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Project Report

An Overview of the Pressurized Therma Issue in the Context of the NURESIM Pr

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Abstract

Within the European Integrated Project NURESIM, the simulation
Pressurized Water Reactors may cause Emergency Core Coolant i

They imply the formation of temperature gradients in the thick v
the potential for propagation of possible flaws present in the ma
that are potentially at the origin of PTS. It summarizes recent
phenomena occurring within the geometric region of the nuclear
where the “PTS fluid-dynamics" is relevant. Available experiment
tools are reviewed and the capabilities of such tools to captu
conclusions show that several two-phase flow subphenomena are
at a qualitative level, but the capability to simulate their intera
limited. In the near term, one may envisage a simplified treatme
effects which are not yet well controlled, leading to slightly conserv

1. Introduction

Pressurized thermal shock (PTS) in general denotes the occurren
(RPV) under pressurized conditions. PTS was identified by the Eu
important industrial needs related to nuclear reactor safety si
throughout the reactor lifetime; it is one of the barriers against
feasible. A very severe PTS scenario is cold water emergency cor
hypothetical small-break loss of coolant accident (SB-LOCA). The
the cold leg, and the mixture flows towards the downcomer wher
(see Figure 1). High thermal gradients may occur in the structural
is partially preserved. Therefore, the transient fluid temperature r
the RPV and the pressure wall toughness. The cooling fluid can e
depending on the leak size, its location, and on the operating cor
PTS has been the objective of a number of international cooperati
ICAS as given by [1].

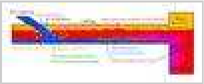

Figure 1: Most important flow phenomena dur

PTS-scenarios were considered in the NURESIM project for the F
Konvoi reactor, the Loviisa 500 MW VVER, and the Russian V
between 700 mm and 850 mm while the sizes of the ECC injec
Loss of coolant accident (LOCA) scenarios, with different leak sizes
leading to ECC injection, which can create PTS situations. For al
(HPI) into the cold leg. For some of the scenarios, the pressure c
conditions in the cold leg. However, for all reactor concepts, the
situations in the cold leg. Injection from the hydroaccumulators n
the accumulators are connected to the cold leg for some PWR, t
downcomer and into the upper plenum in case of the VVER react
either partially uncovered or totally uncovered. Both situations ha
particular, stratified flow with a void fraction range from 0 to 100
leg.

In all the two-phase flow scenarios, the pressure is below 7.5 MP
the pumps are close to zero but may have fluctuations in the ran
flow rates in the considered scenarios are up to 50 kg/s in case
steam generator and up to 15 kg/s for a flow from the steam g
from the HPI are limited to a maximum value of 80 kg/s, while
and 298° C. The maximum accumulator flow rates for the reactor
30 kg/s. The temperature of the injected water is between 25° C

The PTS work package within the frame of the NURESIM Integrate
on a two-phase flow configuration resulting from a partially or f
uncovered cold leg, a stratification of cold water on the bottom of
and steam on top of this cold-water layer may occur (see Figure
Condensation takes place at the free surfaces of the cooling wa
strongly dependent on the turbulence in the fluids. If the water le
leg nozzle, cold water is injected into vapor with direct contac
heating along walls of both the cold leg and the downcomer. S
contact condensation (DCC) is of prime importance in this situatio
Interfacial transfers (momentum—including turbulence—mass and
as well as in the stratified flow.

As shown in Figure 1, different flow phenomena occur. There
horizontal interface), but also dispersed flows occur due to bubble
in the horizontal flow region by entrainment caused by waves).
these interfaces, momentum transfer as well as heat and mass tra
phenomena taking place are strongly coupled, both within the flui
different phenomena depend on very different characteristic lengt
the system scale. Some of the involved phenomena are not y
simulations of the whole system during the ECC injection process a
on the RPV are thus a considerable challenge.

In detail, the following “geometrical” flow regions or flow patter
be distinguished for the two-phase PTS situation (e.g., [2], see als

(i) Free liquid jet:

  (a) momentum transfer at the jet interface, including insta
  (b) splitting of the jet,
  (c) condensation on the jet surface.

(ii) Zone of the impinging jet:

  (a) surface deformation by the jet including generation of
  (b) steam bubble entrainment,
  (c) bubble migration and de-entrainment,
  (d) turbulence production below the jet.

(iii) Zone of horizontal flow:

  (a) momentum exchange at the gas-liquid interface, inclu
  these waves,
  (b) heat and mass transfer (condensation) at the gas-liqu
  transfer,
  (c) heat transfer to the walls,
  (d) turbulence production at the interface,
  (e) turbulence production at the walls,
  (f) influence of the phase change on turbulence and on w
  (g) mixing/stratification of hot and cold water streams.

(iv) Flow in the downcomer in the case of a partially filled col

  (a) turbulence production at the walls,
  (b) mixing/stratification of hot and cold water,
  (c) heat transfer to the walls.

Flow in the downcomer in the case of the water level bei

(v) Flow in the downcomer in the case of the water level bei

  (a) separation of the incoming water jet from the downco
  (b) momentum transfer at the jet interface, including inst
  (c) splitting of the jet,
  (d) phase change at the jet surface,
  (e) heat transfer to the walls.

There are strong interactions between the listed flow regions and gases has to be considered due to nitrogen degassing from ECCS v

It is not possible to reproduce experimentally in full scale, the who location to the inner downcomer, considering the various two-pha required, and two-phase PTS constitutes one of the most challer (CFD) simulation. Improvements of the two-phase modelling capa for the simulation of such flows. A really accurate simulation of all be possible in the far future. To reach this aim, it is necessary to forecasts. However, the use of CFD in industrial studies related to

The main goal of the NURESIM project is the development of a platform for NUclear REactor SIMulation (NURESIM). During the including DCC scenarios, should be enhanced beyond the current phase flow modelling capabilities of current CFD-codes. The Nep framework for the common platform, and both the CFX and FLUEN

Within the above framework, the objective of the paper is on th present status in the simulation of thermal-hydraulic aspects of PT project uses available experimental data for improving and validati leading to two-phase PTS situations as well as a discussion on the of the NURESIM was given by Lucas [5].

2. Experimental Data Basis

CFD methods use many turbulence and two-phase flow models accuracy and universal validity of these models have to be asse experimental data. Depending on the suitability of the data, tes statistical models and for demonstration of model capabilities.

2.1. Validation Experiments

Validation cases focus on separate effects as they test different a successful simulation of the single separated effects is a prerequisi validation test, the quality of the statistical model is checked for method to minimize and quantify modelling errors and to ensure certain types of flows. In an ideal case, a validation test case giv the physical models. In NURESIM, validation data are also obtaine

In the NURESIM database [6], test cases were selected which cle that are to be tested and which are dominant in the validation cas all experiments are described according to the following template:

(i) general description and flow features,
description of measurements and geometry,

(ii) description of measurements and geometry,
(iii) detailed information on boundary and initial conditions,
(iv) availability of experimental data,
(v) information on previous work and related experiments.

Next to the completeness of the data, their quality is of primary i
quality of the data is mainly evaluated by error bounds provic
experiments still do not provide this information. Moreover, even i
systematic errors by the experimentalist. In addition to error bou
experimental data, which allow for testing of the consistency of t
been gathered investigating the same or similar PTS phenomena
different facilities using different experimental techniques.

Experiments investigating jet impingement on a free surface and b
Lahey [7] and Iguchi [8] as follows.

(i) The Bonetto and Lahey experiment investigates jet impi
turbulent jet impinging orthogonally on a free surface. The flov
in an air environment. A laser Doppler anemometer (LDA) sys
(both mean and fluctuations), and both a fiber phase-Doppler a
used to measure the void fraction, depending on the bubble s
was measured at varying depths below the undisturbed surface
(ii) A turbulent nonfragmented water jet impinging on a fre
Iguchi et al. [8] at the University of Hokkaido. LDA was used t
vertical and radial velocity below the free surface. However, nc

Air water flows in horizontal channels were investigat- ed at Forsc
et al. [9] and at INP Toulouse by Fabre et al. [10]:

(i) A horizontal channel with rectangular cross section was b
current air water flow at atmospheric pressure. The measurer
Optical techniques, like video observation, were used to record
Velocity-fields are measured using particle image velocimetry
on the basis of bilateral agreements.
(ii) In the Fabre experiment, air-water turbulent stratifie
(descending) rectangular channel. Systematic measurements
Reynolds stresses were performed with LDA and hot wire aner
The data was used by [11] for validating the turbulence model
in the liquid including the interfacial production terms in adiab
NURESIM partners by CEA.

Stratified steam water flows with condensation were inves- tigated

(i) Lim investigated steam-water turbulent stratified flow v
rectangular cross-section. In the experiment, Pitot tubes were
and conductivity probes to measure the water height at five l
condensation models by Yao et al. [14].
(ii) Ruile [13], Hein et al. [15], and Goldbrunner [16] invest
flows of subcooled water and saturated steam in the LAOKC
experimental equipment was designed to set up co-current
channel with adiabatic walls. Available measured data include
cross section, the inlet water temperature, and the temper
location, where a vertical array of thermocouples was installe
water layer height were also measured. Data for selected test

Water hammer in a horizontal section of a steam-line, induced by
analysed at PMK-2 test facility of the Hungarian Atomic Energy
project, mesh sensor data can be useful for the development and
a horizontally stratified flow. However, it is well known that due t
be as large as 50%.

Condensation pool studies were performed in the Nuclear Safe
Technology, LUT [18]. They were designed to correspond to th
Finland. In the first tests, the formation, size, and distribution o
condensation pool facility POOLEX. In the frame of the national S
gas was injected into the condensation pool test rig in order to st
upward acceleration, detachment, and breakup. The experiments
where the key parameters of the experiments (pool subcooling
instrumentation and a high-speed camera were used in the expe
help of strain gauge measurements.

2.2. Demonstration Experiments

The purpose of a demonstration exercise is to build confi- dence i
flows. While validation studies show for a number of building blo
the basic aspects of the PTS application, demonstration cases test
effects, including geometrical complexity. Typically, the level of c
much lower than for validation cases. Even though the density
required that the quality satisfies the same criteria as for validati
independent measurements.

Suitable demonstration experiments were selected with complex fl

(i) The 1 : 2 scaled HYBISCUS experiments where local t
leg and in the downcomer of a PWR simulating ECC-injecti
available on special bilateral agreement.

(ii) The COSI experiments (see [19]) which provide tempera
cold leg with focus on direct contact condensation in the
concluded that the jet-induced local turbulence in the water
condensation rate since most of the total condensation occurs
enhances heat mixing below the free surface. Data is propert
available.

(iii) Selected 1 : 1 scaled UPTF experiments where conden
were studied in the test series TRAM C1 and TRAM C2. Tempe
downcomer, lower, and upper plenum and in the core regi
instrumentation, and selected data is made available in the fra

(iv) The 1 : 48 volumetrically scaled ROSA test facility wh
system behaviour. However, several spinoff experiments in
focused on stratified flows. Data for temperature and concen
group. Future experiments are planned with focus on the
stratification.

(v) Structural mechanics data resulting from thermal st
available in the NURESIM database. They relate to thermal s
were performed at the University of Pisa, DIMNP.

Although there are a number of experiments available where flo
and as integral effects, there is still a need for well-instrumente
where experimental parameters are varied in order to investigate
resolution in space and time for the whole domain of intere

information on interface between the phases, mean, and fluctuati
and velocity.

For this purpose, the *TOPFLOW PTS experimental programme* has
informed experimental database for both validation of CFD mode
downcomer including flow-wall heat transfer, and the improveme
(TH) phenomena involved. Besides the operational standard
temperature, flow rates), the instrumentation will comprise ther
local void probes equipped with a microthermocouple, high-speed
and a local conductivity probe. It is planned to operate the test n
mass transfer due to condensation as well as in transient operation

3. CFD Capabilities for the Simulation of Two-phase

3.1. Free Liquid Jet

The cold liquid jet injected into the horizontal cold leg pipe
environment. These interactions are strongly dependent on the po
water and the hot gaseous environment. Interface tracking meth
these interactions. Depending on various characteristics of both t
between the two phases or turbulence properties, instabilities at th
be directly generated by the condensation process [20]. They aff
the jet surface have to be applied. The instabilities also influence th
the liquid surface by capturing gas. Adequate modelling of the inte
turbulence fields of the single phases and local mass and heat tran

Numerous theories relating to mechanisms on generation and g
approaches have been used, such as DNS or large-eddy simulatio
various conditions [21, 22]. Even if the individual effects of some
have been separately studied, no computations exist taking into
some models for the treatment of these instabilities are based or
applicability. The LES approach seems the most suitable for t
presuming what would be the best choice for the simulation of the

DCC at the jet surface resulting from the temperature difference
negligible part of the total condensation in the considered flow dor
at the jet surface, correlations exist [19], but no representative ex
No special models were developed for DCC at the jet surface. Th
and the effects of the noncondensable gases have been qualitative
was not fully mature.

3.2. Zone of the Impinging Jet

Appropriate modelling of the turbulence production below the jet
for the mixing of the fluid. Gas entrainment caused by the jet
turbulence below the free surface. The properties of the entra
horizontal migration, and total amount of entrained gas) are deper
The jet velocity is one of the most critical parameters. Dependin
below the free surface have already been experimentally ide
development of theories able to reproduce the properties of the
resulted in global correlations, which are limited to the cor
configuration. Several studies have highlighted the absence of the
prediction of the minimal jet velocity at which the gas entrainme

requires simultaneous consideration of separated (surface) and dis

Two issues have to be considered regarding turbulence productior the jet itself and the influence of the bubbles on the turbulence. I the turbulence production below the jet by CEA and University of P Together with Neptune_CFD standard models, a CEA/Grenoble mo with experimental data was achieved with best performing model were always good, and turbulence was generally not bad but wit region.

In most simulations, the effect of the liquid turbulence on tł (corresponding to the influence of the bubbles on the liquid turł turbulent viscosity, for example, using the Sato model [27], desp region (near the impingement point). Some studies have thus modelling of the coupling between these various processes.Both LE of the zone of the impinging jet. A more general investigation on t flow, including bubble plumes, was undertaken in the frame of the

In the impinging jet zone, four different interface struc- tures hav the free surface of the pool (i.e., liquid level in the cold leg), (3 surface structure in the region where the jet impacts the surface. dispersed (bubbles) flow regions exist simultaneously in one flov transitions between the two types of interfaces (i.e., bubble en interfacial structures, different closure models are needed, for exa for separated flows is thus of crucial importance.

Some computations of the whole plunging jet process (startir considering the impingement zone, the bubble migration below the performed with some success in the past [28]. These were able to surface (small waves at the free surface and shape at the impi migration below the free surface, and the bubble de-entrainment a has been more or less well reproduced numerically (generation of total volume flow rate of entrained gas has been largely overestim during these computations is the treatment of the liquid/gas interf of interface mentioned above have to be modelled using two di different values for the parameters). In the frame of the NURESIM these problems. This resulted in the suggestion to use so-callec which allow to apply two different drag coefficients for free surface the gas void fraction is used to apply the adequate drag coefficient

The behaviour of the entrained gas bubbles below the free liquid individual bubbles. The most important of these forces are buoyan dispersion force. All these forces are strongly dependent on the vertical pipes, a combination of Tomiyama lift- and wall force tog found to reflect the experimental findings in poly-dispersed flo differences have been pointed out between calculations and expe project, the influence of the bubble forces on bubble migratio configuration.

In most computations, the bubble diameters are assumed to b consideration of a number of bubbles classes already exist [33], b bubbles size distribution is strongly influenced by bubble coalesce the literature (e.g., [34 - 36]). The models for bubble forces, a breakup, have consequently to be validated for the plunging jet co

There are also some attempts on a direct tracking of interfaces a techniques have indeed been applied, in combination with LES of t phase flow [37, 38]. These authors incorporated the VOF approacl air/steam injection into a water pool, as investigated previousl computational resources will not allow this approach to be used to routinely used two-fluid formulation remains much less demandinc candidate future technique for tackling flows involving large inter the method have now been made by Liovic and Lakehal [38], na deformable interfaces.

3.3. Zone of Stratified Flow in the Cold Leg

In the horizontal cold leg pipe, a stratified flow has to be cor characterised by intense heat, mass, momentum, and turbulence wall of the cold leg pipe has also to be considered.

3.3.1. Momentum and Turbulence Transfer

Depending on the relative velocities of the gas and the liquid ph perturbed. For low relative velocities, the interface is quasistat perturbed, and small waves are generated. Depending on the actu their propagation in the horizontal pipe. The so-called *Kelvin-Helm* present within a continuous fluid or when there is sufficient vel fluids. The CFD modelling of this instability was investigated in classical theory can be used to predict the onset of instability in flu speeds. In the absence of surface tension, all wavelengths are ur the short wavelength condition; the theory then predicts stability u interface tracking methods or any method which includes surface with high-density differences, such as steam and water in the ca (see [42]). It was found that either a single-fluid approach with interface recognition (Neptune) could predict reasonably wave gen instability could also be qualitatively predicted by Neptune and CFX

In cases with high relative velocities in horizontal pipes, the wa complex system of interactions (presence of gas bubbles and liqui generated waves can, in certain cases of high relative velocity, ent usually characterised by an acceleration of the gaseous phase ar significant amount of liquid with high-kinetic energy. The two-ph dependent on the local conditions but depend also on the char generate waves.

A systematic study of numerical simulation of slug flow in horizont [9] and Vallée et al. [43]. It was shown that the formation of t friction of the liquid phase. In simulations using inlet/outlet boun slug flow regimes strongly depends on the agitation or perturbat Frank showed that the length of the computational domain also experimental data are being used in NURESIM for benchmarking Pisa and CEA do simulations of Fabre et al. [10]. A new mod considering an interfacial layer of 3 cells [44].

Momentum transfer is closely connected with turbulent transfer.

model, the interfacial momentum can be modelled using several [14]) in the gas phase supposes, due to the significant differen interface can be treated as a “moving solid wall” with a velocity the interface is modelled with the two sublayer models, which is si to use the average viscosity assumption (AVM, [14]). This model the case of a thin layer near a smooth interface without phase velocity to be evaluated. Morel [45] has proposed a modificatio multidimensional calculations.

3.3.2. Turbulence Modelling

The mixing of hot and cold water is mainly determined by turbulen gas phases and the coupling between them play also important ro flow regime in the cold leg, and for the transition between differ flow). Close to the interface, three turbulence sources have been i turbulence production by the interfacial friction, and turbulence i the anisotropy of the turbulence has to be considered. It is not cases, the turbulence is modelled using the k-ω or the k-ε (clas hypothesis at the interface [47, 48]. Without any special treatme the free surface generate too high turbulence when using eddy Therefore, a symmetric damping procedure for the solid wall-like c has been proposed by Egorov [28]. A numerical database obtaine in the frame of NURESIM by ASCOMP [49, 50].

Vallée et al. [51] employed the shear stress transport (SST) turb model [52] accounts for the transport of the turbulent shear stre amount of flow separation under adverse pressure gradients. (ANSYS-CFX) was in good agreement with the experiment.

3.3.3. Modelling of the Free Surface

According to Zwart [53], numerical models for free surface flo adaptive methods, interface-capturing methods, and interface-trac

Surface-adaptive methods are typically single-phase approaches i the location of the free surface interface, and the mesh bound methods inherently involve mesh motion. While these methods a typically restricted to modest degrees of interface deformation. been devised, including periodic remeshing and interpolation, methods [54], and the integrated space-time finite volume m significant interface deformation, it remains the case that surfac interface topology is straightforward. Effects such as splashing, challenges. Moreover, the geometries themselves must be simpl interface-wall intersections.

These limitations may be overcome by having a fixed mesh, w *captured* within the mesh by specific algorithms. Most commonly, for one of the phases, in which the dependent variable is the volu volume-of-fluid (VOF) methods. They differ widely in their deta capturing and solve the VOF equation using a continuum advecti advection operator, numerical diffusion will lead to significant s advection schemes have been devised to minimize this diffusion.

controlled downwinding of the fluxes, as with the donor-acceptor winding schemes have compressive characteristics which depend u steps to retain sharp interfaces, even for steady-state free sur compressive characteristics independent of the time step size has l

Other VOF methods are *interface-tracking* and explicitly track th fraction field, the interface is reconstructed using a piecewise rep cell. The volume fluxes may be calculated either geometrically or Further details of these algorithms can be found in [59, 60]. Anoth involves the use of level set method [61]. The level set strategy f signed distance to the free surface interface; the interface itself method has the advantage that the level set variable is smooth, ra therefore easier to solve. Its disadvantage is that the level set ne strictly mass-conservative.

Surface tension effects are important in many free surface flows a force method [62] formulates the surface tension force as a volum uating the interface curvature; it is challenging because it in effe volume fraction field. Care must be used in order to avoid errors Kothe et al. [60].

In addition to the surface adaptive, interface-capturing, and int method of large interface recognition in a two-fluid model [44]. interfaces (the characteristic length scale being larger than the me order to being able to model interfacial transfers by an extension combine the merits of the two-fluid model which models statis droplets) with the specific treatment of large interfaces required fo

3.3.4. Direct Contact Condensation

In the context of PTS, the gas-liquid interface is characterised by effects discussed in the previous section. Some simulations exist o rapid contact condensation of vapour occurs during the emergen condensation models were tested by Yao et al. [14] in a turbule [12].

(i) Interfacial sublayer concept (ISM), using “wall function gas-liquid interface. The modelling of the interfacial heat trans friction transfer. Schiestel [68] and Jayatilleke [69] have prop Prandtl number, using a formulation similar to the interfacial su

(ii) A model based on asymptotic behaviour of the eddy visco viscosity in the boundary layer with a Gaussian function.

(iii) A model based on surface renewal concept [63, 64, 73 Banerjee [75]. He has proposed a relation for the heat transfer introducing the Kolmogorov time scale for the small eddies. Th theoretically questionable as discussed by Yao et al. [14].

An alternative model was then proposed [23] in order to avoid this the Kolmogorov length scale and the turbulent velocity (velocity theoretical framework of surface renewal an acceptable domain o model has been validated with SIMMER and Neptune_CFD codes o test [76]. It is being tested and used within the 3D two-fluid mo PTS related transients.

Various experiments are being used to test these condensation m
various 3D CFD codes.

(i) Condensation of hot steam in the stratified flow of the LA
Munich is being modelled in the frame of the NURESIM project
models of the computer codes Neptune_CFD and CFX.
(ii) Condensation-induced water hammer experiment, where
filled with hot steam, has been performed at KFKI, Budapest [
example of condensation of hot steam on a stratified cold liqu
pressure peaks due to the condensation-induced slug accel
benchmarking Neptune_CFD and CFX are done in NURESIM pr
of new models are planned.
(iii) Test STB-31 at the POOLEX experimental facility is the t
geometry of a stratified flow: steam is being introduced into tl
selected test case exhibits a condensation over a flat and st
experiment was done by LUT in the frame of the nationa
Simulations of the experiment are done by LUT and VTT using

The KFKI water hammer experiment and the POOLEX experime
calculations that take into account heat transfer in the structure
physical phenomenon relevant for the integral PTS simulations.

In the frame of the NURESIM project, a database generated by DN
used by ASCOMP to obtain new scaling laws for the normalized he
phases. The database has been initially developed to infer modellin
two-phase flows without phase change. In a second step, a therma
has been exploited in order to understand the importance of the
heat transfer in both phases [50]. New scaling laws for the normal
both the steam and liquid phases. On the gas side of the interface,
the interfacial friction velocity and Prandtl number like in the passiv
In the liquid phase, the DNS results produced a condensation hea
at a given total shear velocity. However, an augmentation of he
exchange and interfacial waviness has been observed. The surface
to apply in the liquid phase, with an excellent agreement in the
Regarding the interfacial friction, the DNS data confirm that in t
stress is influenced by the mass exchange, and a correction facto
correctly predict the variation of the friction coefficient.

3.4. Flow in the Downcomer and Wall Heat Transfer

In the case of a partially filled cold leg, the flow in the downcor
temperature distribution of the fluid cooling the pressure vessel
mixing phenomena, and geometrical constraints. On the other har
nozzle of the cold leg, a complex two-phase flow regime occurs.
another impingement region has to be considered. The same mod
for the impinging jet. Depending on the water velocity when enter
the walls is possible. If this detachment occurs, the heat transfe
Because of the variations in the flow regime and the presence
constant when the liquid enters the downcomer. The presence o
changing the turbulence properties, the liquid temperature, and th
downcomer have been performed [81] and have been able to re
downcomer.

The prediction of the transient and local heat transfer to the RPV simulation of the PTS situation. However, the heat transfer to the is a feedback from the wall temperatures on the flow. The variou influence the heat transfer at the walls. The numerical prediction on the accuracy with which the other phenomena are representec the liquid and the gas phases are strongly dependent on the mix phenomena. Conversely, the heat transfer at the walls influences the temperature fields of the fluids.

As far as the simulation of the wall heat transfer is con- cerned, Various models exist and have been extensively studied. In most solid wall are available. These models require the definition of th These models have already been used successfully in various cor the local Nusselt number is not properly predicted [82].

3.5. Integral Simulation

The thermal-hydraulic phenomena at the origin of the two-phas subphenomena in the sections above. Each of those subphenomer presence of inherent: (a) transient conditions, (b) thermo-dynam (d) three-dimensional situation, and (e) nonfully-developed flow co perform an integral simulation (i.e., considering all together the lis PTS thermal-hydraulics phenomena are at worst meaningless, or r pointed out in the text before (e.g., attempts to consider together

Three calculation types can be identified:

(A) licensing analysis accepted or acceptable by regulatory au
(B) support (i.e., to licensing) calculations performed by “ad
(C) scoping calculations by “advanced” methods to un
computational tools.

Advanced methods mean two-phase CFD in this case. Analyse hydraulic codes and typically based on conservative assumptions a (however, see below): there is no or limited consideration for phe estimate of the safety margins rather than to the prediction of the those analyses, there is the experience of safety technologists, in of deficiencies of the available computational tools. At the bottom from analyses of type (A), and results from methods discussed definitely prove the quality of the adequacy of the adopted conse licensing authorities nowadays. Therefore, only analyses of type suffer from all the limitations and the problems discussed in Sectio

In the frame of the NURESIM project, simulations are done by CE the Neptune_CFD code. They found that some results are gener level, the liquid heat up in the cold water injection region, and th not satisfactory, for example, water temperature profiles upstre region in some cases. Simulations of UPTF TRAM experiments were

Further code improvements are required to allow reliable simulati the involved phenomena.In the near term, one may envisage a s neglecting some effects which are not yet controlled like the bubbl the free surface. A better modelling of interfacial transfers of heat with a reasonable coarse mesh is still required to be able to pre downcomer. It is very likely that neglecting entrained bubbles and since both phenomena may increase condensation and mixing.

4. Conclusions

A comprehensive overview of the thermal-hydraulic phenomer pressurized water reactors has been provided, with emphasis giver

The outline given in relation to single-phase phenomena shows t hydraulics and CFD codes are mature enough to be used for te evaluation of safety margins, though improvements are still need game) in the area of convection heat transfer.

The detailed analysis performed in relation to the two-phase phenomena. Computation techniques are capable to reproduce subphenomena) but fail, so far, in the prediction of the interact system behaviour.

The NURESIM EC project, that constitutes the key source of inforr dozen EU institutions to cooperate and create a synergy for bette hydraulic phenomena at the basis of PTS, and a continuation of t listed in Sections 3.1 to 3.5. Best practice guidelines [52] have to b

List OF Abbreviations

AIAD:	Algebraic interfacial area density.
AVM:	Average viscosity model.
CFD:	Computational fluid dynamics.
DCC:	Direct contact condensation.
DNS:	Direct numerical simulation.
ECC:	Emergency core cooling.
EVM:	Eddy viscosity model.
FPDA:	Fiber-phase doppler anemometry.
HPI:	High pressure injection.
HDM:	Hughes &Duffey model.
ISM:	Interfacial sublayer model.
ITM:	Interface tracking methods.
LES:	Large eddy simulation.
LDA:	Laser Doppler anemometry.
LOCA:	Loss of coolant accident.
PIV:	Particle image velocimetry.
PTS:	Pressurized thermal shock.
PWR:	Pressurized water reactor.
RANS:	Reynolds-averaged Navier-stokes.
RMS:	Root mean square.
SB-LOCA:	Small break loss of coolant accident.
TDM:	Taitel and Dukler model.
VOF:	Volume of fluid.

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