Modelling of a converging/diverging tube using CATHARE-3 two-phase flow system code for sodium cavitation studies

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Abstract. For reactor design and safety purposes, the French Alternative Energies and Atomic Energy Commission (CEA) is currently working on Sodium Fast Reactor (SFR) thermal-hydraulics. A SFR is a system composed of three circuits (primary and secondary: liquid sodium and tertiary: nitrogen gas or water) and designed to both produce electricity and optimize nuclear fuel cycle. In such SFR systems, primary pumps are associated as a parallel circuit. Then, throughout primary pump seizure transients, cavitation may occur in non-affected pumps because of the induced hydraulic resistance drop. Studying sodium flow cavitation occurring in simple geometries such as a Venturi tube (converging/diverging tube) is the first step to better understand the phenomenon and its sensitivities. The long term aim is to validate the flashing model used for sodium applications in the CATHARE-3 code in order to be confident when simulating more complex geometries. In this article, a Venturi tube test section experimented in the CANADER facility at CEA Cadarache in the 1980s and its modelling are presented. Cavitation is obtained by flow rate variation at fixed tank pressure and circuit temperature conditions. Several computations are made in order to study the sensitivity of results to numerical and physical parameters. A set of parameters supposed to constitute the most representative case is defined and comparison of the predicted Thoma number against the experimental one is made. Detailed results of quantities of interest as profiles along the test section and evolutions during the transient are also presented.

1. Introduction

1.1. Context of sodium flow cavitation studies
The cavitation phenomenon occurs in liquids when the local static pressure drops below the vapor pressure. Cavitation has been widely studied using water as working fluid. Liquid metal cavitation is less known because experiments are much more expensive and difficult to operate. First interest on sodium cavitation came out in the 1950s in the United States with the aircraft nuclear powerplant project [1]. In France, sodium cavitation started to be studied in the 1970s in the frame of Sodium-cooled Fast neutron breeder Reactors (SFR). At CEA Cadarache in particular, Courbiere et al [2] [3] [4] [5] [6] [7] [8] worked on the CANADER sodium cavitation tunnel. Various types of test section geometries were tested in this facility: diaphragm, Venturi tube, hydrofoil or cylinder types. More recently (2008-2011) but still linked to SFR thermal-hydraulic studies, Japan has made a research effort on sodium cavitation with the work of Ardiansyah et al on a Venturi tube [9] [10] [11] [12] [13]. Today, France is still working on
SFR thermal-hydraulics with the design of ASTRID 4th reactor generation demonstrator [14]. High flow rates involved in such reactors can lead to cavitation occurrence in pumps or orifices in incidental or accidental operating conditions. For this reason, several experimental tests on the Venturi tube test section geometry of CANADER were modelled with the two-phase flow thermal-hydraulic code CATHARE-3, which is the reference thermohydraulic system code for french SFR safety studies. A comparison of computation results and experimental data of these cavitation inception tests is presented in this paper.

1.2. Objectives of the study and method

Objectives of this study are the following:

- identify main parameters affecting sodium flow cavitation phenomenon
- model sodium cavitation in a Venturi tube geometry
- extend CATHARE-3 flashing model validation for sodium applications

To reach these goals, the Venturi tube test section experimented in the CANADER loop has been modelled with CATHARE-3 and validation has been made on the Thoma number corresponding to cavitation inception obtained for several pressure and temperature conditions.

2. Description of the experimental setup

2.1. The CANADER facility

CANADER is a sodium loop whose scheme is shown on figure 1. It has the following boundary operating conditions:

- Temperature: 200 °C to 600 °C
- Flow rate: 1 to 7 l/s
- Downstream vessel argon pressure: 1.15 to 5 absolute bars
Flow rate is controlled with an electromagnetic pump and the maximal pressure generated at pump outlet is 8 absolute bars. Minimum downstream vessel argon pressure is 1.15 absolute bars (a bit greater than atmospheric pressure) to limit oxygen admission in the circuit.

The experimental test matrix of temperature and pressure conditions tested on the Venturi tube geometry of CANADER and associated Reynolds numbers (corresponding to the cavitation inception flowrates) are presented in table 1.

### Table 1. Sodium test matrix and corresponding Reynolds number (see below for Re definition).

| P (bar) | T (°C) | 1.15 | 2.5 | 4 |
|---------|--------|------|-----|---|
| 545     | 9.48e+05 | 1.40e+06 | 1.76e+06 |
| 450     | 8.41e+05 | 1.23e+06 | 1.55e+06 |
| 350     | 7.10e+05 | 1.04e+06 | 1.31e+06 |
| 250     | 5.66e+05 | 8.28e+05 | 1.05e+06 |

2.2. The Venturi tube test section geometry

The test section is composed of:

- a profiled converging tube with a ratio of 27 between the inlet tube section and the throat section which is about 2cm².
- a cylindric throat
- a conic diverging tube characterized by a half-angle of 7°

2.3. Obtaining cavitation in CANADER facility

In CANADER facility, cavitation is obtained following this method:

- fluid temperature is stabilized in the whole circuit
- gas pressure in the downstream vessel is kept constant
- cavitation phenomena is obtained only by acting on flow rate.

Starting from a non-cavitating state, flow rate is gradually increased until the onset of cavitation.

The Thoma number and the Reynolds number are respectively used to characterize the onset of cavitation and the hydraulic conditions:

\[ \sigma = \frac{P_{us} - P_{sat}}{\frac{1}{2}\rho LV_L^2} \]  

\[ Re = \frac{\rho LV_L D_{throat}}{\mu_L} \]

*Figure 2. Venturi tube.*

- \( P_{us} \) is the absolute static pressure measured upstream from the throat
- \( P_{sat} \) is the saturation pressure
- \( \rho_L \) and \( \mu_L \) respectively are the density and the dynamic viscosity of the liquid
- \( V_L \) is the average velocity of the liquid through the throat
- \( D_{throat} \) is the diameter of the Venturi tube throat

3. Modelling

3.1. Description of the CATHARE-3 thermal-hydraulic code

CATHARE-3 is a french two-phase flow modular system code. It is owned and developed since 1979 by CEA and its partners EDF, Framatome and IRSN. See [15] for more details on the code development and validation strategy. One-dimensional (1D), three-dimensional (3D) or point (0D) hydraulic elements can be associated together to represent a whole facility. Thermal and hydraulic submodules (as warming walls, valves, pumps, turbines...etc) can be added to main hydraulic elements respectively takes into account thermal transfer, flow limitation, pressure
rise or pressure drop. Six local and instantaneous balance equations (mass, momentum and energy for each phase) make possible liquid and gas representation for transient calculations. By this way, mechanical and thermal disequilibrium between phases can be represented [16]. Phase average make necessary the use of physical closure laws in the balance equations system. One closure law concerns the flashing model, which is presented by Bestion in reference [17]. Cavitation and flashing correspond to the same phenomenon which is a phase change from liquid to vapor when pressure drops locally or in the whole system.

The CATHARE-3 flashing model contains two parts:

- a part existing with or without the presence of non-condensable (NC) gas, depending on the liquid phase Reynolds number and on the difference between the liquid temperature $T_l$ and the saturation temperature $T_{sat}(P)$.
- a part existing only in the presence of NC gas which tends to facilitate the vapor creation in this case.

3.2. Venturi tube modelled with CATHARE-3
The converging/diverging tube is modelled using a 1D hydraulic element. The choice of a 1D mesh implies one direction allowed for liquid and gas velocities but two possible ways (positive or negative). That means that the flow is radially averaged. Several meshings have been tested in this study (see paragraph 4.3.1). The meshing presented on figure 3 is composed of 50 cells.

Two boundary conditions (BC) are defined:

- an inlet BC (down) which imposes fluid velocity and temperature (for both liquid and gas even if gas phase is residual) and void fraction as functions of time.
- an outlet BC (up) which imposes static pressure as a function of time.

4. Validation against experimental data
4.1. Available experimental data: Thoma number as a function of the Reynolds number
Liquid sodium is an opaque fluid and as a result cavitation cannot be observed with the naked eye. Acoustic methods are used to detect cavitation inception either for small test sections or for a whole SFR. First cavitation detection acoustic method was used in 1957 by Robertson et al [18]. The sigma definition used below corresponds to cavitation inception and to the first change of slope in acoustic characteristics [7]. The $\sigma$-$Re$ graph on figure 4 was obtained by Courbiere et al in the 1980s by experimenting the Venturi tube test section in the CANADER loop and in another loop called CALYPSO. Indeed, all test section geometries were also tested with water as working fluid in the CALYPSO loop [3]. In the present paper only sodium tests are compared to computations. Sodium-water similarity will be studied in the next future.
4.2. CATHARE-3 transient defined to obtain the σ-Re graph

For each pressure-temperature (P-T) couple of conditions, a CATHARE-3 computation is run. As explained in the paragraph 3.2, temperature is imposed as an inlet BC and pressure is imposed as an outlet BC. Both are kept constant during the calculation. Fluid velocity (directly linked to flow rate) is imposed at the inlet BC and gradually increased to obtain cavitation.

The onset of cavitation is detected with a condition on the void fraction reaching a threshold noted $\alpha_{thr}$ at the end of the Venturi tube throat. When this condition is verified, fluid velocity is kept constant at its last value corresponding to cavitation inception.

Some physical parameters have to be defined to run calculations:

- $\alpha_{thr}$ is the void fraction threshold used to detect cavitation inception (value between 0 and 1).
- AVAP is the void fraction imposed at the inlet BC (value between 0 and 1).
- XARGON is the fraction of argon NC gas if defined in the computation (value between 0 and 1).
- model is the flashing model type used in the computation.
- rugosity is the pipe rugosity used in the computation.

Numerical parameters also have to be defined:

- Ncell is the number of cells used to model the Venturi tube test section. All cells along the Venturi tube have the same length noted $dz$.
- DTMAX is the maximal allowed duration of a time step during the calculation (in seconds).

In the following paragraph, sensitivity studies are made by varying these parameters. First, numerical parameters are tested and a reference set of numerical parameters is chosen according to mesh and time convergence results. Second, physical parameters are tested and a case as representative of the real experiment as possible is defined.
4.3. Numerical sensitivities

The order of magnitude of cells’ lengths used in CATHARE-3 calculations varies in general from 10cm to 1mm. Here, cells’ lengths from $2.4 \times 10^{-2}$ cm (25 cells) to $0.6 \times 10^{-3}$ mm (1000 cells) are tested in order to evaluate mesh convergence of calculations (section 4.3.1).

A standard value of $\text{DTMAX}$ used in CATHARE-3 calculations is 1s. Two other values are tested here: 0.1s and 0.01s in order to evaluate time convergence of calculations (section 4.3.2).

The numerical sensitivity tests matrix is the following:

| Case name | $\alpha_{th}$ | AVAP | XARGON | model | rugosity | Ncell | DTMAX |
|-----------|---------------|------|--------|-------|----------|-------|-------|
| m25dt1    | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 25    | 1.    |
| m50dt1    | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 50    | 1.    |
| m100dt1   | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 100   | 1.    |
| m150dt1   | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 150   | 1.    |
| m200dt1   | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 200   | 1.    |
| m250dt1   | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 250   | 1.    |
| m300dt1   | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 300   | 1.    |
| m500dt1   | $10^{-2}$     | $10^{-3}$ | 0.     | rev1  | standard | 500   | 1.    |
| m1000dt1  | $10^{-2}$    | $10^{-3}$ | 0.     | rev1  | standard | 1000  | 1.    |
| m100dt0.1 | $10^{-2}$    | $10^{-3}$ | 0.     | rev1  | standard | 100   | 0.1   |
| m100dt0.01| $10^{-2}$    | $10^{-3}$ | 0.     | rev1  | standard | 100   | 0.01  |

Table 2. Numerical sensitivities tests matrix.

4.3.1. Mesh convergence

To test the mesh convergence, computations using 25, 50, 100, 150, 200, 250, 300, 500 and 1000 cells are run with other parameters kept constant. Results are available on figure 5 representing the calculated Thoma number for one computation (350°C-4bars case) as a function of the cell length logarithm. Results are slightly sensitive to the defined mesh. A convergence is obtained by refining the meshing, what is satisfactory.

The case using 100 cells, with a relative error of 0.2% compared to the case using 1000 cells, is applied for all other following computations.

4.3.2. Time convergence

CATHARE-3 is an implicit code which means that the time step duration is calculated and adapted by the code itself during the computation. $\text{DTMAX}$ is the maximal time step duration allowed, which is imposed by the user. To test the time convergence, computations using a $\text{DTMAX}$ value of 1, 0.1 and 0.01 seconds are run for the 100-cell case. A maximal time step duration of 1s seems to be sufficient according to the results obtained on the global $\sigma$-$Re$ graph on figure 6.
Indeed, 1s, 0.1s and 0.01s DTMAX computations are superimposed. For this reason, the larger DTMAX value of 1s is chosen for all the following computations.

4.4. Physical sensitivities
The effect of varying physical parameters is analyzed here. Concerning the NC gas presence, from Courbiere [7] it can be considered that the minimal and maximal realistic NC rates respectively are $5 \times 10^{-6}$ and $3 \times 10^{-4}$ cm$^3$Ar/cm$^3$Na.

In this study, the argon volumetric concentration is assumed to correspond to the AVAP void fraction defined as gas volume divided by total volume. Indeed, the argon volume is negligible compared to the sodium volume. The minimal value of NC gas presence that can be modelled is the residual one ($10^{-5}$) which has no effect by definition. Above this residual value, an effect of NC gas presence is expected.

### Table 3. Physical sensitivities tests matrix.

| Case name         | $\alpha_{thr}$ | AVAP   | XARGON | model | rugosity | Ncell | DTMAX |
|-------------------|----------------|--------|--------|-------|----------|-------|-------|
| m100dt1           | $10^{-2}$      | $10^{-5}$ | 0.     | rev1  | standard | 100   | 1     |
| m100dt1mod        | $10^{-2}$      | $10^{-5}$ | 0.     | rev3  | standard | 100   | 1     |
| m100dt1rug45      | $10^{-2}$      | $10^{-5}$ | 0.     | rev1  | 45.10^{-6} | 100   | 1     |
| m100dt1rug152     | $10^{-2}$      | $10^{-5}$ | 0.     | rev1  | 152.10^{-6}| 100   | 1     |
| m100dt1thr        | $10^{-4}$      | $10^{-5}$ | 0.     | rev1  | standard | 100   | 1     |
| m100dt1aliq       | $10^{-2}$      | 3.10^{-4}  | 0.     | rev1  | standard | 100   | 1     |
| m100dt1aliqNC     | $10^{-2}$      | 3.10^{-4}  | 1 - 10^{-6} | rev1 | standard | 100   | 1     |
| m100dt1aliqNCval  | $10^{-2}$      | 3.10^{-4}  | 1 - 10^{-5} | rev1 | standard | 100   | 1     |

4.4.1. Sensitivity to the threshold value
A sensitivity to the threshold value ($\alpha_{thr} = 10^{-2}$ or $10^{-4}$) has been conducted. Results are not sensitive as shown on figure 7 (m100dt1thr vs m100dt1), then, the value of $\alpha_{thr} = 10^{-2}$ is kept in the following.

4.4.2. Sensitivity to the void fraction without NC gas
A sensitivity to the void fraction imposed at inlet BC without presence of NC gas (AVAP = $10^{-5}$ or $3.10^{-4}$ with XARGON=0, in both cases) has been conducted. Results are not sensitive to this parameter without NC gas presence as shown on 7 (m100dt1aliq vs m100dt1).
4.4.3. Sensitivity to the presence of NC gas  A sensitivity to the presence of NC gas imposed at inlet BC (XARGON=0. or XARGON=1−10−6 with AVAP = 3.10−4 in both cases) has been conducted. Two high-T and low-P tests donnot converge in the presence of NC gas (545 and 450 °C at 1.15 bars). This remains to be analyzed. Results are really sensitive to the NC gas presence as shown on figure 7 (m100dt1aliqNC vs m100dt1). It is a important parameter to take into account in sodium cavitation studies, what was also identified by Courbiere [7].

4.4.4. Sensitivity to the argon rate value  The argon rate value XARGON cannot be set exactly to 1 (which means 100% of gas phase) because residual sodium vapor phase always exists in CATHARE-3 two-phase computations for numerical reasons. The effect of defining a XARGON value to 1−10−6 or 1−10−5 is investigated here (m100dt1aliqNC vs m100dt1aliqNCval). Results presented on figure 7 show a little dependence on the value of XARGON. Consequently, the value of 1−10−6 is kept in the following.

4.4.5. Sensitivity to the flashing model  The default flashing model used in all calculations of this study is the one developed for water applications (see [17] for its expression). But, in the frame of SFR thermalhydraulics studies, the CATHARE development team at CEA proposed to modify two constants of the initial flashing model in order to better represent sodium flow conditions. On figure 8, results of the Thoma number prediction using the modified sodium flashing model are compared to those using the initial flashing model (m100dt1mod vs m100dt1).

In this cavitation inception study, the modification of the two constants in the flashing model seems to have a negligible influence on results. Currently, there is a lack of data allowing to validate correctly flashing models for sodium applications. Depressurization validation cases need to be experimented in support of model development.

4.4.6. Sensitivity to the rugosity  Pipe rugosity impacts the pressure drop along the test channel by influencing the wall friction coefficient. For this reason, a sensitivity to the rugosity is conducted here. Results using two absolute rugosities of 45.10−6 m (stainless steel) and 152.10−6 m (galvanized steel) [19] are compared to results using the classical CATHARE-3 model that corresponds approximately to an absolute rugosity of 1.5.10−6 m in this range of Reynolds number. Results presented on figure 9 show a great sensitivity to the pipe rugosity.

In the following, the value of 45.10−6 m is kept as it is the most plausible rugosity of the test channel because sodium facilities often are composed of stainless steel.
4.5. Detailed results of the most representative case

Considering the sensitivity studies conducted and physical considerations mentioned previously, the following representative case is defined:

| Case name  | αthr | AVAP | XARGON | model | rugosity | Ncell | DTMAX |
|------------|------|------|--------|-------|----------|-------|-------|
| representative | 10^{-2} | 3.10^{-4} | 10^{-6} | rev1 | 45.10^{-6} | 100 | 1 |

Comparison of computation results of the most representative case to experimental data is made here. Scale boundaries of initial experimental graph are defined but scaling is linear instead of 2-logarithmic. Difference between the two scalings is small in this case. The experimental line represented in the experimental graph has been reproduced on figure 10. Globally, results are underestimated of approximately 13% compared to experimental data. However, the qualitative quasi-flat trend of the σ-Re curve is respected.

Additionally to the global σ-Re curve, detailed profiles and evolutions of main physical quantities are presented in the following. Evolutions of the inlet velocity and the void fraction at the end of the Venturi tube throat are available on figures 11 and 12 for each P-T couple of conditions. Pressure and void fraction profiles obtained at the end of the transient are presented on figures 13 and 14. It can be seen on figure 11 that for higher pressure conditions, flow rate has to be more increased to obtain cavitation inception. When cavitation is detected, flow rate is kept constant and void fraction stops rising, what can be observed on figure 12.

On the pressure profiles presented figure 13, the Venturi tube slope can be easily recognized: static pressure drops when reaching the converging part of the tube, then slightly decreases due to wall friction at high velocity, and finally increases in the diverging part of the Venturi tube.
Figure 13. Pressure profiles (see figure 14 for legend).

The detection of cavitation is made at the end of the Venturi tube throat, where the void fraction is maximal (figure 14). Void fraction profiles are similar for each couple of conditions. Finally, evolutions of the Thoma number for each $P$-$T$ couple of conditions as a function of time are presented on figure 15. What can be concluded from all these detailed results is that temperature seems to have a small effect on cavitation inception flow rate instead of pressure for this Venturi tube test case. That was expected because the sodium saturation pressure is low-depent on temperature below 600°C. Temperature play a role just by modifying sodium density and viscosity and associated Thoma and Reynolds numbers, and by influencing argon solubility and diffusivity. Geometry of the test section defines also the type of cavitation which takes place (profile cavitation or swirl cavitation). In the case of a Venturi tube geometry, cavitation may take place on the throat edge and does not depend on temperature as much as the orifice geometry [7].

Conclusions and perspectives
The objective of the present study is to identify main parameters affecting sodium cavitation phenomenon. Water cavitation occuring in Venturi tubes has been well studied in the past, but experimenting sodium loops is much more difficult and expensive, which explains the lack of available experimental data on the subject. The CANADER facility operated in the 1980s at CEA Cadarache has been presented in this paper and the tests experimented on the Venturi tube geometry have been modelled using the CATHARE-3 two-phase flow thermalhydraulic code. Numerical and physical sensitivity tests have been respectively conducted to better control the modelling and evaluate the effect of parameters on the predicted Thoma number. The Thoma number corresponding to cavitation inception and its dependence on the Reynolds number has been studied. Profiles along the test section and evolutions during the transient of quantities of interest have been presented. Perspectives of this work are the following: (1) taking into account singular pressure drops at abrupt area changes in the modelling could lead to greater Thoma numbers and ameliorate results; (2) studying water-sodium similarity by simulating the CALYPSO tests on the same Venturi tube test section geometry.
Nomenclature

**Acronyms**

| Symbol | Description |
|--------|-------------|
| ASTRID | Advanced Sodium Technological Reactor for Industrial Demonstration |
| BC | Boundary Condition |
| CATHARE | Code for Analysis of THERmalhydraulics during an Accident of Reactor and safety Evaluation |
| CEA | French Alternative Energies and Atomic Energy Commission |
| CPU | Central Processing Unit |
| EDF | Electricité De France |
| IRSN | Institut de Radioprotection et de Sûreté Nucléaire |
| NC | Non-Condensable |
| SFR | Sodium Fast Reactor |
| xD | x-dimensional |

**Subscripts**

| Subscript | Description |
|-----------|-------------|
| L | liquid |
| sat | saturation |
| thr | threshold |
| us | upstream |

**Latin letters**

| Letter | Description |
|--------|-------------|
| D | Diameter |
| dz | Cell length |
| P | Pressure |
| Re | Reynolds number |
| T | Temperature |
| V | Fluid velocity |

**Greek letters**

| Letter | Description |
|--------|-------------|
| α | void fraction |
| µ | dynamic viscosity |
| ρ | density |
| σ | Thoma number |

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