlet pipe at the bottom of the vessel. The air is modelled as compressible and an ideal gas law is used for the equation of state.

2.2.2 Discretisation

The model is run in unsteady mode with the first order temporal gradients. All other numerical schemes (spatial, VOF and thermal) are 2nd order.

The 3D mesh is constructed of 570,000 polyhedral cells inside the vessel and 150,000 cells within the vessel wall. Refinements are made near the walls of the vessel within the fluid because of the boundary layer there. The achieved y^+_{max} in the vessel is 5 and y^+_{max} is 2 in the air phase of the vessel. In the outlet tube the y+ is higher $30 < y^+ < 150$, necessitating the use of a wall function there. At the water surface these settings are sufficient to maintain a sharp interface between gas and liquid phase throughout the simulation.

2.2.3 Boundary conditions

At the outlet of the outlet pipeline a transient discharge rate is specified to simulate the emptying of the vessel, see Figure 4. A no slip boundary condition is specified at the internal wall and symmetry boundaries are defined at the faces of the 5° sector. For the wall model in the fluid, a two-layer wall function is used, this splits the boundary layers in two sections to get more accurate results. The mesh sizes are chosen such that a low y+ value is achieved in the air phase in the vessel where the heat transfer is of interest. In the outlet pipeline the velocity is higher but the heat transfer in this region is not of interest and therefore a higher y+ and use of wall functions in this region can be justified. It is assumed that the air temperature on the outside wall of the surge vessel remains constant at 15°C. Table 2 shows the initial conditions used in the simulations. The system does not start at equilibrium. This has been done to investigate the effect of the heat transfer from the solid phase to the gas phase.

Table 2 Initial conditions of the 3D simulations

	Water phase	Gas phase	Solid phase
Temperature	15 °C	1° C	15 °C
Pressure	Hydrostatic profile	2.8 bar	-
Water level	2.8 meters	-	-
Mass fraction of water vapour	-	0.006	-
Turbulence intensity	1%	1%	-

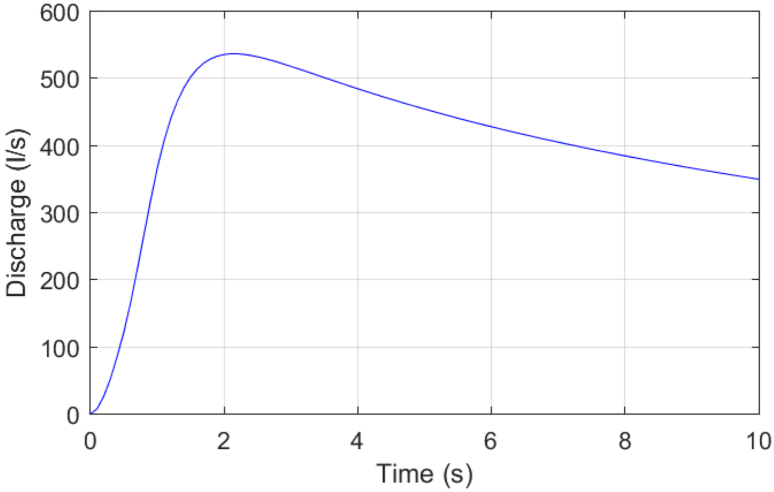

Figure 4 Discharge time series used as boundary condition

2.3 The extended rational heat transfer model

The extended rational heat transfer model (eRHT) is described in [1]. Basically it extends the rational heat transfer model with a more accurate relation for the heat transfer. The simulations with the extended rational heat transfer model (eRHT) have been performed with Wanda [3]. The model has been implemented in a Wanda component. This surge vessel component is connected to a discharge boundary, set to predefined discharge.

3 RESULTS AND COMPARISION

In this section a comparison is made between the 3D CFD simulation and the simulation performed with the eRHT model. At first a simulation is performed to compare the heat transfer from the eRHT model with the heat transfer in the 3D simulations. For this a simulation is done in which there is no out or inflow in the surge vessel, meaning the air will not be compressed or expanded. Since the air starts at a lower temperature heat transfer will occur in this system. In the second simulation the same starting point is used, but now water is flowing from the surge vessel, as specified by the time series in Figure 4 resulting in expending of the air. This simulation can be sued to compare the expansion effects of both models. Please note that only a small time window has been simulated due to the computational effort required.

3.1 Heat transfer from surroundings

Figure 5 shows a comparison of the temperature between the 3D simulations and the eRHT model. In the first few time steps there is a sharp increase of temperature for the 3D simulations, after which the temperature changes at an almost constant rate. In the 3D simulations the air starts at a constant temperature throughout the entire air domain. Therefore the temperature at the beginning increases relatively sharp, since the boundary layer still needs to develop. In other words, the temperature difference between the wall and the air next to the wall is large and a large heat flow is the result. The temperature of this boundary layer will increase reducing the heat transfer from the wall. In the meanwhile the heat is slowly transported into the air domain, resulting at the end at a constant heat flow from the wall into the air. In the eRHT model results this effect does not occur and the heat transfer, which is based upon Nusselt-relation does immediately take into account the establishment of a boundary layer (it assumes a steady heat flow). Therefore this heat transfer is almost at a constant rate. Furthermore it can be seen that the heat transfer for the eRHT model is at a higher rate than the 3D simulations. The eRHT model heat transfer is based upon Nusselt relation, however the relation used is for free convection between two horizontal plates in the horizontal direction and free convection at a vertical plate for the top and bottom (at the water surface) layers. However in the surge vessel these three heat transfers will influence each other reducing their effectiveness. Hence the higher heat transfer result from the eRHT model. However this situation reported here is only for free convection, while when the surge vessel is filling or emptying forced convection will play a role due to the expanding or compressing of the air. Therefore no effort has been made to exactly match the heat transfer for this case.

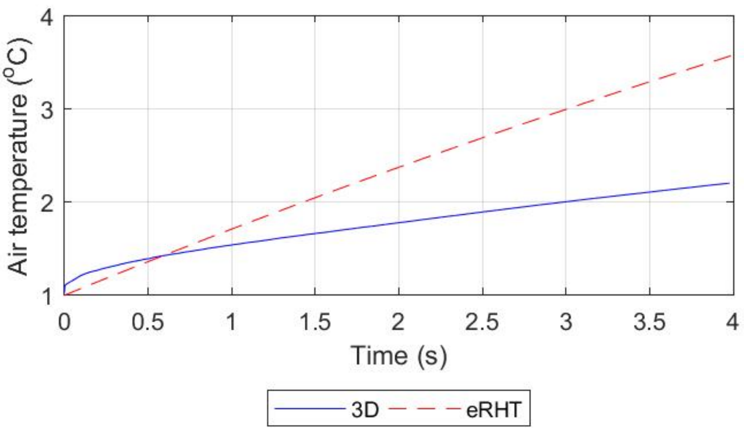

Figure 5 Comparison between the air temperature of the 3D simulations and eRHT model for the heat transfer only

3.2 Air expansion

Figure 6 shows a comparison between the 3D simulations and eRHT model. In the results it can be seen that there is first a small increase in temperature due to the difference in air temperature and temperature outside of the surge vessel. After which the temperature starts to decrease due to the expansion of the air. As can be seen the eRHT model follows the 3D simulation quite well for the first second. In this period the heat transfer from the surroundings is less dominant and the effect of using the Nusselt relation, which is not fitted exactly, has less influence on the results. The difference here is caused by the heat used for the expansion of the air, which cools the air. In the 3D model an ideal gas model with a Laplace coefficient of 1 has been used. Therefore the expansion of the air is slower and less heat is required. This will result in a higher temperature, as seen in the results. After the firsts second the heat transfer from the surroundings becomes more dominant and since this is overestimated by the eRHT model, the temperature rises above the result of the 3D simulations.

In conclusion the eRHT model shows a good first comparison, but it should be noted that this is a very limited comparison. First the 3D simulations need to be verified with measurements. Then additional and longer simulations are required to make a complete validation of the eRHT model.

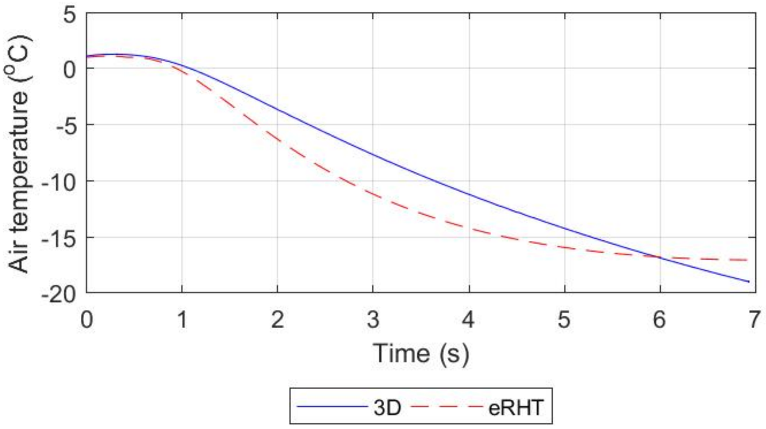

Figure 6 Comparison between 3D simulations and eRHT model for the heat transfer and expansion

3.3 Adjustments to the eRHT model

Based on the result it is investigated what the effect is of adjusting the Nusselt relation for heat transfer. For this the Nusselt number is multiplied with a factor (between 0.25 and 1). Figure 7 and Figure 8 show the results for the two simulations. For both it can be seen that multiplying with a factor of 0.25 gives the best match, since the temperature of the eRHT model best follows the trend of the 3D simulations. This trend is of interest since it is the rate of change of temperature, which is directly related to the amount of heat transfer, which is calculated with help of the Nusselt number.

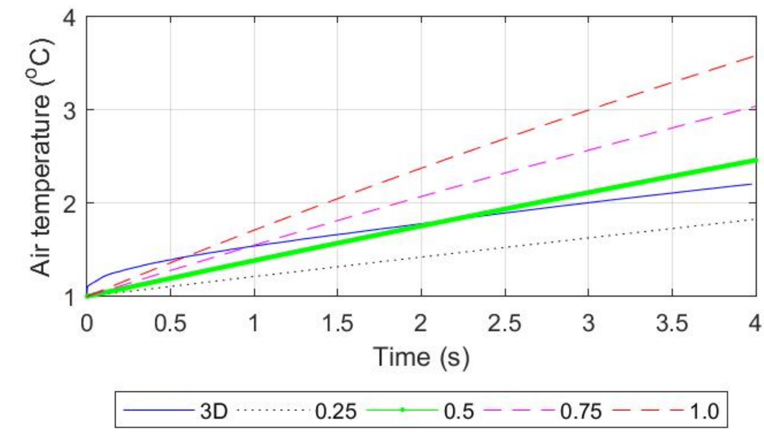

Figure 7 Comparison between 3D simulations and eRHT for which the Nusselt number is multiplied with the given factor for the case heat transfer only

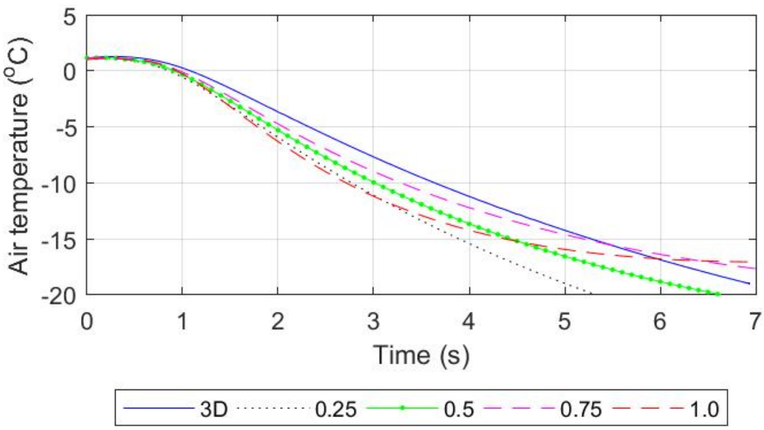

Figure 8 Comparison between 3D simulations and eRHT for which the Nusselt number is multiplied with the given factor for the case with heat transfer and the air is expanding

4 CONCLUSION

The following conclusions are drawn in this paper:

1. Measurements are required to validate the 3D simulation as well as the eRHT model.
2. The Nusselt number used over predicts the heat transfer, since it is for an ideal flat plate situation, which is not the case here.

3. When there is expansion of air, the results of both simulations are very similar. The main difference is caused by using an ideal gas model in the 3D simulations.

The following is recommended:

1. Perform measurements to validate both models.
2. Carry out 3D simulation with a real gas model.
3. Run 3D simulations for a longer period and also for compression to fully validate the eRHT model.

REFERENCE

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