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# ADVANCING THE UNDERSTANDING OF NON-CONDESABLE GASES IN REACTOR COOLANT SYSTEM: NCGDENSE PROGRAM

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## ABSTRACT

Understanding how non-condensable gases (NCGs) behave in the coolant systems of light water reactors (LWRs) is essential because their presence can make accidents and transients severe by hindering heat transfer and flow routes, particularly during long-term post-accident reactor cooling. The reactor coolant system's possible sources of NCGs have been carefully examined. Nevertheless, there are few published studies that discuss the specifics of NCG release and dissolution, despite their significant role in the reactor coolant system. The NCG release and dissolution are complex phenomena. It is essential to consider several physical factors while modeling the dissolution and release of NCGs. These include the equations of state for a mixture of two components, where one of the components is water that can exist in liquid and vapor forms, the transport equation for dissolved gas concentration, release and dissolution rates, and the conservation equations for the gas phase. The inadequacies in modeling NCG release and dissolution are covered in this work. The study offers information about the LUT University of Finland's ongoing NCGDENSE project, which is supported by SAFER2028 (National Nuclear Safety and Waste Management Research Program 2023-2028). The limitations of the present SYS-TH codes for simulating the NCG phenomena are covered in this paper, which focuses on analytical, experimental, and numerical approaches. Under the NCGDENSE, a Separate-Effect-Test (SET) facility will be constructed to provide a platform for measuring direct NCG release and dissolution.

## 1 INTRODUCTION

Non-condensable gases (NCGs) like air, hydrogen & nitrogen have a significant impact on the thermal-hydraulic behaviour of light water reactors under both transient and normal operating conditions. These NCGs lower the heat transfer efficiency by building up at the vapor-liquid interface & creating a diffusion barrier further modifying the system depressurization properties and also hinders the steam condensation. Heat exchangers, passive containment cooling systems (PCCS), emergency core cooling system (ECCS) are a few examples of safety components whose performance may be jeopardized by these NCGs, especially in the event of main steam line breaks (MSLB) or loss of coolant accident (LOCA).

Though reactor behaviour can be simulated using various System Thermal-Hydraulic (SYS-TH) codes like RELAP, TRACE, APROS & CATHARE, etc but still the handling of NCGs in these codes is limited as most of them still use simplified assumptions that do not account for the dynamic & interfacial processes that are seen in tests that includes empirical time constant for release and dissolution of NCGs. Specifically, processes like bubble formation, mass transfer across the surfaces and the transport of NCGs in transient conditions across the liquid & vapor phases are frequently not well treated in these models.

The NCGDENSE program is established as a multidisciplinary effort at LUT University to address these constraints. It is an initiative that will provide a precise and physics-based depiction of NCG behaviour in the reactor coolant system by combining measurements from experiments, theoretical model development, along with system code improvement. This program attempts to connect the bubble dynamics with system-scale safety assessments. The paper aims to a summary of the program´s goal, modelling advancement and various experimental validation approaches.

## 2 MODELING CHALLENGES & CODE LIMITATIONS

The reactor safety analysis relies quite heavily on the SYS-TH codes like TRACE, APROS, RELAP, CATHARE, etc. Though in recent years, multi-phase models have been added to these codes, their ability to handle the NCGs accurately & comprehensively is still restricted. Further, the accuracy of the simulations during transient conditions like condensation, sudden depressurization which is limited by simplified assumptions in majority of the cases to deal with the release and dissolution of NCGs.

## 2.1 Assumptions in Current Models

Majority of these SYS-TH codes uses time-constant models that approximate the gas transport. In doing so, instead of solving the interfacial mass transfer from first principles, empirical correlations are used, which results in a number of limitations such as:

- **Simplified Mass Transfer Dynamics –** In these codes, it is typically assumed that time constants determined from a variety of empirical correlations govern the release and dissolution of the NCGs. The time constant oversimplifies the interaction of variables such as pressure, interfacial area, temperature, and turbulence due to its dependence on these empirical correlations.
- **Two-Phase Interaction –** Most of the codes that primarily model the NCGs as independent entities within the gas or liquid phase frequently ignore the dynamic interaction and relationship between the two phases during the processes of boiling and condensation.
- **Assumption related to uniform Distribution –** The majority of models often assume that the NCGs are equally distributed inside a phase, ignoring changes brought about by stratification, bubble coalescence, or different flow regimes.
- **Limited Interfacial Area Representation –** Although interfacial area is an essential parameter in heat and mass transfer, it is often handled in most codes using a variety of empirical or simplified models that are unable to accurately depict behavior in transient scenarios.

## 2.2 Limitations of Current Approaches

Although the development of SYS–TH modelling has been progressive, the simulation of NCGs behavior is still inaccurate. At present, the models are still based on certain assumptions and empirical equations which are not very accurate especially in the case of transient analyses. This section discusses the assumptions and limitations of the current SYS-TH codes and the gaps that exist which are crucial to enhance nuclear safety analyses.

1. **Lack of High-fidelity Models –** Most SYS-TH codes employ semi-empirical correlations to approximate the interaction of NCGs with steam and liquid phases. However, these approximations do not capture the full complexity of real conditions. Some of the major gaps include:

**NCG Behavior Focused on Steam Phase:** Most SYS-TH codes are concerned with how NCG affects steam condensation in which it acts as an insulating layer that slows down heat transfer and do not model the NCGs' effect and ignore their behavior in the liquid phase in terms of solubility, degassing, and phase transition rates.

**Limitation on Two-Phase Coupling:** In real reactor conditions, NCGs are transferred between steam and liquid phases and therefore move constantly. However, many SYS-TH models operate in a manner where these phases are considered separately rather than modelling the constant exchange that occurs at phase interfaces. This results in errors when attempting to predict condensation rates, bubble formation and reactor pressure fluctuations.

**Interfacial Transfer Mechanisms:** Another area where simplifications are not accurate is the movement of heat and mass across phase boundaries. Existing models are typically based on an assumption of evenly distributed NCGs across a phase, instead of modeling localized accumulations or flow regime changes that affect heat transfer efficiency.

2. **Insufficient Experimental Validation –** A fundamental limitation in the development of robust NCG models is the lack of high-resolution experimental data for validation. SYS–TH codes depend significantly on empirical datasets obtained from separate effects test facilities (SETFs) and integral test facilities (ITFs), but these datasets are generally incomplete or inaccurate in the following respects:

- **Few or Incomplete Data Sets:** Many of the parameters used to model NCG dissolution and release are derived from limited experimental studies. These datasets often focus on specific conditions, making it difficult to extrapolate findings across various reactor configurations and operating conditions.
- **Scale Issues related to Experimental Facilities:** The release and dissolution phenomena must work in similar conditions as in an NPP. The experiments carried out in Separate Effect Test Facility (SETFs), and ITFs are often smaller than the actual reactor systems. However, such tests are not always accurate in making same predictions for full scale conditions, particularly at high pressures and

temperatures and as NCG behavior is significantly affected by the thermodynamics. Thus, replicating the conditions plays an important role.

- **Inadequate Real-Time Measurements:** The dynamics of NCG release and dissolution are very fast in real reactor conditions which make it very difficult to monitor them. Most of the data are indirect, such as pressure or gas concentration sensors, which introduce extra uncertainties to the modelling.

The limitations and constraints across popular SYS-TH codes are summarized in Table 1 (Appendix). It is quite evident and noteworthy that none of the code's accounts for the evolving bubble pressure that happens due to mass transfer and also the interfacial stresses due to the diffusion-driven concentration gradients. Thes limitations highlights the need for a more thorough model that will integrate diffusion, pressure driven expansion, & interfacial processes. To tackle this, NCGDENSE program tries to solve the limitations from first principles and an extension of Rayleigh-Plesset equation is presented in the next section.

## 3 MODELING INNOVATION: MASS TRANSFER CORRECTED BUBBLE DYNAMICS

NCGDENSE is a proposed integrated approach that combines high resolution experiments, theoretical modelling, and direct code enhancement of the industry standard SYS–TH codes with incorporation of the mass transfer term in the R-P equation. This will allow to better understand and model the bubble growth with NCGs, whereas previous research efforts have focused on the analysis of NCG behaviour in isolation. In addition to improving knowledge of the fundamentals of NCG interactions in nuclear reactor systems, this comprehensive method will produce validated models that can be added to simulation tools.

The dynamics of bubbles that form and dissipate in the system fluid environment is governed by complex physical process that depends on temperature, pressure, interfacial forces, flow regimes, and fluid properties which has a significant impact on how NCGs behave in reactor coolant systems. These dynamics are crucial for accurately simulating NCG behavior.

In a system, if the pressure is dropping below the saturation conditions, the dissolved gas forms microbubbles which leads to degassing & undersaturated scenarios leads to dissolution of these gases.

The Rayleigh-Plesset equation describes the dynamics related to a spherical bubble inside a liquid and is given as (4):

$$r_B \frac{d^2 r_B}{dt^2} + \frac{3}{2}\left(\frac{dr_B}{dt}\right)^2 = \left(\frac{P_B - P_\infty}{\rho_l}\right) - \frac{4v_l}{r_B}\frac{dr_B}{dt} - \frac{2\sigma}{\rho_l r_B} \qquad (1)$$

where $r_B$ is bubble radius, $P_B$ is bubble surface pressure, $P_\infty$ is local far-field pressure and $\rho_l$ is liquid density, $\sigma$ is the surface tension. The Rayleigh-Plesset equation describes the bubble dynamics, but the equation does not have a mass transfer term which can be used to model NCG i.e. the diffusion of gas in and out of the bubble, release, and dissolution.

If we want to model this properly in SYS-TH codes, interfacial mass exchange has to be taken into account along with modifying the momentum balance at the interface taking into consideration the jump condition for dissolution and release of the NCGs. From conservation of mass & momentum along with the jump condition, we get:

$$J = \rho_g\left(U_g - \dot{R}\right) = \rho_l\left(U_l - \dot{R}\right) \qquad (2)$$

where, $J$ is the mass flux across the interface, $\dot{R}$ is the velocity of interface (bubble wall velocity) and $U_g$ & $U_l$ are the velocities of the gas/vapor and liquid respectively.

Further, the mass flux into the bubble across the interface is determined by the concentration gradient assessed at the interface, as described by Fick's first law and is given as:

$$J(t) = \left(\dot{R} - U_l\right) C(R,t) + D\frac{\partial C}{\partial r} \qquad (3)$$

where, $D\frac{\partial C}{\partial r}$ is at $r = R(t)$ and $C$ represents the mass-based concentration field and $D$ is the gas diffusion coefficient in the liquid.

## 4 EXPERIMENTAL AND COMPUATTAIONAL ROADMAP: NCGDENSE PROGRAM

It is essential to integrate the models into the STS-TH codes and include experimental validation of the modeling of NCG release and dissolution processes in nuclear reactor systems. To provide comprehensive information on the properties of bubbles, such as their formation, growth, separation, and dissolution, fundamental experiments by utilizing advanced equipment will be conducted at LUT University by creating a Separate Effects Test (SET) facility. Additionally, the modified R-P equation will be used to simulate the NCG more accurately in SYS-TH codes. The above constraints can be further addressed by calibrating the mass flow (*J*) and the interfacial terms for simulations using experimental data.

High-speed video imaging, which offers real-time images of bubble dynamics, including nucleation and growth behavior, is one technique that can be used. Another technique is laser-induced fluorescence (LIF), which can be used to visualize gas concentration gradients in bubble interfaces and enhance mass transfer modeling. Inverse modelling techniques will be used to determine the optimal mass transfer coefficients for given accident conditions, such as LOCAs and steam generator transients.

## 5 CONCLUSION

Although a great deal of research has been done regarding the NCG behaviour, a review of experimental and numerical investigations showed that the present SYS-TH codes still rely on oversimplified models, assumptions, and correlations. The integration of mass transfer term and its proper modelling along with bubble dynamics, and the improvement of phase coupling into the SYS-TH models is still a major issue and if solved correctly can improve understanding of the NCG behaviour in NPPs.

The release or dissolution of the NCG´s is dependent on local pressure gradients, interfacial concentration variations (as described by Fick’s law), and the motion of the bubble wall—frameworks which existing models are not able to resolve. This paper proposes an extension to the current Rayleigh-Plesset model with bubble scale physics and interfacial mass transfer to capture the described dynamic effects. It connects microscale (bubble collapse or growth) and macroscale (system pressure, void fraction) frameworks for the system to enable accurate modelling of reactor transients.

The NCGDENSE project offers a systematic approach to close these gaps by combining theoretical modeling, experimental validation, and direct enhancement of SYS-TH codes like TRACE and APROS. High-resolution studies of NCG transport phenomena will be made possible by the development of a SET facility, and the information obtained from this facility may then be utilized to enhance the SYS-TH codes. Furthermore, interfacial area transport models and multiscale modeling techniques can be used to improve the ability to predict the NCG behavior at various reactor conditions.

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## APPENDIX

Table 1. Comparison of NCG Modelling Capabilities in different SYS-TH Codes

| Code | NCG Modeling (Vapor Phase) | Liquid Phase Dissolution | Interfacial Mass Transfer | Limitations |
|---|---|---|---|---|
| TRACE | Yes (In vapor/gas phase) | No dedicated mass transfer in liquid phase | Fixed time constants; empirical | Problems for solving dissolution and release; No interfacial mass transfer between phases |
| APROS | Yes | Yes, but empirical treatment | Modeling via time constants | Dissolution model uses a fixed time constant τ |
| RELAP5 | Yes | No | No | More focus on NCGs in vapor phase; no bubble mass transfer modeling |
| CATHARE | Yes | Limited | Simplified coupling | Modeling of interface kinetics not proper |
| ATHLET | Yes | Partially | approximations via source term | Assumes uniform mixing; bubble formation & growth not solved |
| COCOSYS | Yes (For Containment) | No | recombination of $H_2$ | Used for containment analysis |