UNCERTAINTY ANALYSIS OF DELAYED EQUILIBRIUM MODEL (DEM) USING THE CIRCE METHODOLOGY

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ABSTRACT

In the context of nuclear reactor safety, a pipe breach in the primary circuit is the initiator of a Loss of Coolant Accident (LOCA). The calculation of leak rates involving the discharge of water and steam mixtures plays an important role in the modeling of LOCA's for both GEN II and GEN III reactors, and also for the Supercritical Water Reactor of GEN IV. Indeed, the flow through the breach determines the depressurization rate of the system and the time to uncover the core, which in turn are of major concern for when and how different mitigation auxiliary systems will be initiated and be efficient.

This paper deals with the assessment of the Delayed Equilibrium Model (DEM), which physically tackles thermodynamic non-equilibrium conditions prevailing in the flashing flow process near the breach section. This model, developed at the Université catholique de Louvain (UCL), is the 1-D Delayed Equilibrium Model (DEM) for choked or critical flow rate in steady state or quasi-steady state conditions. One of the major issues of this kind of model is its reliability as far as the uncertainties of the results are considered. The DEM has been recently assessed against six different sets of experimental data using the CIRCE (Calcul des Incertitudes Relatives aux Corrélations Elémentaires) iterative procedure developed at CEA. This procedure is based on a systematic statistical analysis referring to the "maximum of likelihood" principle in order to reach the best fitting of the DEM model against the experimental data. The uncertainties of the results are then deduced on the basis of a 95% variation interval.

KEYWORDS
Flashing Choked Flow, LOCA, DEM assessment, uncertainty analysis

1. INTRODUCTION

The Delayed Equilibrium Model (DEM) model deals with choked two-phase flashing flows. A flow is said critical or choked when the mass flow rate becomes independent of the downstream flow conditions ([1]). Typically when a flow is choked in a pipe connecting two vessels at different pressures, any further decrease of the pressure in the downstream vessel does not result in a change of the mass flow rate. This limit, which corresponds to the maximum mass flow rate between both vessels, exists because the acoustic signal related to the pressure decreases can no longer propagate upstream of the critical section. This condition occurs when the fluid velocity reaches the propagation velocity or the speed of sound ([2-9])

In the context of nuclear reactor safety, a pipe breach in the primary circuit is the initiator of a Loss of Coolant Accident (LOCA). The calculation of leak rates involving the discharge of water and steam mixtures plays an important role in the modeling of LOCA's for both GEN II and GEN III PWR and BWR reactors, and also for the Supercritical Water Reactor of GEN IV. Indeed, the flow through the breach determines the depressurisation rate of the system and the time to core uncover, which in turn are of major concern for when and how different mitigation auxiliary systems will be initiated and be efficient (SBLOCA, Aksan et al. [10]). The pipe involved could be a main coolant pipe leading to a large break LOCA (LBLOCA), or a pipe connected to the main coolant loop (e.g. an ECC line, defect at a pressurizer valve) leading to an intermediate or small break. The way in which the flow evolves as a function of time can be different for the case of a small broken pipe from that corresponding to a small hole in a large pipe even if the initial break flows are the same in both cases. In many licensing applications, the knowledge of the actual flow rate through a break of a given size is not required because what is of interest is the behaviour of the plant for a range of break sizes. Exceptions are the determination of the maximum flow for particular types of breaks (for instance from an instrument penetration in the pressure vessel), and the likely flow from a broken steam generator tube.

The modelling of critical flow in several of the thermal-hydraulics codes is based on semi-empirical models which in general require user defined adjustment factors to obtain a satisfactory agreement with data in individual situations. In this regard, more universal models should be developed taking into account a wide range of operating and geometry conditions. In order to validate or assess such developments, appropriate benchmarks should be selected from previous tests, or new experiments should be conducted with a "model-grade approach". In this context, the CIRCE methodology developed in the Commissariat à l'Energie Atomique (CEA) has been fruitfully used to assess the DEM model developed at the Université catholique de Louvain (UCL) for choked flashing flow and its associated uncertainty, which is a major issue for the NPP's commissioning.

2. DEM MODEL FOR CHOKED FLASHING FLOW

2.1. Basic assumptions of the DEM model

Let us recall the basic equations of the Delayed Equilibrium Model (DEM) ([2-9]). In addition to the classical assumptions made in the Homogeneous Equilibrium Model (HEM), some additional assumptions explained here under support the DEM.

Let us consider the adiabatic expansion of a liquid in a pipe (Fig. 1). Let us assume that the state of the liquid at the inlet of the pipe is (p_{in}, T_{in}), with $p_{in} > p_{sat}(T_{in})$. Due to the friction, the pressure decreases along the pipe, and reaches saturation at section "s". Between section "s" and the onset of flashing, the liquid is metastable. The onset of flashing occurs at section "o", where the pressure p_o has been deduced experimentally and is typically ([11]):

$$p_o = 0.975 p_{sat}(T_{in}) \tag{1}$$

For turbulent liquid flows, the slope of the straight pressure line between the inlet and the onset of flashing, i.e. the pressure gradient is proportional to the square of the mass velocity. The distance between point "o" and the tube outlet depends on the inlet subcooling and on the mass velocity. Here we will assume that the inlet subcooling and the mass velocity are such that the onset of flashing is located inside the pipe. Between point "o" and the pipe outlet, a two-phase bubbly flow develops rapidly, and the pressure gradient increases. If the pressure at the outlet is low enough, the flow is choked, and the outlet pressure is the critical pressure p_c. One can expect that the over-heating (or metastability) of the liquid phase does not vanish instantaneously at point "o", but persists within the two-phase part of the flow, depending on one hand on the intensity of the heat transfer from the bulk of liquid to the interface, and on the other hand on the rate of pressure decrease.

For large subcoolings, the onset of flashing is close to the pipe outlet, and the critical mass velocity can be approximately deduced from the single-phase pressure gradient, considering that it is constant over the whole pipe length (Lackmé [11]). For small subcoolings, accurate predictions of the critical mass velocity cannot be obtained without the complete modeling of the flow. For all cases, the accuracy on the prediction of the critical pressure is a relevant indicator of the validity of the two-phase critical flow modeling.

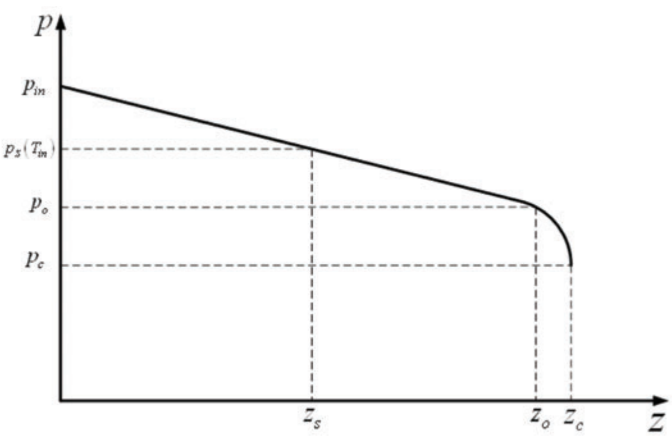

Fig. 1 A typical pressure profile along a pipe with a critical section at its end.

The Delayed Equilibrium Model ([2-9, 11-12]) assumes that, at a given cross-section, only a mass fraction y of the fluid is transformed into a saturated mixture, the remaining $(1-y)$ fraction being the bulk metastable liquid. This fraction undergoes a near-isentropic evolution since the heat of vaporization is exchanged between the saturated liquid and saturated vapor. The mass fraction of vapor in the saturated part of the mixture is denoted by x, and, consequently, the following relations give the specific volume and the mixture enthalpy of this "three-phase mixture":

$$v_m \triangleq (1-y)v_{fM} + xv_{g,sat} + (y-x)v_{f,sat}$$
$$h_m \triangleq (1-y)h_{fM} + xh_{g,sat} + (y-x)h_{f,sat}$$

To distinguish the two liquid phases, we use subscript "M" for "metastable", and the subscript "sat" for saturated. This new variable y requires a closure law. Féburie et al. [13] have proposed a correlation for flows through steam generator tube cracks and for subcooled inlet conditions:

$$\frac{dy}{dz} = 0.02\frac{P_w}{A}(1-y)\left[\frac{p_S(T_{fM}) - p}{p_{crit} - p_S(T_{fM})}\right]^{0.25} \qquad (2)$$

This relaxation law expresses that the decrease of the mass fraction of superheated liquid

$d(1-y)$ over an element of length dz is proportional to the remaining quantity of superheated liquid, and to the metastability ratio to the power 0.25.

This relaxation law has been generalized and recently improved to take into account not only the nucleation at the wall (constant C_1) but also in the bulk of the flow (constant C_2) These constants have been determined from an extensive number of experiments in small as well as in very large nozzles ([3, 13-17]). This improved relaxation law can be written as:

$$\frac{dy}{dt} = w\left(C_1\frac{P_w}{A} + C_2\right)(1-y)\left[\frac{p_S\left(T_{fM}\right)-p}{p_{crit}-p_S\left(T_{fM}\right)}\right]^{C_3} \tag{3}$$

where

$$C_1 = 0.008$$
$$C_2 = 0.56$$
$$C_3 = 0.25$$

By analogy to the equation system obtained for the HEM model and by choosing the quality x the pressure p, the velocity w_m and the mass fraction y as dependent variables, the equations system in the framework of the DEM can be written in Eq. 4

$$\begin{bmatrix} v_g - v_{f,sat} & v_{f,sat} - v_{fM} & \begin{array}{c} xv'_g \\ +(y-x)v'_f \\ +(1-y)v'_{fM} \end{array} & -\frac{v_m}{w_m} \\ 0 & 0 & 1 & \frac{w_m}{v_m} \\ h_g - h_{f,sat} & h_{f,sat} - h_{fM} & \begin{array}{c} xh'_g \\ +(y-x)h'_f \\ +(1-y)h'_{fM} \end{array} & w_m \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \frac{dx}{dz} \\ \frac{dy}{dz} \\ \frac{dp}{dz} \\ \frac{dw_m}{dz} \end{bmatrix} = \begin{bmatrix} \frac{v_m}{A}\frac{dA}{dz} \\ -\frac{P}{A}\tau_w - \frac{1}{v_m}g\cos\theta \\ -g\cos\theta + \frac{v_m}{w_m}\frac{P}{A}q_w \\ f(p,y,T_{fM}) \end{bmatrix} \tag{4}$$

with the derivatives of quantities related to the saturated mixture and to the metastable liquid defined as:

$$v'_k = \left(\frac{\partial v_k}{\partial p}\right)_{sat} \text{and} \qquad h'_k = \left(\frac{\partial h_k}{\partial p}\right)_{sat}$$
$$v'_{fM} = \left(\frac{\partial v_{fM}}{\partial p}\right)_S \text{and} \qquad h'_{fM} = \left(\frac{\partial h_{fM}}{\partial p}\right)_S \tag{5}$$

where the properties of the metastable liquid and their derivatives depend only on the pressure if an isentropic evolution is assumed for this phase.

In particular, the derivatives of the enthalpy of the metastable liquid can be easily deduced from the following relation:

$$dh_{fM} - v_M dp = TdS = 0$$

Which means that:

$$v'_{fM} = 0$$

$$\left(\frac{\partial h_{fM}}{\partial p}\right)_S = v_M$$

2.2. Consistency of the DEM model ([6-8])

The DEM model assumes that the metastable liquid phase is somewhere frozen since the onset of flashing (cross-section z_0 of fig.1) and up to the critical section (cross-section z_c of Fig.1).

Considering the very high velocity during the flashing, the transit time between these two cross-sections is very short, i.e. a few millisecond depending on the subcooling of the liquid at the entrance of the nozzle.

Suppose that at time $t = 0$, the metastable liquid at a temperature $T_{f,M}$ is suddenly in contact with the saturated liquid at a temperature $T_{f,sat}$ maintained constant during the transient. In fact, this saturated temperature of the mixture is decreased very rapidly during the flashing due to the very steep pressure drop.

The analytic solution for a semi-infinite transient heat conduction problem is given in Fig. 2.

Fig. 2 shows the temperature profile in the metastable liquid for different time delay (3 ms, 6 ms and 9 ms). The temperature front only penetrates on a few tens microns. Most of the metastable liquid remains at the same initial thermodynamic state, which exist at the onset of flashing.

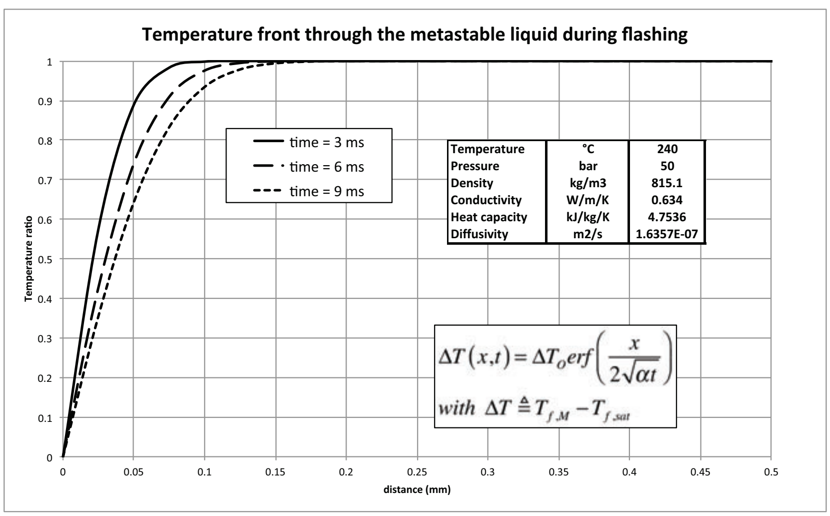

Fig. 2 Temperature profiles in the metastable liquid

This illustrates that the characteristic time driving the heat transfer between saturated phases is much smaller than that of between the metastable phase and the saturated liquid, justifying the thermodynamically frozen assumption.

The increase of the amount of the saturated liquid is thus mainly due to the increase of the interfacial area density, because of a very fast change of the flashing flow patterns from bubbly flow at the onset (void fraction close to zero) of flashing to droplets flow at the critical section.

The DEM model considering 3 phases (frozen metastable liquid, saturated liquid and saturated vapor) seems to properly model the physics of the flashing process.

3. CIRCE METHODOLOGY AND APPLICATION TO THE DEM MODEL

3.1. CIRCE methodology ([18-22])

CIRCE has been developed in the CEA (France) and is a tool to quantify the uncertainty of the parameters associated to physical correlations.

Let us consider the parameters α_i (constants) of a correlation relevant in a given physical phenomenon illustrated by different sets of experiments (for example flashing flows). The parameters α_i are supposed to follow a normal law.

The methodology used in CIRCE is based on a systematic statistical analysis referring to the "maximum of likelihood" principle often used in statistics.

The input data for the CIRCE tool are:

$$\begin{array}{l} (R_{i,exp} - R_{i,code}) \\ U\left(R_{i,exp}\right) \\ \dfrac{\partial R_{i,code}}{\partial \alpha_i} \end{array} \tag{6}$$

where $R_{i,exp}$ - $R_{i,code}$ is the discrepancy between the experimental data i and the physical correlation response, $U(R_{i,exp})$ is the uncertainty on the experimental data i and

$\dfrac{\partial R_{i,code}}{\partial \alpha_i}$ is the derivative of the physical correlation response according to the parameters α_I.

For each parameter α_I which is supposed to be zero, CIRCE tool evaluates the best fitting values of the parameters denoted by the b_i bias on α_I and the standard deviation of α_I. The relevance of the CIRCE tool depends on the number of independent observations of the physical phenomenon, which should statistically sufficient (more than 20) and as much as possible on different operating conditions.

For a seek of simplicity, the CIRCE tool considers the following change of variables:

$$\frac{\partial R_{i,code}}{\partial \alpha_i} \text{ with } \alpha_i = 0 \quad \Rightarrow \quad \frac{\partial R_{i,code}}{\partial p_i} \text{ with } p_i = 1$$

This first step of calculation of the CIRCE tool is known as "CIRCE" nominal.

Knowing the bias on the parameters α_I from "CIRCE nominal", a iterative procedure of the CIRCE tool can then be followed using new sets of the parameters α_I for converging to better fitting values of the parameters α_I with the bias as low as possible.

3.2. Application of the CIRCE tool to the DEM model

3.2.1 Choice of the sets of experiments for the DEM assessment by the CIRCE tool

The constants of the DEM correlation for the vaporization index y have already been adjusted against 500 data of experiments performed on different nozzles, different fluids and different subcooling or saturated conditions at the entrance ([2-3, 12-17]).

In the context of nuclear reactor safety, a pipe break in the primary circuit is the earliest mechanism for initiating a LOCA. The pipe involved could be a main coolant pipe, in which case it leads to a large break LOCA, or a pipe connected to the main coolant loop (e.g. an ECC line) which could lead to an intermediate or small break LOCA.

In a large break LOCA, the critical section can be located at the breach or at some restricted cross section in the surge line or the pump. No specific separate effect test relating to either of these last two possibilities has been found. The pressurizer surge line should in principle be covered by the database for critical flow in pipes.

When a break occurs in a separating wall structure between a high and low pressure system the flow through the break will depend on conditions upstream of the break and on the break area and shape. Critical flow through a break is similar to critical flow through a nozzle, but the geometry of the break can encompass any shape, location and size from a small crack to a complete 200 percent guillotine break in a flow pipe.

The Nuclear Energy Agency has selected different experiments as reference tests for critical flows occurring during a LOCA. In this regards, we have chosen six different series of tests in the context of the NURESAFE project for reassessing the DEM model by the CIRCE tool. These series are summarized in the following table.

Set of experiments	Range of pressure	Range of Temperature	Lenght	Diameter
Super MobyDick Short Nozzle	20 to 120 bar	190 °C to 325 °C	500 mm	20 mm
Super MobyDick Long Nozzle	20 to 120 bar	190 °C to 325 °C	1000 mm	20 mm
Bethsy 2"	30 to 100 bar	200 °C to 310 °C	91 mm	5.25 mm
MARVIKEN tests	30 to 50 bar	230 °C to 255 °C	160 to 1800 mm	200 to 500 mm
UCL - Environment project	2 to 5 bar	120°C to 155 °C	1400 mm	17 mm
UCL - Step project Crosby safety valve	4 to 6.5 bar	120 °C to 155 °C	+/- 40 mm	10 mm

The Super Moby-Dick ([14]) and BETHSY experiments performed by the CEA-Grenoble during the eighties consist in two-phase critical flashing flow experiments.

Steady state critical flow conditions were measured in a long nozzle and in a short nozzle for the Super Moby-Dick test. The long nozzle has an elliptic convergent section at the entrance followed by a straight pipe of about 0.380 m long and of 20 mm inner diameter and ended by a 7° divergent section. The short nozzle has almost the same geometry without the divergent section.

The BETHSY test was also performed at high pressure with different temperatures at the entrance on a short nozzle of 2" long and 5 mm diameter.

The Marviken Full Scale CFT (Critical Flow Tests, [17]) tests were conducted at the Marviken Power Station as a multinational project at the end of the seventies. Twenty-seven different experiments were performed by discharging subcooled water or steam-water mixtures from a quasi-full sized reactor vessel through a large diameter discharge pipe that supplied the flow to a test nozzle. Nine test nozzle geometries were all equipped with a rounded entrance followed by a nominally 200, 300 or 500 mm constant diameter cross-section. The nozzles ranged in lengths from 166 to 1809 mm, which correspond to so-called "short nozzles".

Most tests were conducted with a nominal initial steam dome pressure of 50 bars and with a subcooling temperature of water between 50°C and 1°C (with respect to the steam dome pressure). The vessel, discharge pipe and nozzle were well instrumented to determine the test behavior and to provide a basis for evaluating the stagnation conditions and mass fluxes through the nozzle. The Marviken CFT tests [17] were considered as reference tests for assessing critical two-phase flow models dedicated to LOCA of NPP.

The UCL tests (Step and Environment EC projects, [2-3, 12) have been performed during the nighties at the Université catholique de Louvain. The Environment project concerns choking two-phase flows throughout a discharge line consisting of a pipe of 1400 mm long and of 17 mm inner diameter followed by a second pipe of 1400 mm long and 27 mm inner diameter. This particular geometry allows performing "double choked flows" as it is presented in [2]. Safety valve geometries have been tested in critical flashing flow during the Step EC project ([12]).

In total, we have collected 112 data for the DEM correlation assessment by CIRCE.

Fig. 3 shows the agreement between the experimental data and the DEM model before the assessment by the CIRCE tool.

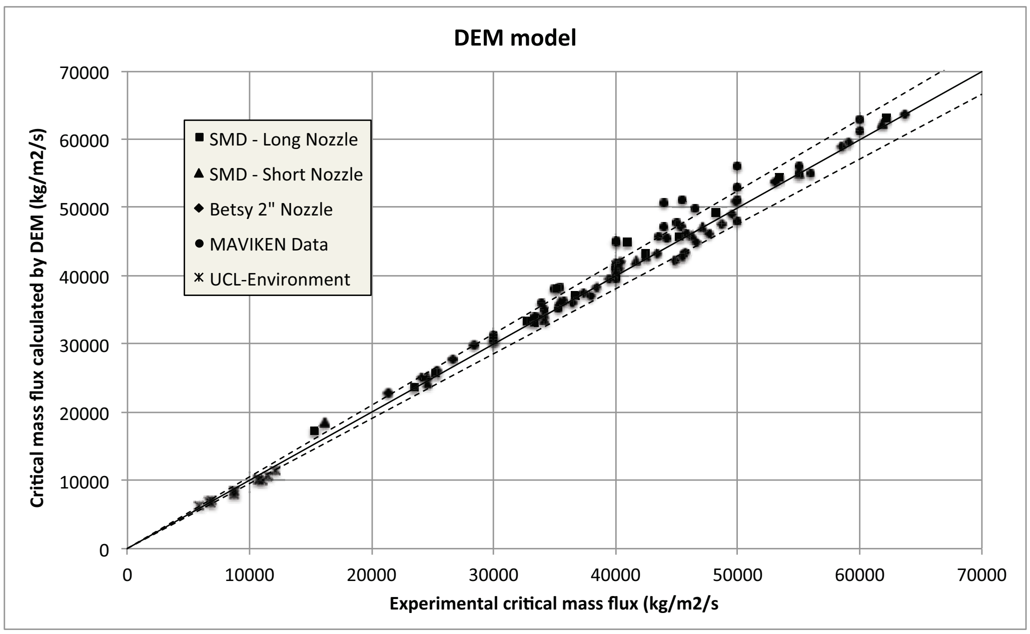

Fig 3. Comparison between experimental critical mass flux and DEM calculation – Dashed lines +/- 5%

3.2.2 Application of the CIRCE iterative procedure for the DEM correlation assessment and results

CIRCE nominal has been used at first for the DEM correlation considering that the following initial values of the C_i parameters:

$$C_1 = 0.008$$
$$C_2 = 0.56$$
$$C_3 = 0.25$$

The DEM correlation used for CIRCE can be written in the following form:

$$\frac{dy}{dt} = w\left(0.008p_1\frac{P_w}{A} + 0.56p_2\right)(1-y)\left[\frac{p_S\left(T_{fM}\right)-p}{p_{crit}-p_S\left(T_{fM}\right)}\right]^{O.25p_3} \quad (7)$$

where p_i parameters are equal to 1. At each step of the iterative procedure of CIRCE, the bias on the p_i parameters are calculated as it is shown on the following table to converge on a very low bias.

CIRCE iterative procedure				
	old	nominal	iteration 1	iteration 2
C1	0.008614	0.008895	0.008303	**0.008390**
C2	0.6651	0.6919	0.624769	**0.633691**
C3	0.25	0.2476	0.227501	**0.228127**

Compared to Fig. 3, Fig. 4 shows the improvement on the fitting of the parameters C_1 C_2 and C_1 against the experimental data after the assessment by the CIRCE tool.

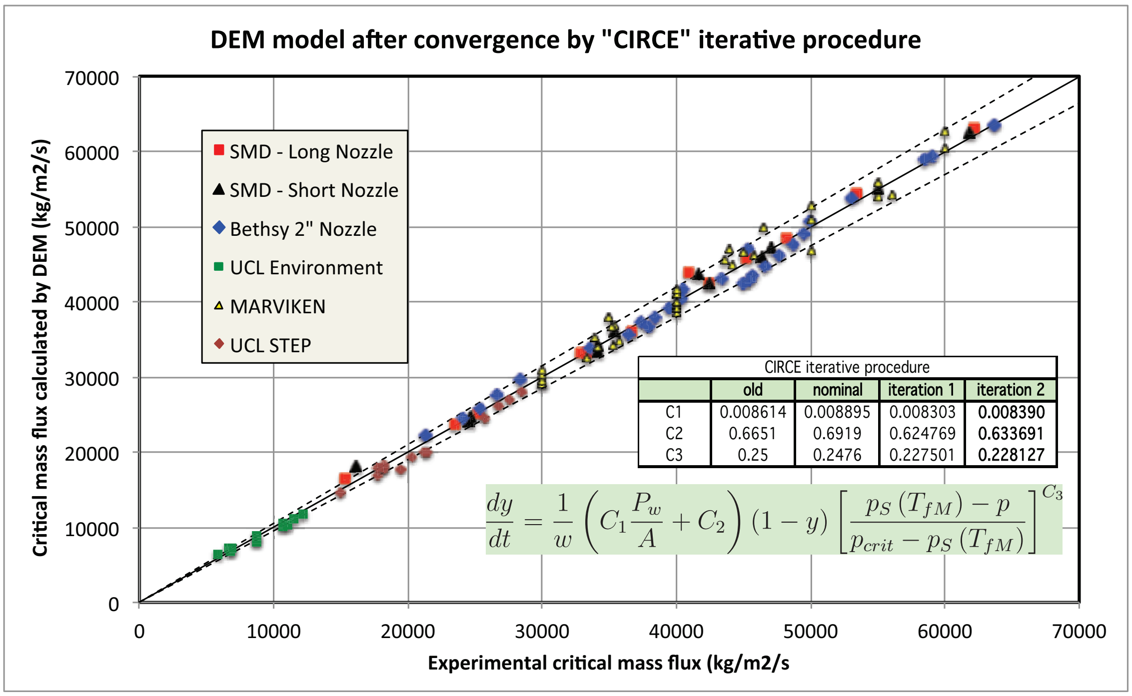

Fig 3. Comparison between experimental critical mass flux and DEM calculation - Dashed lines +/- 5%

3.2. Uncertainty evaluation on the DEM model

The uncertainty evaluation on each p_i parameter is based on a variation interval of 95% and can be deduced from the standard deviation on p_i parameters multiplied by 2 (in fact, the Student coefficient corresponding to a variation interval of 95 % is close to 1.96 for a very large number of observations).

Considering the iterative procedure of CIRCE, the following table gives the standard deviation on p_i parameters at each step of this procedure.

	CIRCE nominal		**CIRCE iteration 1**		**CIRCE iteration 2**	
	Mean	standard deviation	Mean	standard deviation	Mean	standard deviation
parameter p1	0.032595	0.164772	-0.066573	0.144762	0.010537	0.169185
parameter p2	0.04032	0.004238	-0.097046	0.003809	0.01428	0.004081
parameter p3	-0.009777	0.228516	-0.081013	0.237489	0.002755	0.251602

Finally, the global uncertainty on the DEM model taking into account the uncertainty of the experimental data can be deduced from the following relation:

$$U_{global}\left(R_{i,code}\right)=2\sqrt{\sum_{j=1}^{3}\frac{\partial R_{i,code}}{\partial p_j}^{2}\sigma\left(p_j\right)^2+\sigma\left(R_{i,exp}\right)^2} \tag{8}$$

We also can evaluate the so-called *En* score often used in the assessment of the uncertainty of measurements in accredited laboratories defined by:

$$E_{n,i}=\frac{R_{i,code}-R_{i,exp}}{U\left(R_{i,code},R_{i,exp}\right)} \tag{9}$$

The En score has been evaluated for the all sets of data used for the DEM correlation assessment. As expected, about 5 % of the data are out of the following range:

$$-1\leq E_{n,i}\leq 1 \tag{10}$$

Figs. 4 to 6 give examples of uncertainty evaluation of the DEM model applied to the Super-Mobydick and Bethsy experiments for different pressures at the entrance of the nozzles. In these figures, the dashed lines illustrate the uncertainty band of the DEM model calculated by eq. (8).

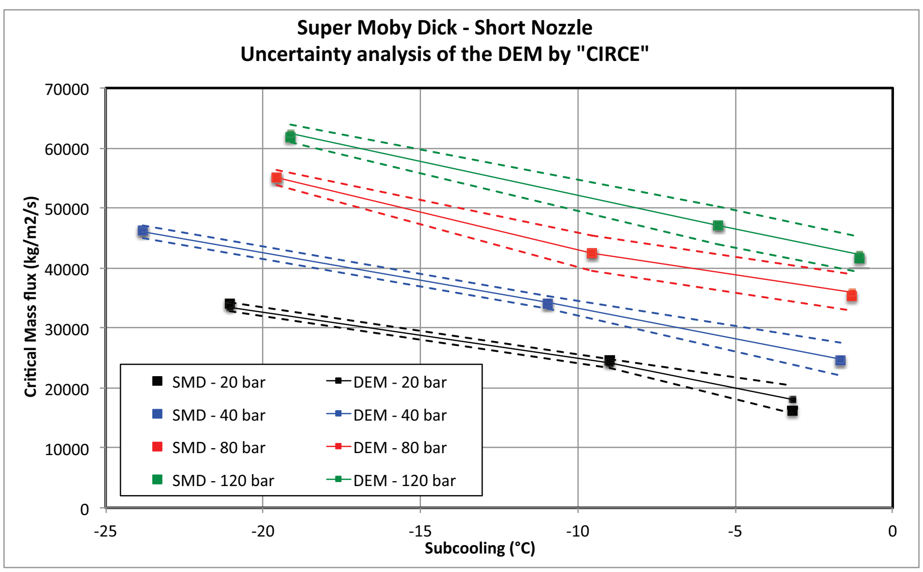

Fig. 4: Uncertainty evaluation of the DEM model on the Super-Mobydick short nozzle

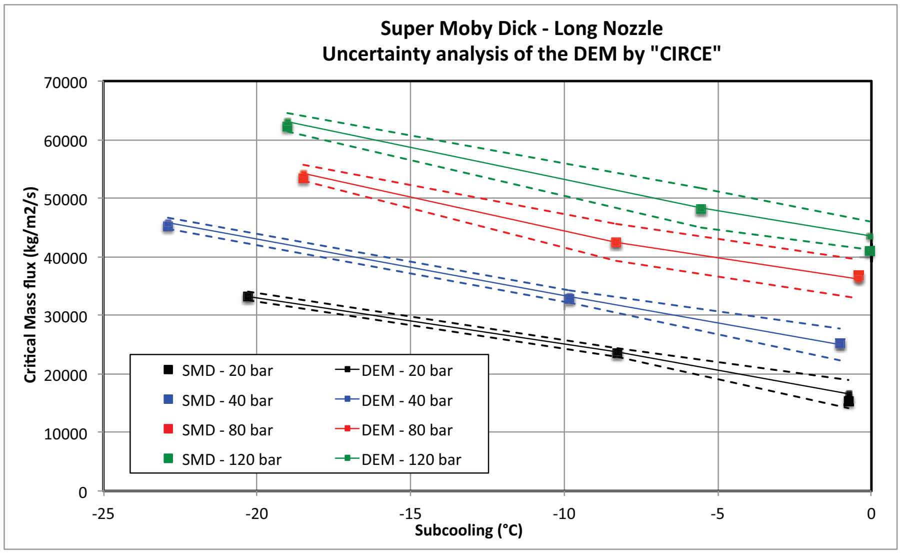

Fig. 5: Uncertainty evaluation of the DEM model on the Super-Mobydick long nozzle

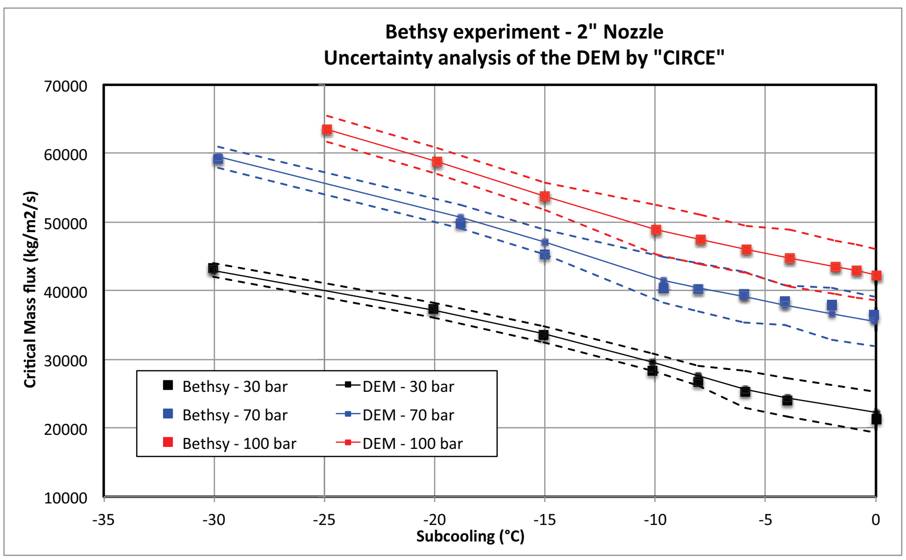

Fig. 6: Uncertainty evaluation of the DEM model on the Bethsy 2” nozzle

4. CONCLUSIONS

This paper revisited the modeling techniques for the computation of critical two-phase flows relevant to nuclear safety in GENII, GENIII power plants. In addition, several possible benchmarks have been reviewed and proposed for validation purposes in system codes.

The results presented in this paper demonstrated that the DEM model is a good candidate since it performs well and is physically consistent.

The CIRCE tool for improving the DEM correlation describing the mass transfer between the metastable liquid phase and the saturated liquid phase has been successfully used. The improvement of the DEM model is clearly shown in the paper.

Moreover, the CIRCE tool also has been used for determining the uncertainty band of the DEM model, which is of paramount importance for the commissioning of NPP's as far as the safety issue in case of LOCA is concerned. This has been applied successfully for all the sets of the experimental data presented in the paper, in particular for the Super-Mobydick and Bethsy tests performed in CEA (France) during the eighties.

NOMENCLATURE

A	cross section (m^2)
G	mass flux ($kg/(m^2.s)$)
θ	inclination angle (rad)
g	acceleration of the gravity (m/s^2)
h	specific enthalpy (J/kg)
P	wetted perimeter (m)
p	pressure (Pa)
p_{crit}	critical pressure of the fluid (Pa)
q	wall heat flux (W/m^2)
v	specific volume (m^3/kg)
w	velocity (m/s)
w	wall
x	mass fraction of the vapor (-)
y	vaporization index (-)
z	axial coordinate (m)

Greek letter

θ	inclination angle (rad)
ρ	density (kg/m^3)
τ	shear stress (N/m^2)

Subscript

f	liquid phase
g	gas (vapor) phase
m	mixture
M	metastable liquid phase
w	wall
S	entropy
sat	at saturation conditions

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REFERENCES

1. A. H. Shapiro, *The dynamics and thermodynamics of compressible fluid flow Vol. II*, Ronald Press, New-York, USA (1954).
2. A. Attou, J. M. Seynhaeve, "Steady-state critical two-phase flashing flow with possible multiple choking phenomenon. Part 1: Physical modeling and numerical procedure", *J. of Loss Prevention in the Process Industries*, **vol. 12**, pp. 335-345 (1999).
3. A. Attou, L. Bolle, J. Franco, J. M. Seynhaeve, *"Flow through singularities and ducts downstream of safety valves, Towards a better design of pressure relief system in Chemical and Petroteum industries"*, Environment program E. U., UCL-TERM contribution (1996).
4. Y. Bartosiewicz, M. Giot and J.-M. Seynhaeve *"Revisiting Modeling Techniques and Validation Experiments for Two-Phase Choked Flows Relevant to LOCA"* The 8th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-8), Shanghai, China, October 10-14, 2010
5. Y. Bartosiewicz, G. Serre, J.-M. Seynhaeve *"Delayed Equilibrium Model and validation Experiments for Two-Phase Choked Flows Relevant to LOCA"* The 14th Internantional Topical Meeting on Nuclear Reactor Thermahydraulics, Toronto, Canada, September 25-30, 2011
6. Y. Bartosiewicz, J.-M. Seynhaeve *"Delayed Equilibrium Model (DEM) of Flashing Flows Relevant to LOCA and Validation Experiments"* ASME International Mechanical Engineering Congress and Exposition, published in Nuclear Science and Technology International Journal, IMECE13, November 2013, San Diego, CA, USA
7. Y. Bartosiewicz, J.-M. Seynhaeve *"Delayed Equilibrium Model (DEM) of Flashing Flows Relevant to LOCA. "* Multiphase Science and Technology, **vol. 25 (2-4)**, pp. 117-131 (2013)
8. Y. Bartosiewicz, J.-M. Seynhaeve *"Delayed Equilibrium Model (DEM) of Flashing Flows Relevant to LOCA and Implementation in System Codes"* Proceedings of the 22nd International Conference on Nuclear Engineering, ICONE22, July 2014, Prague
9. J. Bouré, A. A. Fritte, M. Giot, M. Réocreux, "highlights of two-phase critical flow: on the links between maximum flow rates, sonic velocities, propagation and transfer phenomena in single and two-phase flows", *Int. J. Multiphase Flow*, **vol. 3**, pp. 1-22 (1976).
10. N. Aksan, F. D'Auria, H. Glaeser, R. Pochard, C. Richards, A. Sjoberg, *OECD/NEA-CSNI Separate Effects Test Matrix for Thermal-Hydraulic Code Validation, Volume I – Phenomena Characterisation and Selection of Facilities and Tests*, Report NEA/CSNI/R(93)14/PARTI/REV (1994).
11. C. Lackmé, "incompleteness of the flashing of supersaturated liquid and sonic ejection of the produced phases", *Int. J. Multiphase Flow*, **vol. 5**, pp. 131-141 (1979).
12. L. Bolle, P. Downar-Zapolski, J. Franco, J. M. Seynhaeve "Experimental and theoretical analysis of flashing water flow through a safety valve" *Journal of Hazardous Materials*, **vol. 46**, pp. 105-116 (1996).
13. V. Féburie, M. Giot, S. Granger, J. M. Seynhaeve, "A model for choked flow through cracks with inlet subcooling", *Int. J. Multiphase Flow*, **vol. 19**, pp. 541-562 (1993)
14. J. C. Rousseau, "Flashing flow", *Multiphase Science and Technology*, **vol. 3**, pp .378-389 (1987).
15. G. L. Sozzi, W. A. Sutherland, "Critical flow of saturated and subcooled water at high pressure", Proceedings of *ASME Symp. of Non-Equilibrium Two-phase Flows*, pp. 19-25 (1975).
16. T. Véneau, "*Etude expérimentale et modélisation de la décompression d'un réservoir de stockage de propane",* PhD thesis - Institut National Polytechnique de Grenoble, France (1995).
17. *The Marviken full scale critical flow tests*, Joint Reactor Safety Experiments in the Marviken Power Station in Sweden, Third series-conclusions, NEA report MXC-402 (December 1979).
18. A. de Crécy, *"Determination of he uncertainties of the constitutive relationships of the CATHARE 2 code",* M&C 2001, Salt Lake City, Utah, USA (September 2001).

19. A. de Crécy, P. Bazin *"Quantification of the Uncertainties of the Physical Models of CATHARE 2"*, BE 2004, Washington DC, USA (November 2004).
20. A. de Crécy, P. Bazin *"CIRCE, a tool to quantify the uncertainty of physical models"*, Technical Meeting on the Application of Deterministic Best Estimate Safety Analysis, organized by IAEA and OECD (NEA), Pisa, Italy (September 2009).
21. D.G. Cacuci *"Sensitivity Theory for Nonlinear Systems: I. Nonlinear Functional Analysis Approach"*, J. Math. Phys., **vol. 22**, 2794 (1981).
22. A.P. Dempster, D.B. Rubin, R.K. Tsutakawa *"Estimation in Covariance Components Models"*, Journal of the American Statistical Association, **vol. 76**, Number 374 (1981)