THERMAL-HYDRAULIC STUDY OF SIPHON BREAKING PHENOMENON ON A TWO-PHASE GAS/LIQUID FLOW

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ABSTRACT

While siphon breakers are well known and widely used, the relationship between the undershooting height (defined as the height difference between the siphon breaking device and the final water volume level) and the system design is poorly understood. The system code RELAP5 simulation tool has been tested to assess its ability to correctly predict the undershooting height. The results show the deficiency of such 1D code to correctly predict the stratification in the system piping leading to siphon breaking. This deficiency leads the code to over predict the undershooting height for large siphon breaking diameter.

A typical application of siphon breaker device is nuclear spent fuel pools. Several piping systems are connected to these pools to ensure cooling, cleaning or level control while the stored fuel elements must be protected against fast loss of coolant accident.

The present study extends the simulations performed with RELAP5 to a wide range of designs. It presents a method to conservatively assess the ability of the siphon breaking devices to prevent fuel uncovery in nuclear spent fuel pools. Additionally, the siphon breaking phenomenon has been studied with two-phase gas/liquid flow 2D Computational Fluid Dynamics (CFD) simulations in ANSYS CFX.

Experimental results are compared with simulation results from both 1D system code and CFD. They are discussed to draw conclusions on the driving parameters and on the limits of available computational tools.

KEYWORDS
Siphoning, two-phase flow simulation, Computational Fluid Dynamics (CFD)

1. INTRODUCTION

In the framework of the Stress Tests applied to the Belgian nuclear power plants, it was decided to re-evaluate the siphon breaking devices set on the different systems linked with the spent fuel pools. In case of a break in a pipe connected to the pool and located at a lower level than the stored fuel assemblies, pool siphoning will occur and will lead to an unacceptable uncovery of the fuel assemblies.

In order to avoid this uncovery, siphon breaking devices were installed on all the lines connected to the spent fuel pools. These devices consist in a hole made in the line which, when being uncovered, brings air in the line and, as a consequence, stops the siphoning flow rate.

Depending on the size of the hole, a pool level undershoot (pool level decrease under the level of the siphon breaking device) can be observed. This undershoot has to remain limited to avoid any fuel uncovery.

This paper provides a deterministic conservative evaluation method in order to quantify the pool water level undershoot. The chosen computer code is RELAP5/mod3.3 as it allows to model multiphase flow. Additionally, in order to better understand the phenomenon, 2D Computational Fluid Dynamics (CFD) simulations were performed.

The used models are described. The results issued from the simulations are compared with the experimental data presented in [1]. Final conclusions on the relationship between the siphon breaking device design and its efficiency are given.

2. SIPHON BREAKING PHENOMENON

The siphon breaking phenomenon can be divided in four stages from the break initiation until siphoning stop. These four stages are illustrated in Figure 1 where the siphoning flow rate is plotted as a function of time [1].

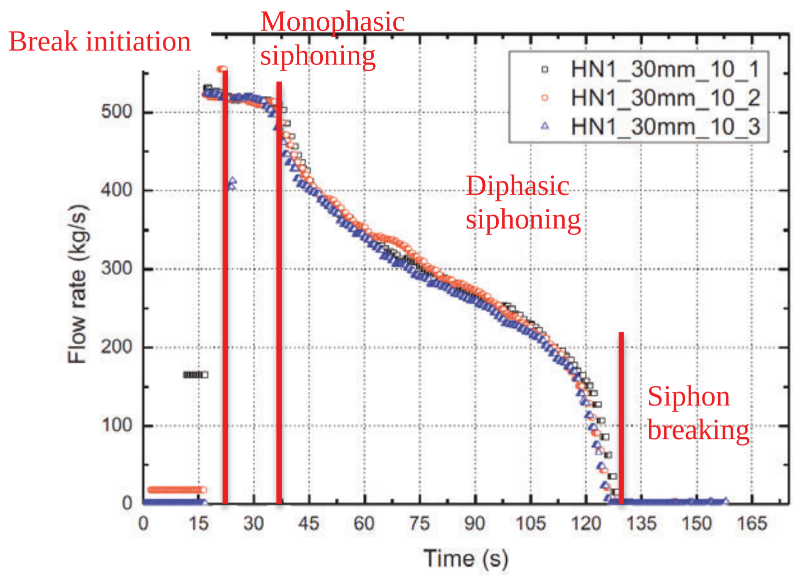


Figure 1. Siphoning flow rate with a siphon breaking device of 30 mm [1].

If a break appears in a line connected to a large pool at a level lower than the pool level, the pool siphoning is initiated whatever the elevation profile of the line.

After a break initiation, the monophasic siphoning phase starts. The siphoning flow rate is a function of the line pressure losses and the available driving head through equation (1). As the pool level decreases, so does the available driving head and the siphoning flow rate decreases.

$$g * \rho * \left(level_{pool}(t) - level_{break}\right) = K \frac{\rho v^2}{2} \quad (1)$$

Where:

g	Gravity Constant [9.81 m²/s]
ρ	Density [kg/m³]
K	Loss coefficient [-]
v	Velocity [m/s]

The pool level decreases until the siphon breaking device is uncovered. From this moment on, air is sucked into the line due to the pressure difference across the siphon breaking device due to both elevation difference and pressure losses. The siphoning flow rate drops as the pressure losses increase due to interphase drag and to an important decrease of the driving head. Indeed, the downward pipe fills up with air reducing the density and so the driving head. However, the siphoning effect is not directly stopped and the pool level keeps decreasing.

During the diphasic siphoning stage, air accumulates in the upper part of the line. This accumulation is a function of both air flow rate at siphon breaking device and of the siphoning flow rate which keeps decreasing with the pool level. As sufficient air is trapped in the upper part of the line, stratification occurs and the pool siphoning stops.

3. USED EXPERIMENTAL DATA

The experimental data are taken from reference [1]. The experimental facility at KAERI is schematically presented in Figure 2. Two different breaks can be initiated at two different levels (named LOCA#1 and LOCA#2 in [1]). Two different siphon breaking devices can be simulated: a siphon breaking hole (located above the pool level) and a siphon breaking line located at the upper part of the line.

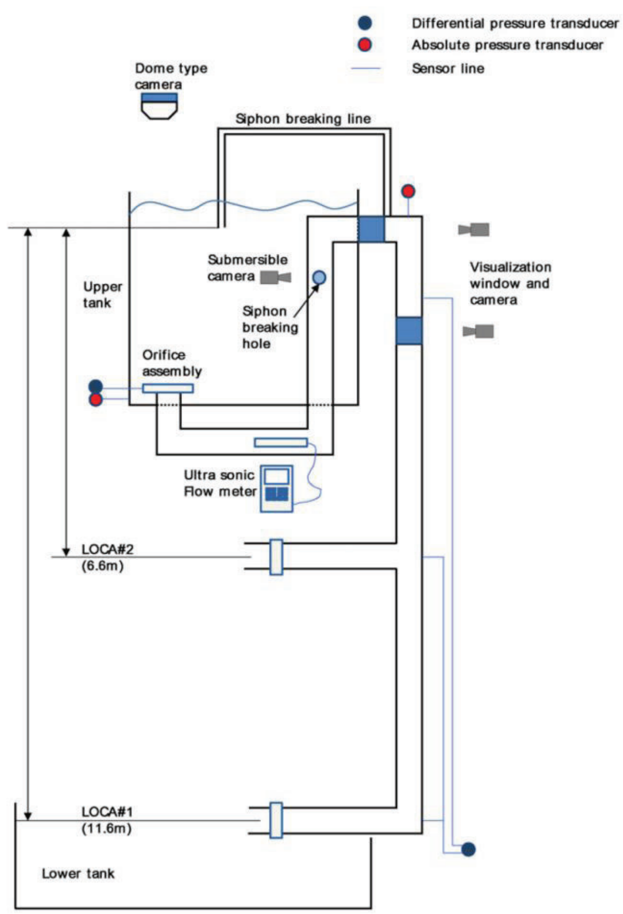


Figure 2. Scheme of the experimental facility [1].

The undershooting height for different siphon breaking devices, diameters and break location can be found in Figure 3 and Figure 4, respectively, of reference [1]. This undershooting height, that measures the siphon breaking efficiency, is defined as the difference between the siphon breaking device level and the final water volume level after the siphoning stop.

Three conclusions can be drawn from these experimental data:

- The efficiency of the siphon breaking device (line or hole) is directly related to its diameter and thus to the amount of air that enters the pipe;
- The efficiency of the siphon breaking device (line or hole) is directly related to the available driving head (height difference between LOCA#1 and LOCA#2); the siphoning flow rate influences directly the repartition between the amount of air entrained and the air trapped in the upper part of the pipe;
- At equivalent diameter, the siphon breaking holes are more efficient; siphon breaking lines induce high pressure losses in the line reducing the air flow rate entering the pipe and thus the efficiency of the siphon breaking device.

4. RELAP5 SIMULATIONS

4.1. Nodalisation

The RELAP5 nodalisation is presented in Figure 3. In this figure, the rectangles are either single volume pipe or branch components. The triangles represent single junction components. The siphon breaking device (hole in the figure presented) is modelled by a cross junction meaning that the air enters by the side of the pipe linking the two "branch" components 4 & 8.

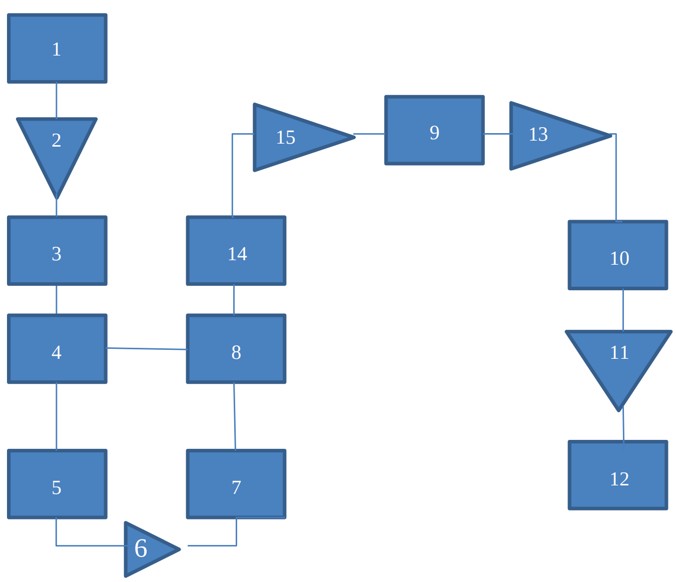


Figure 3. RELAP5 nodalisation scheme.

It is important to notice that the simulations performed show a very little dependence of the undershooting height with the pool area which, thus, can be arbitrarily fixed. The lever triggering the siphon breaking effect is thus more related to the ratio of air and siphoning flow rates than an integral effect during the diphasic flow stage.

4.2. Model and Assumptions

The proposed evaluation method is based on the following assumptions:

- The pressure losses are minimized: the singular pressure losses are not considered;
- The selected choked flow model is the Ransom-Trapp model as proposed in reference [2].

4.3. Results

Figure 4 shows the results obtained for the siphon breaking hole device. These results show that RELAP5 overestimate the undershooting height, which is consistent with simulations results of reference [2]. The main reason for this systemic overestimation is the capture of the flow stratification in the upper part of the pipe. Indeed, the RELAP5 system code compensates its lack of multidimensional capacities by using flow regime maps. With the implemented flow regime maps, the stratification is detected by using flow parameters such as velocity and void fraction. For siphon breaking phenomenon, it appears that the stratification is systematically detected too late.

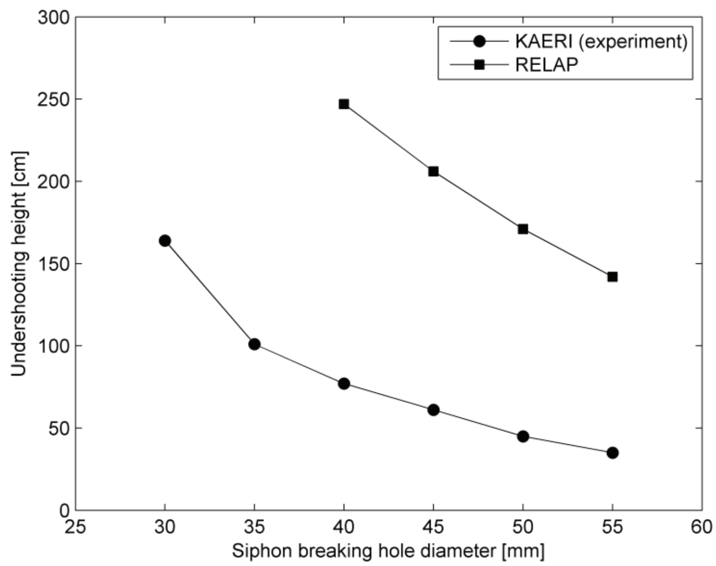


Figure 4. Comparison between experimental data [1] and RELAP5 results.

The developed evaluation method was applied to several geometrical configurations (driving head, piping diameters and siphon breaking diameters). For the cases simulated, the siphoning flow rate ranges from 150 kg/s to 630 kg/s; the siphoning flow rate for the LOCA#1 experimental case is about 500 kg/s [1]. All the simulations performed are shown in Figure 5.

An interpolation of the experimental data shows that the undershooting height depends exponentially on the siphon break diameter (with an exponent of about 2.23). The undershooting height is almost directly related to the surface of siphon breaking hole. The air flow rate being choked, the undershooting height is then almost directly related to the air flow rate considering a constant siphoning flow rate. The RELAP5 simulations and experimental measurements show that the undershooting height is also directly related to the siphoning flow rate.

These two considerations are summarized in Figure 6 where the ratio between the siphoning flow rate at break initiation (function of the available driving head and piping system geometry) and the air flow rate (computed with choked flow relationship and the siphon breaking device diameter) is plotted as a function of the undershooting height. These results are issued from the RELAP5 model. This figure can be used to design a siphon breaking device. For instance, for a piping system for which a break scenario gives a siphoning flow rate of 500 kg/s, the air flow rate needed to limit the undershooting height to 1m is about 0.1% or 0.5 kg/s (see Figure 6). Based on an air choked flow mass flux of 230 kg/s/m² (corresponding to an air pressure of 1 bar), it gives a siphon breaking device diameter of 50 mm.

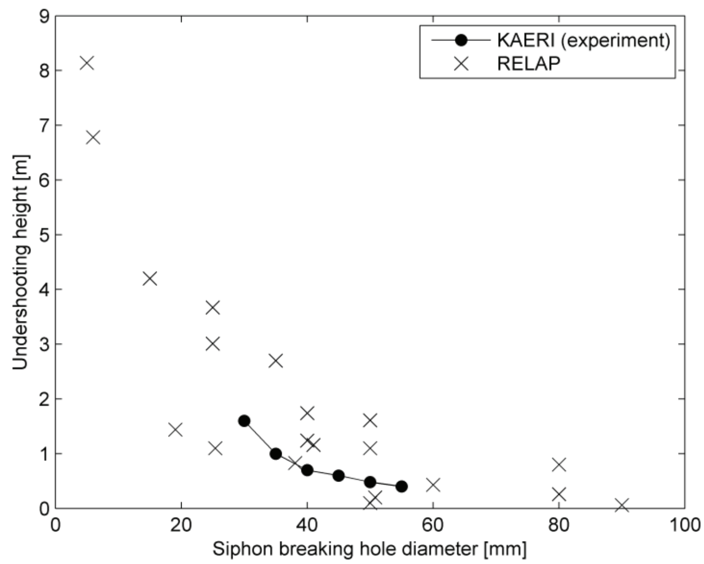


Figure 5. Siphon breaking hole – RELAP5 results.

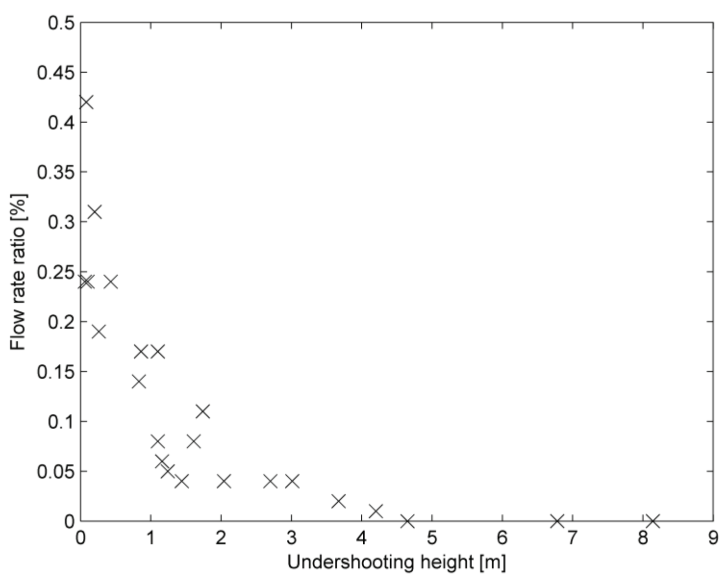


Figure 6. Undershooting height vs. flow rate ratio.

From Figure 6, it appears that a flow rate ratio of 0.1% is a good compromise between siphon breaking efficiency and design. This flow rate ratio value gives an estimated undershooting height between 1 m and 2 m. From this point, the flow rate ratio has to be significantly increased to improve the siphon breaking device efficiency. For instance, decreasing the undershooting height from 2 m to 1 m requires two times more air and thus a siphon breaking device area larger by a factor of 2 and a siphon breaking device diameter larger by a factor of 4.

For the siphoning flow rate range considered in the RELAP5 simulations (150 kg/s to 630 kg/s), a flow rate ratio of 0.1% corresponds to siphon breaking device diameters between 30 mm and 60 mm. If this siphon breaking device is used to protect spent fuel elements in a spent fuel pool, it should be placed within the 1 m of water below the nominal level to guarantee 3 m of water above the fuel elements.

4.4. Parameters Sensitivity

The sensitivity of the results to several simulation parameters has been tested. This analysis is summarized in Table 1. It confirms that the siphon breaking mechanism is related to the air and siphoning flow rates and to the void fraction in the upper part of the pipe.

First the choked flow model shows an important impact. The Ransom-Trapp model has been used for all simulations as advised by [2]. Results obtained with the Henry-Fauske choked flow model shows that the undershooting height is even more overestimated.

The interphase drag model characterizes the friction between the two phases. For the parameters sensitivity, the "no-slip" option has been activated. With this option, the undershooting height shows an increase of 9 cm (6%) when the pressure losses are slightly increased and the void fraction in the upper part of the line modified.

Both tank area and initial level are parameters related to the dynamic of the transient. The outcome of the sensitivity analysis shows that the impact of these parameters on the undershooting height is small.

Table I. Results for parameters sensitivity

Parameter modified	Undershooting height [cm]	Reference value[1] [cm]	Experimental result [cm]
Choked flow model (Henry-Fauske)	194	142	35
Interphase drag	151	142	35
Tank area (200%)	140	142	35
Tank level (+1m)	146	142	35

[1] The reference value is the value computed with the parameters at their nominal value.

5. CFD SIMULATIONS

The siphon breaking phenomenon has been studied with 2D Computational Fluid Dynamics in ANSYS CFX (version 15.0) in order to test the conclusions drawn from the comparison between experimental data [1] and the RELAP5 simulation results.

5.1. Mesh

The mesh (Figure 7) has been refined at the locations considered important for the siphon breaking phenomena:

- At the siphon breaking device where strong velocity and pressure gradients are expected as air is sucked into the pipe.
- At the pipe upper part where flow stratification occurs leading to siphon breaking.
- At the connection between the pipe and the tank. A diaphragm has been installed at this location in order to limit the siphoning flow rate; this diaphragm has been calibrated to obtain a liquid velocity identical to the one measured [1].

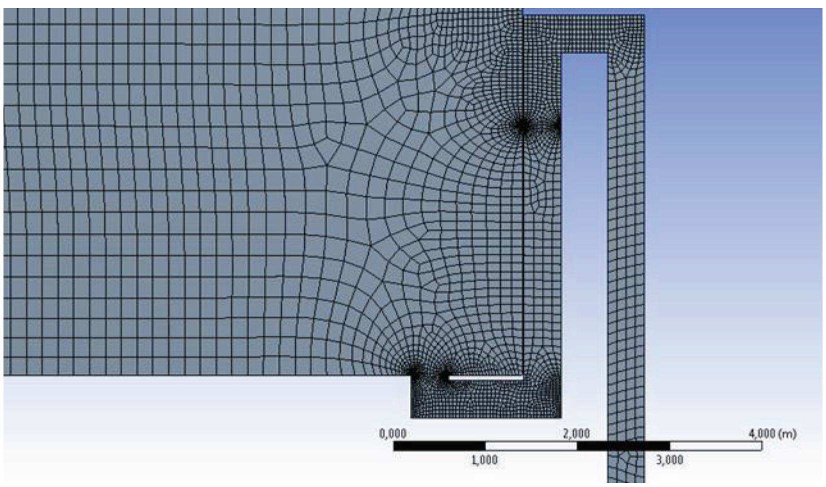


Figure 7. 2D mesh for the CFD analysis of the KAERI experiment.

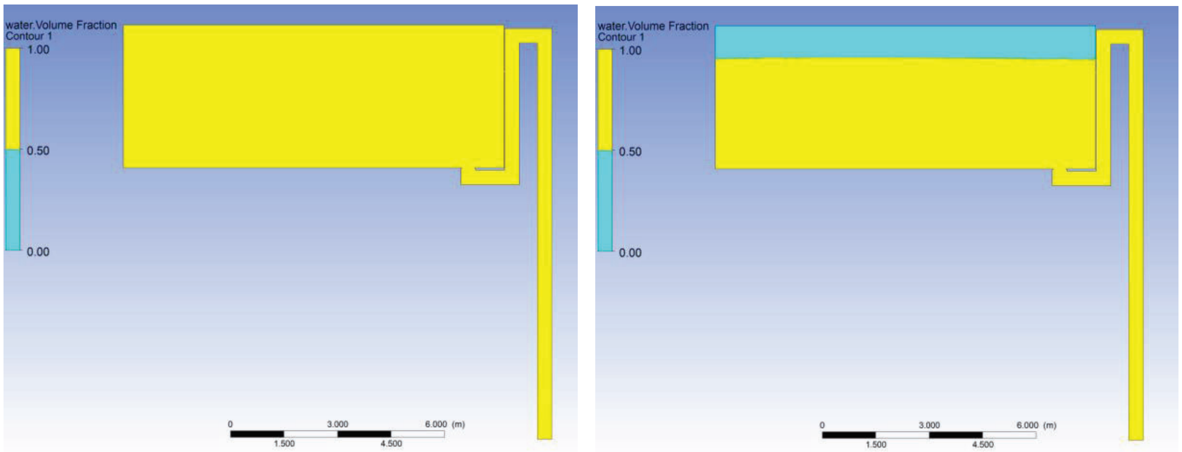
5.2. Models and Boundary Conditions

The opening boundary condition type (allowing both inflow and outflow) has been selected on the top of the tank (volume fraction of water: 0, volume fraction of air: 1, relative pressure: 0 Pa). For the outlet condition, a relative static pressure of 0 Pa was imposed at the lower face of the domain (where the break of the pipe is assumed).

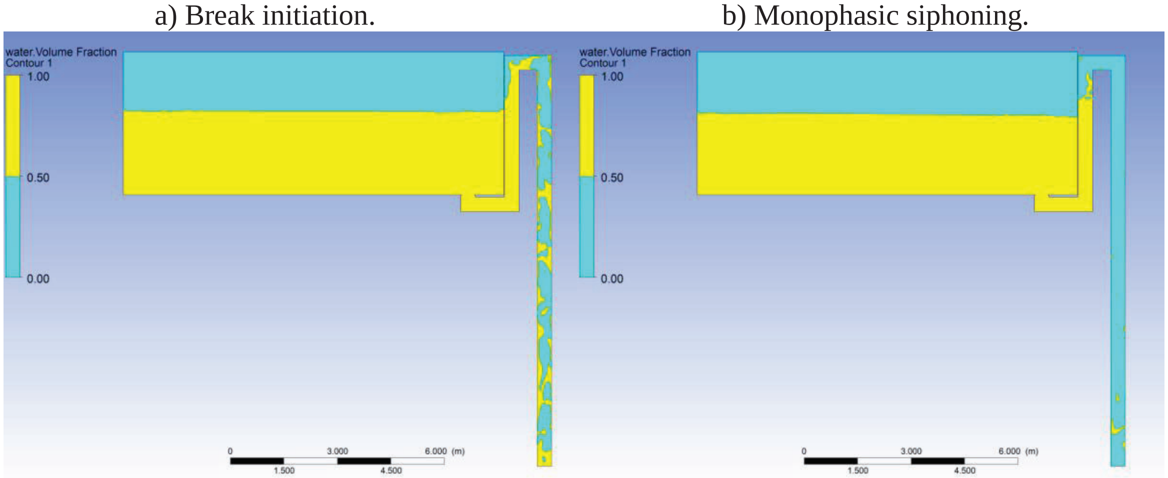
To model the multiphase flow, the Volume Of Fluid (VOF) model has been chosen. It is a surface-tracking technique applied to an Eulerian mesh. In this model, a single set of momentum equations is shared by the fluids, and the volume fraction of the different phases in each computational cell is tracked (in steady or transient mode) throughout the domain. In addition, to reduce the complexity and improve the calculation, the homogeneous option has been activated meaning that both phases share the same velocity field. This assumption is equivalent to the "no-slip" assumption used in the RELAP5 sensitivity analysis (Table 1). It has been found that this assumption has a limited impact on the results (+6% on the computed undershooting height).

5.3. Results

Figure 8 presents the volume fraction profile (yellow liquid phase, cyan gas phase) at 4 different time steps showing the 4 different siphoning stages: break initiation, monophasic siphoning, diphasic siphoning and siphon breaking.



a) Break initiation. b) Monophasic siphoning.



c) Diphasic siphoning. d) Siphon breaking.

Figure 8. Volume Of Fluid evolution during siphon breaking.

Figure 9 shows a comparison between the undershooting height obtained with both RELAP5 (see §4.3) and CFD simulations and the experimental data [1]. This comparison is performed for the siphon breaking device diameter range considered for the experimental measurements.

With this 2D CFD analysis, the undershooting height is systematically under estimated and does not show the expected sensibility with respect to the siphon breaking hole diameter. The computed undershooting height is close to the experimental results especially for the largest siphon breaking diameter. Using both a non-homogeneous model and 3D simulation shall improve this agreement further.

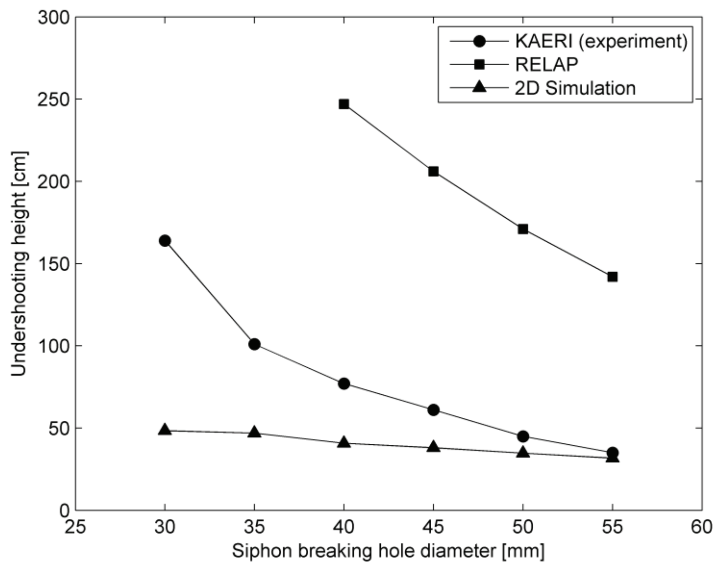


Figure 9. Comparison between experimental data, RELAP5 and CFD simulation results.

Finally, the influence of the tank area has been analyzed. The results are presented in Figure 10. It comforts the conclusion drawn in §4.4, that the tank area has a very limited impact in the results. The dynamic of the transient is not a driving parameter for the undershooting height, the latter being fixed by the ratio between the air and siphoning flow rate. However, as the 2D CFD model shows a low sensibility (see Figure 9), this conclusion should be confirmed by additional experimental results.

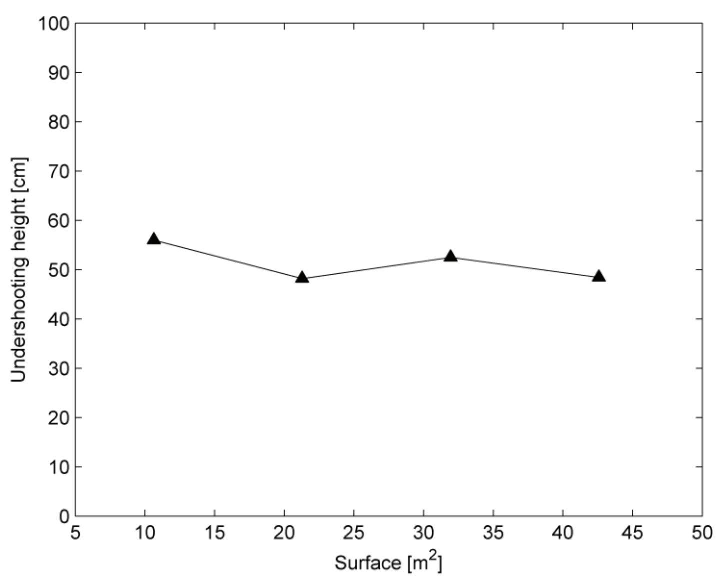


Figure 10. Influence of the tank area – CFD results.

6. CONCLUSIONS

The siphon breaking phenomenon has been analyzed with the 1D system code RELAP5/mod3.3 and 2D Computational Fluid Dynamics in ANSYS CFX. The obtained results were compared to experimental data referenced in [1].

From this comparison, it can be concluded that:

- The Henry-Fauske choked flow model implemented in RELAP5 is not appropriate for siphon breaking simulation; this conclusion is consistent with reference [2];
- The evaluation method developed with the RELAP5 1D system code overpredicts the undershooting height even if it shows a comparable trend;
- Using 2D CFD analysis leads to results close to the experimental ones especially at large siphon breaking hole diameter but with a different sensibility with respect to this diameter; this agreement shall be improved further with a 3D model.

The RELAP5 evaluation method has been applied to several configurations (siphoning flow rate, siphon breaking device design). Additionally, a sensitivity analysis on a set of parameters has been performed. From all these simulation results, it can be concluded that:

- The leading parameters for siphon breaking are the air and siphoning flow rates. If the air flow is choked, the air flow rate is directly related to the siphon breaking device flow area; therefore, the siphon breaking device efficiency is proportional to the square of its diameter;
- The siphon breaking efficient can be directly related to the ratio between air and siphoning flow rates;
- In the range of a siphon flow rate between 150 and 630 kg/s, a flow rate ratio of 0.1% leads to a siphon breaking device with a reasonable design (30 mm to 60 mm, representing about 20% of the considered piping diameter) with an undershooting height limited to maximum 2 m (conservative evaluation according the RELAP5 evaluation method);
- The siphon breaking efficiency is not related to the dynamic of the transient (initial level, water volume area …).

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