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Assessment of the CATHARE Code over SUPERCLAUDIA tests for a jet in a liquid water pool

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ABSTRACT

Steam injection into a sub-cooled pool is an attractive phenomenon due to its high thermal transfer capacity and since many years, it is an important subject of studies. Several applications exist for both industrial and nuclear heat removal systems, such as suppression pools and depressurization systems. In this context, accurate prediction of the mass and energy liquid-gas exchanges such as in the Direct Contact Condensation (DCC) is a significant research effort in nuclear thermal hydraulics. The understanding of these transfers is therefore critical in order to predict system behavior, particularly under accidental conditions. Several experiments have been carried out over the years to investigate the physics and characteristics of direct condensation phenomenon and the steam water exchanges; specifically, the results of SUPERCLAUDIA experiment are presented in this work. The investigation of the involved physics and the validation of the employed CATHARE system code are presented hereafter. The direct condensation of the vapor jet in the liquid pool, the heat exchange at the free surface or the bubble vapor rise dynamics are so investigated. A comparison of simulated and calculated results reveals some differences. The challenge for codes is modelling the corresponding multiscale physics. This paper discusses the significant modelling effort required to improve the CATHARE code, as well as the need to understand the relationship between small- and large-scale phenomena. The use of a CFD code is planned to complete the system scale modelling.

KEYWORDS

Cathare, thermal hydraulics, steam injection, Direct Contact Condensation, nuclear safety

1. INTRODUCTION

The understanding of the efficiency of a vapor jet in a liquid water pool involves a good comprehension of several phenomena occurring during this transient. A good prediction of the jet shape and the corresponding penetration length, the heat transfer on the jet contour and the following direct condensation [1] or the mixing efficiency in the pool and the resulting thermal stratification [2,3] is as challenging as crucial. Several industries employ components based on this configuration since its high heat transfer capacity and the good prediction of all these phenomena allows industries to better design component and optimize associated systems. Therefore, several experimental campaigns [4 - 7] have been proposed in the world to better investigate these aspects trying to propose some models or improve CFD codes [8, 9].

For the direct condensation phenomenon, even if widely investigated, it seems that no global model exists to predict accurately enough the different behaviors and dedicated studies are often necessary. Some efforts are made to classify the condensation regime maps trying to identify a specific condensation behavior depending on particular boundary conditions. In most cases, authors [10 - 14] conducted experiments focusing on the impact of the water sub-cooling and the injected mass. Others proposed an extension on multidimensional maps in which the dependence of other characteristic parameters is taken into account. For instance, Petrovitch [13] studies the impact of the injection jet diameters and Wu et al. [14] the dependence on the inlet to the exit pipe pressure ratio.

The study presented in this paper aims to evaluate the prediction capability of the system CATHARE code on the direct contact condensation in the subcooled pool at low-pressure condition. To do that, SUPERCLAUDIA [15] experiments are analyzed. In the '90, the French Atomic Energy Commission (CEA) performed an experimental campaign aimed to investigate the efficiency of a depressurization system. This system was designed to control the PWR primary pressure and avoid a possible in-pressure core melt accident. It consisted in a valve located at the top of a pressurizer, discharging in a water pool placed inside the nuclear containment (IRWST: In Reactor Water Storage Tank). Pool pressure was closed to one bar and the water volume corresponded to five m³.

This paper presents a first comparison of CATHARE code [16] simulation against one experimental test of the SUPERCLAUDIA campaign. The first section of the paper describes the facility and the test matrix. The second part is focused on the CATHARE code description and modelling. Results and future perspectives are presented and discussed in the last section.

2. SUPERCLAUDIA EXPERIMENTS

Experiments were performed in SUPERCLAUDIA test facility [15], at CEA Cadarache, France. Purpose was to perform a series of tests aimed to better investigate the direct contact condensation and in particular the condensation efficiency. The system apparatus consists of - a steam generator, used as a pressurizer to generate saturated steam at constant pressure, - a cylindrical open pool (2.5 m of diameter and 1.6 m of height) filled with subcooled water and representing the IRWST volume and - a pipe line used to discharge saturated steam into the pool. The water level in the pool is generally fixed at about one meter. As shown in Figure 1, the experimental facility was equipped with several instrumentations. Five racks of four thermocouples are fixed in the water pool to measure the thermal stratification. Three pressure transducers are placed on the jet axis to investigate the pressure fluctuation in this area and the mass flowrate was measured by a vortex flowmeter in the pipe. The efficiency of the condensation is assessed starting from the weight of the pool using three load cells while cameras are fixed close to the pool to observe the condensation area in the water pool [15].

Sixteen tests are performed in the test facility to evaluate the impact of the different parameters as the nozzle shape, the injection pressure or the initial water pool level against the condensation phenomena.

During the test, a constant steam flowrate is drawn from the pressurizer into the water pool through a nozzle submerged for about 0.4 meters. A fraction of the vapor jet immediately condenses in the subcooled liquid pool. The remaining steam rises at the liquid/gas surface in the form of vapor bubbles. The liquid/gas surface represents the free interface between the liquid pool and the atmosphere. In time, the mass of condensed steam in the pool increases as well as the pool temperature. Condensation stops when the temperature reaches the saturation value. Experiments finish at this condition. Pressure and temperature measurements are performed in the pressurizer, discharge line, and the pool.

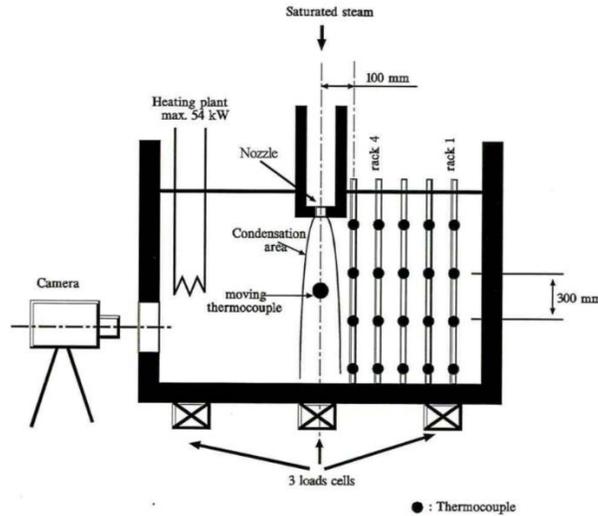


Figure 1. SUPERCLAUDIA pool instrumentation.

3. CATHARE SIMULATION

The system CATHARE code is a multi-fluid thermal-hydraulic system code [16] capable of simulating thermal phenomena occurring in the PWRs. As shown in Figure 2, SUPERCLAUDIA facility is modeled by a 0D component corresponding to a volume element and two junctions/connections lines (green line). The pool is so connected to the steam injection and the external ambient conditions. The steam injection (vapor flowrate, temperature and void fraction) and the ambient conditions (ambient pressure and temperature) are fixed via specific boundary conditions (BC). As discussed in the next paragraph, no thermal stratification is observed during the experiment. This is why a CATHARE volume element is chosen to represent the water pool (the 0D component averages the liquid and gas temperature since no mixing velocity is calculated).

For the 0D module, the basic set of differential equations are completed by closure equations chosen to model some important phenomena as the mass and energy transfers. In particular, the code models the liquid-bubble and the free surface heat and mass exchanges. At the same time it takes into account the mass transfer of bubbles directly rising to the gas continuous phase.

The mass balance equation in the bubble may be written as:

$$\frac{dM_{totB}}{dt} = \dot{M}_{JB} + \dot{M}_{BR} + \dot{M}_{EC} \quad (1)$$

Where the M_{totB} is the total bubbles mass in the system, \dot{M}_{jB} is the mass bubbles flowrate injected through the junctions, \dot{M}_{BR} is related to the bubble rise and the last term \dot{M}_{EC} on the right side is the bubble/continuous liquid mass transfer due to the condensation and the evaporation at the interface (if condensed the sign convention is negative).

At the same time, the continuous liquid mass balance can be written as:

$$\frac{dM_{totL}}{dt} = \dot{M}_{jL} + \dot{M}_{EC_Sur} + \dot{M}_{EC} \quad (2)$$

With M_{totL} the liquid total mass, \dot{M}_{jL} is the mass liquid flowrate in the junction, \dot{M}_{EC_Sur} is the exchange at free surface (if evaporation is negative) and \dot{M}_{EC} is analogous to the previous equation but with the opposite sign.

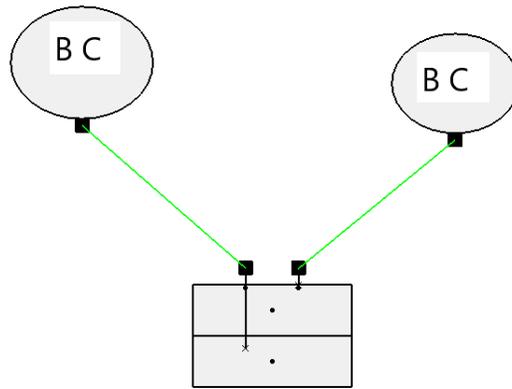


Figure 2. Cathare system's modelling. 0D volume with junctions and boundary conditions.

This paper presents just one of the tests realized in SUPERCLAUDIA facility and in particular that one characterized by a relatively low injected flowrate. Conditions are reported in Table I. The water pool is practically adiabatic. The vertical injection is placed at 0.6 m under the water level. The initial water level is about 1 m and the sonic vapor flowrate is 0.076 kg/s. Test keeps 13300 seconds before stops.

Table I: Initial boundary conditions

Q [kg/s]	0.076
Injector level [m]	0.6
orientation	vertical
P pool [Pa]	101325
h water [m]	~1
t test [s]	13300

4. RESULTS AND DISCUSSION

In this section, comparison between the experimental and calculated results is presented. In particular, the experiments are focused in the study of parameters as condensation area, pool thermal distribution and

condensation efficiency. CATHARE code will be validated against the available experimental results and so the efficiency condensation prediction. Figure 3 shows the comparison between experimental and simulated results of the liquid mass over time. The black dotted line is the sum of the integrated injected vapor and the water pool mass. Since the beginning, experimental results show a quasi-linear mass rise in the liquid pool and a very good agreement with the integrated curve. It means that the injected vapor mass corresponds to the liquid mass variation and a total direct condensation occurs. Starting from about 7'500 seconds, the inclination of experimental curve changes and a difference to the integrated curve is observed. Experimental mass slowly rises. This behavior suggests a weaker direct condensation (the possible presence of experimental bubble rise) or a more important mass transfer at the free surface (higher surface evaporation). Indeed, starting from Eq. (1) and (2), the experimental mass balance may be written as:

$$\frac{dM_{totL}}{dt} = \dot{M}_{jB} - \dot{M}_{BR} - \dot{M}_{EC_Sur} \quad (3)$$

With the hypothesis that there is no bubble temporal variation. As demonstrated in the following paragraph, the bubble rise is negligible and the contribution may be attributed to the evaporation rate at free level. A different behavior is predicted by the code. The mass in the pool is globally lower than in the experiments. CATHARE considers a bubble rise phenomenon starting from the beginning of the transient, strongly accelerated during the last phase of the transient. Hence, the origin of this discrepancy with the experimental results may be attributed to the bubble rise prediction, or to a possible under prediction of the direct condensation in the pool or better, an over prediction of the free surface evaporation.

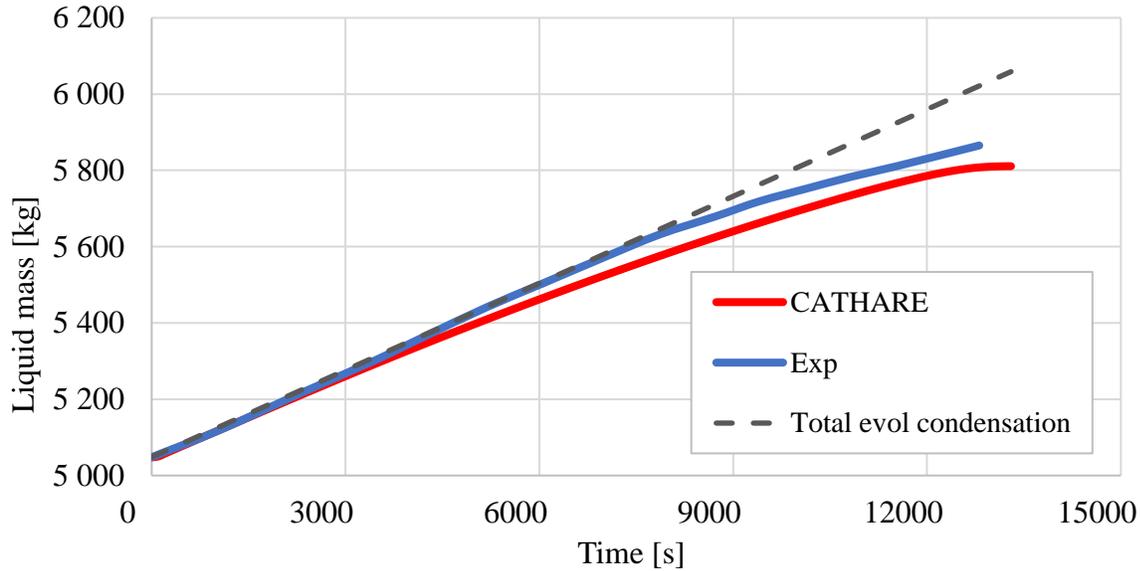


Figure 3. Liquid pool mass evolution versus time. The red line is the CATHARE simulation, the blue line is the experience and the black dotted line represents the integrated vapor injection with the initial liquid mass.

Experimentally, the total energy balance in the liquid pool is [15]:

$$\frac{dM H_l}{dt} = P_{cond} - P_{BR} - P_{loss}$$

(4)

Where the terms on the right side are respectively the power added to the water pool by vapor condensation, power extracted by bubbles rise and power losses (evaporation + convection + wall heat losses). Supposing that during this experiment, the bubble rise is negligible and the condensation is total:

$$P_{evap} = \dot{M}_{EC_Sur} \cdot H_{vl} \quad (5)$$

And

$$P_{loss} = P_{evap} = \dot{M}_{jB} \cdot H_{jB} - \frac{dM H_l}{dt} \quad (6)$$

With H_{vl} and H_{jB} respectively, the latent heat and the injection vapor mass enthalpy. These terms are easily calculated starting from experimental results. Figure 4 shows that the power associated to the experimental losses and evaporated rates corresponds up to practically 90 °C. It suggested that, if the condensation efficiency in the pool is defined as the ratio between the condensed and injected power:

$$\varepsilon = \frac{P_{cond}}{\dot{M}_{jB} \cdot H_{jB}} \quad (7)$$

the hypothesis of a perfect condensation without bubble rise is respected since the initial hypothesis ($P_{loss} = P_{evap}$) is verified. Beyond this temperature, the efficiency is different from the unity and a bubble rise is expected.

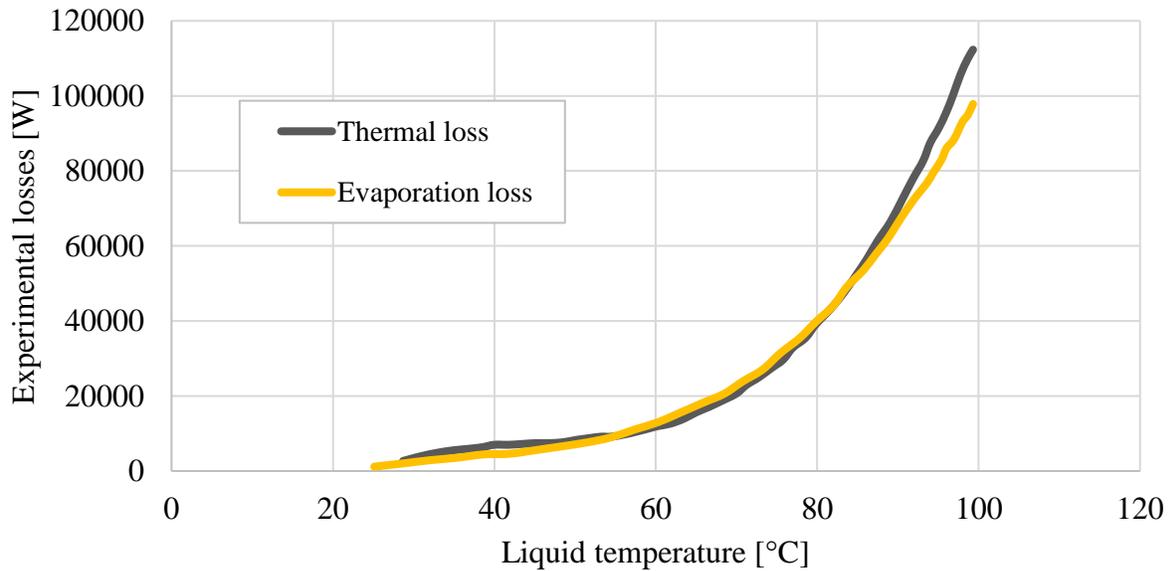


Figure 4. Powers P_{loss} and P_{evap} versus liquid temperature. The yellow line corresponds to the experimental evaporation power and the grey line corresponds to the thermal losses (evaporation + convection + wall losses).

Figure 5 shows the comparison between calculated and experimental evaporation rates at the free surface versus liquid temperature. Up to 70°C, the calculated evaporation is higher than the experiment and it may partially explain the more important mass difference showed in Figure 3. For temperatures beyond 70°C, the simulated evaporation rate is lower and the mass difference cannot be explained by a higher evaporation rate at the free surface. The calculated lower liquid mass may be attributed to the simulated bubble rise or to the underestimation of the liquid/bubbles direct condensation mass transfer.

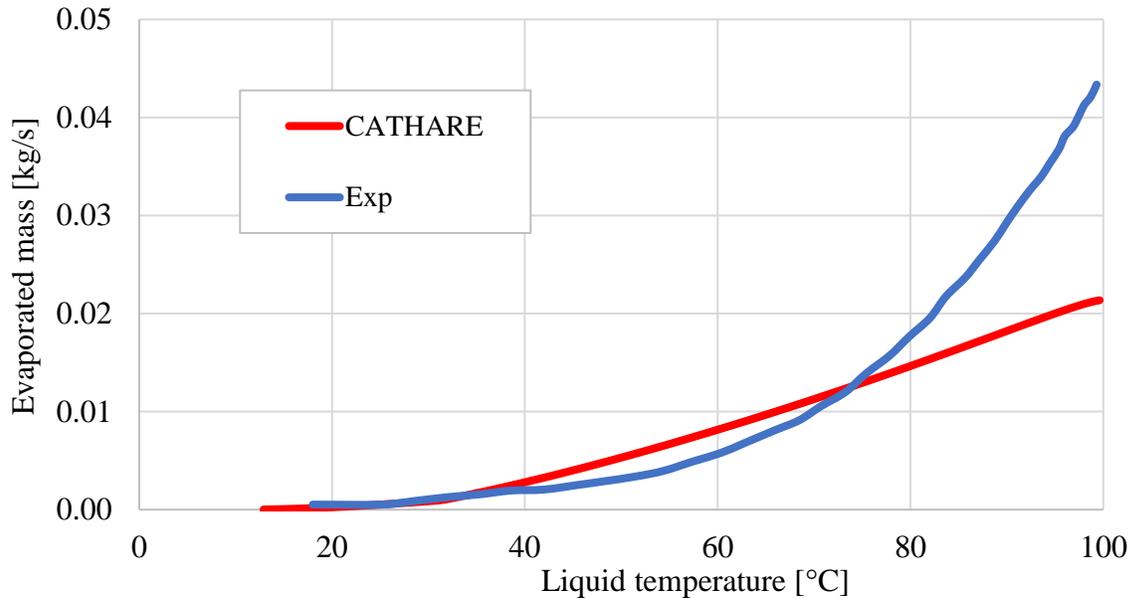


Figure 5. Evaporate mass at the free surface versus liquid temperature. The simulated (red line) and experimental (blue line) results.

The experimental and calculated temperature in the water pool are presented in Figure 6. Thermal stratification in the water pool is practically negligible [15] and it justifies the CATHARE 0D module to represent the water pool behavior. The simulated temperature curve corresponds to the experiment. Starting from Figure 6 in agreement with the previous figures and equation (4), it may be supposed that up to a liquid temperature of about 70 °C, CATHARE code over predicts the evaporation at the free surface and the direct condensation rate with the presence of a bubbles rise. Beyond 70 °C the code under predicts the evaporation rate at the free surface and a more important energy amount is deducted by the pool by a high bubbles rise prediction or an under prediction of the direct condensation rate.

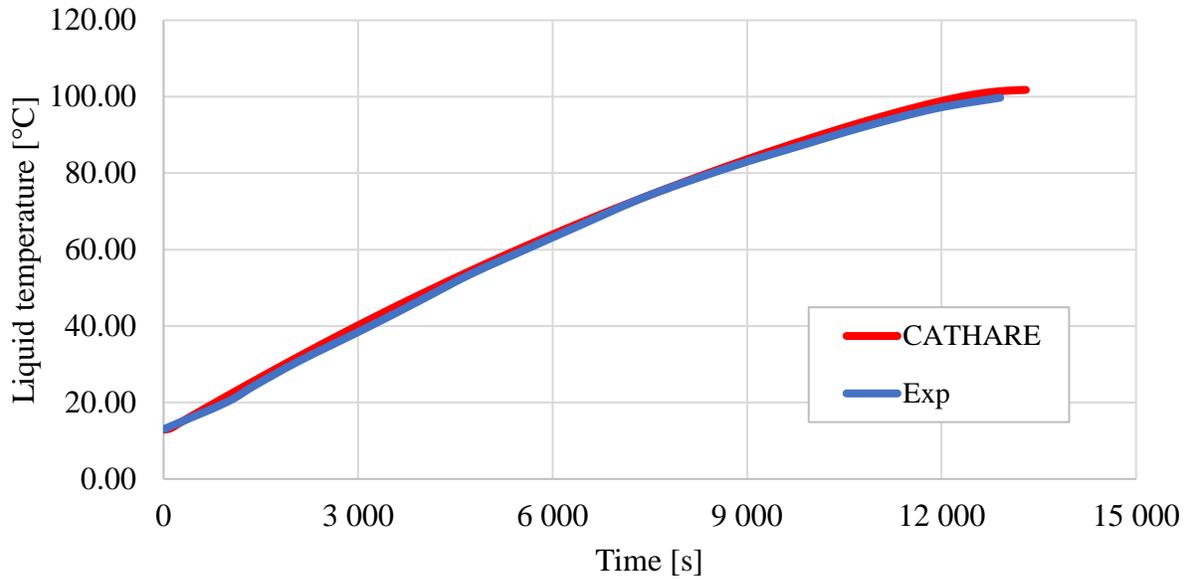


Figure 6. Average pool temperature over time. The simulated (red line) and experimental (blue line) results.

Finally, from equation (7), Figure 7 shows the condensation efficiency over liquid temperature. While Figure 4 shows an experimental efficiency $\varepsilon = 1$ up to the saturation temperature, CATHARE code predicts an efficiency close but not exactly equal to the unity. As said before, it may be due to the bubble rise prediction since the beginning of the injection or to a difference in the liquid/bubble mass transfer interface (condensation rate).

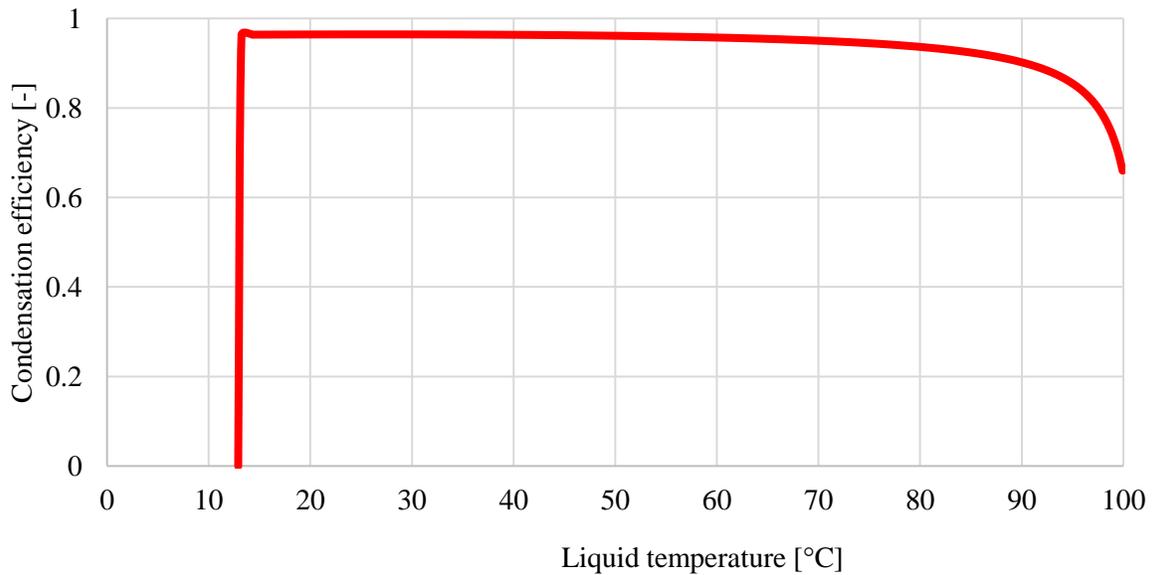


Figure 7. Efficiency in relation to water temperature.

5. CONCLUSIONS

This work presents a first analysis of a SUPERCLAUDIA experimental test and the simulation by using CATHARE code. The injection of a saturated vapor jet in a liquid water pool is here analyzed. Different contributions to the mass and energy balance equations are investigated to better understand all of the phenomena occurring during the transient.

This first analysis shows a general good agreement between the CATHARE code and the experiments. Nevertheless, some improvements are necessary to better predict crucial phenomena that take place during this transient. This work suggests some potential future developments and in particular, it focuses the attention over three physical models: the free surface evaporation rate model in an open pool as well as the direct condensation allowed by a vapor jet and the associated bubble rise.

However, an additional work is necessary to extend the validation matrix with the analysis of supplementary tests necessary to identify the possible CATHARE models upgrading.

A parallel with the CFD simulation could provide some interesting and additional elements to the validation of the code and the physics comprehension.

NOMENCLATURE

H	Enthalpy [J/kg]
M	Mass [kg]
\dot{M}	Mass flux [kg/s]
P	Power [W]
t	Time (s)

Subscripts

B	Bubble
BR	Bubble rise
EC	Evaporation/condensation
EC_sur	Evaporation/condensation at free surface
L	Liquid
J	Junction

REFERENCES

1. Wang, Jue, Lisheng Chen, Qi Cai, Chen Hu, and Cong Wang. 'Direct Contact Condensation of Steam Jet in Subcooled Water: A Review'. *Nuclear Engineering and Design* 377 (June 2021): 111142. <https://doi.org/10.1016/j.nucengdes.2021.111142>.
2. Song, Chul-Hwa, Seok Cho, and Hyung-Seok Kang. 'Steam Jet Condensation in a Pool: From Fundamental Understanding to Engineering Scale Analysis'. *Journal of Heat Transfer* 134, no. 3 (1 March 2012): 031004. <https://doi.org/10.1115/1.4005144>.
3. Gallego-Marcos, Ignacio, Walter Villanueva, and Pavel Kudinov. 'Modelling of Pool Stratification and Mixing Induced by Steam Injection through Blowdown Pipes'. *Annals of Nuclear Energy* 112 (February 2018): 624–39. <https://doi.org/10.1016/j.anucene.2017.10.019>.

4. Paladino, Domenico. 'Thermal Stratification Evolution in a Water Pool, HP5 Test Series Report'. Paul Scherrer Institut, 5232 Villigen PSI, Switzerland: Nuclear Energy and Safety Research Department Laboratory for Thermal-Hydraulics, 2016.
5. Laine, J, and M Puustinen. 'Condensation Pool Experiments with Steam Using DN200 Blowdown Pipe', n.d., 50.
6. Li, Hua, Walter Villanueva, and Pavel Kudinov. 'Approach and Development of Effective Models for Simulation of Thermal Stratification and Mixing Induced by Steam Injection into a Large Pool of Water'. *Science and Technology of Nuclear Installations* 2014 (2014): 1–11. <https://doi.org/10.1155/2014/108782>.
7. Laine, Jani, Markku Puustinen, and Antti Räsänen. 'PPOOLEX Experiments with a Sparger'. Finland: Lappeenranta University of Technology Nuclear Safety Research Unit, April 2015.
8. Kang, Hyung Seok, and Chul Hwa Song. 'CFD Analysis for Thermal Mixing in a Subcooled Water Tank under a High Steam Mass Flux Discharge Condition'. *Nuclear Engineering and Design* 238, no. 3 (March 2008): 492–501. <https://doi.org/10.1016/j.nucengdes.2007.02.044>.
9. Moon, Young-Tae, Hee-Do Lee, and Goon-Cherl Park. 'CFD Simulation of Steam Jet-Induced Thermal Mixing in Subcooled Water Pool'. *Nuclear Engineering and Design* 239, no. 12 (December 2009): 2849–63. <https://doi.org/10.1016/j.nucengdes.2009.08.003>.
10. Chun, Moon-Hyun, Yeon-Sik Kim, and Jee-Won Park. 'An Investigation of Direct Condensation of Steam Jet in Subcooled Water'. *International Communications in Heat and Mass Transfer* 23, no. 7 (November 1996): 947–58. [https://doi.org/10.1016/0735-1933\(96\)00077-2](https://doi.org/10.1016/0735-1933(96)00077-2).
11. Du, Yu, Xiao Yan, Jinguang Zang, et Yan Zhang. « Review of Regime Maps of Steam-Submerged Direct Contact Condensation ». *Frontiers in Energy Research* 8 (10 juillet 2020): 119. <https://doi.org/10.3389/fenrg.2020.00119>.
12. Chan, C.K., and C.K.B. Lee. 'A Regime Map for Direct Contact Condensation'. *International Journal of Multiphase Flow* 8, no. 1 (February 1982): 11–20. [https://doi.org/10.1016/0301-9322\(82\)90003-9](https://doi.org/10.1016/0301-9322(82)90003-9).
13. Petrovic de With, A., R.K. Calay, and G. de With. 'Three-Dimensional Condensation Regime Diagram for Direct Contact Condensation of Steam Injected into Water'. *International Journal of Heat and Mass Transfer* 50, no. 9–10 (May 2007): 1762–70. <https://doi.org/10.1016/j.ijheatmasstransfer.2006.10.017>.
14. Wu, Xin-Zhuang, Jun-Jie Yan, Dong-Dong Pan, Guang-Yao Liu, and Wen-Jun Li. 'Condensation Regime Diagram for Supersonic/Sonic Steam Jet in Subcooled Water'. *Nuclear Engineering and Design* 239, no. 12 (December 2009): 3142–50. <https://doi.org/10.1016/j.nucengdes.2009.08.010>.
15. G. Avakian, S. Casaburi, C. Boulay, B. Duc, G.M. Gautier, "Direct contact condensation of steam injected into a water pool," *6th International Conference of Nuclear Engineering*, ICONE-6025, May 10-14 1998
16. R. Pr ea et al., "CATHARE-3 V2.1: the new industrial version of the CATHARE code" *Proceedings of Advances in Thermal Hydraulics (ATH'20)*, pp. 730-742 (2020).