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A non-equilibrium control oriented model for the pressurizer dynamics

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ABSTRACT

This paper deals with a new Control Oriented Model (COM) aimed at studying the dynamic behaviour of the pressurizer in Pressurized Water Reactors (PWRs). In literature, most of the pressurizer COMs treat the vapour and the water filling the system as a homogeneous mixture by adopting the thermodynamic equilibrium assumption. This hypothesis involves a reduced set of governing equations that is suitable for the study of the pressurizer dynamics in a simplified way since interphase and non-equilibrium phenomena (e.g., water drops and vapour bubbles generation) are neglected. To overcome this limitation, an innovative COM based on the non-equilibrium approach is developed. The new model is obtained from closed-rigid system mass, energy and volume balances and allows selecting a different thermodynamic state for each phase, according to the non-equilibrium framework. In addition, while equilibrium models take into account only the heat transfer from the electrical heating of PWR pressurizers, the new COM considers also the following processes occurring in the system volume: the water drops and vapour bubbles generation (inside the vapour and liquid phase, respectively), the condensation on sprayed drops, the heat exchange between vapour and water and thermal losses toward the external environment. The new COM is also characterized by a multiple control volume formulation to reach a good accuracy for several transients (also the complete emptying) that can be experimented by a pressurizer. The experimental data of "loss-of-load" transients in the Shippingport reactor are used to assess the new COM. A code to code comparison is carried out using RELAP5 as reference.

1. Introduction

In Pressurized Water Reactors (PWRs), the cooling water of primary loop expands or contracts whenever temperature variations occur. In order to accommodate the resulting volume changes and keep the pressure of the system within prescribed limits, the pressurizer is needed. Such component is a cylindrical steel tank containing, at steady-state, saturated water in the lower region and saturated vapour in the upper one. Moreover, it is provided with:

- Electrical heaters immersed in the water to prevent pressure decrease.
- Sprayers in the upper region to contrast pressure increase.
- Relief valves on the top of the tank to counteract excessive overpressure.

Since the control of the pressure during transients is essential to operate PWRs safely and mitigate the consequence of a possible accident, the pressurizer dynamics must be carefully modelled and investigated.

Pressurizer models can be distinguished between Safety Oriented Models (SOMs) and Control Oriented models (COMs). SOMs adopt a complete description of the system based on mass, momentum and energy balances. They are able to reproduce carefully the pressurizer transients, but are not suitable to study its dynamic and control features. On the contrary, COMs employ a simplified set of governing equations (usually mass and energy balance for homogenous water vapour mixtures), which allows for a straightforward investigation of the control characteristics of the system.[2]

As for the possible modelling approaches, two different strategies can be also followed in order to describe vapour and fluid interactions: the Equilibrium Approach, usually adopted for COMs, (EA) and the Non-Equilibrium Approach (NEA), generally implemented in SOMs. Equilibrium models apply the conservation balances to the vapour and

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[2] COMs allow for low-cost real-time simulations (conversely SOMs' computational burden can be very high) and can be adopted to develop and optimize different control strategies. In this regard, COMs are usually based on block structures and permit a clear identification of inputs, outputs and state variables. A feature that is very useful to analyse the dynamic properties of a system (e.g., the linearization process can be applied with low efforts).

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water as a saturated homogenous mixture. Conversely, non-equilibrium models apply the conservation equations to the water and vapour in the pressurizer separately. According to Nahavandi and Makkenchery (1970), non-equilibrium models are more realistic than the equilibrium ones.

The paper is organized as follows. Section 2 deals with the state of the art of pressurizer-dynamics modelling. In Section 3, the new COM is described. In Section 4, the mathematical formulation of the new model is presented. Section 5 illustrates the validation of the model against Shippingport experimental data (Redfield et al., 1967). Besides, a comparison between new COM results and a RELAP5 pressurizer model is presented. Section 6 presents a complete emptying out-surge test. In Section 7, the main conclusions are drawn. At the end of the paper, an Appendix provides more details about the matrix representation adopted to solve the governing equations.

2. State of the art

Regarding safety applications, the first study of the pressurizer behaviour is presented in Gajewski (1955) and adopts the thermodynamic equilibrium assumption, while the first non-equilibrium approach is proposed by Sorenson (1960). In this study, the system is divided into three rigid boundary control volumes with fixed thermodynamic state. In particular, the pressurizer is composed by an upper zone of saturated vapour, an intermediate one of saturated water and a lower one of subcooled water.

The a priori assumption concerning the thermodynamic is overcome in Redfield et al. (1967), where a single control volume coinciding with the entire pressurizer is chosen. In particular, such control volume is subdivided into two moving boundary regions (one for the vapour and one for the water) whose thermodynamic state is dynamically selected during the simulation according to the enthalpy value.

From the control analysis point of view, equilibrium COMs are presented in Szabo et al. (2010), Zhang et al. (2012) and Sungwhan and Jin (2012) for the study of different control strategies, while non-equilibrium COMs can be found in Kuridan and Beynon (1998) and Botelho et al. (2010). In the work of Kuridan and Beynon (1998), a linearized non-equilibrium model with single control volume and two moving boundary regions is developed in order to study the pressurizer dynamics of the Safety Integral Reactor (SIR). In the analysis of Botelho et al. (2010), a Multiple Control Volume (MCV) strategy is adopted. The pressurizer is divided into two fixed boundary control volumes, a lower one with a single region for subcooled water (a priori fixed thermodynamic state) and an upper one composed by two regions with moving boundary (one for the vapour and one for the water) whose thermodynamic state can vary during the simulation. Thanks to the adoption of MCVs, the axial temperature distribution inside the liquid phase can be reproduced. However, a fixed thermodynamic state region is introduced. This is a limitation that is ridden over by the new COM developed in the present work.

3. Description of the model

Hereinafter, the new COM developed in this work (based on NEA and on the selection of MCVs) is indicated with the acronyms COM-MCV. In this model, mass and energy balances are applied to each phase in all control volumes and heat and mass transfers are possible between the different zones. Moreover, the following assumption are adopted:

- Water evaporation is considered as bulk process.
- Vapour condensation is considered both as bulk and surface phenomenon.[3]
- Heat losses occur from pressurizer tank to external environment.
- The water sprayed inside the pressurizer comes from the reactor coolant cold leg (enthalpy fixed during the simulation).
- Spray and condensate mixture enters the liquid phase as saturated water.
- In-surge[4] water comes from the reactor coolant hot leg (enthalpy fixed during the simulation).
- Vapour condensation on pressurizer walls, and delay times of bubble (condensate) rise (fall) are neglected.

To completely avoid a priori assumptions about the thermodynamic state of the different regions and to take into account axial temperature distributions inside the liquid phase, the COM-MCV is composed by three sub-models (see Fig. 1):

- Two Regions Single Volume sub-model (TRSV).
- Two Regions Double Volume sub-model (TRDV).
- Two Regions Triple Volume sub-model (TRTV).

During every simulation, a global routine selects the correct sub-model by means of a thermodynamic and a water level criterion. If necessary, multiple switches are possible. The TRSV sub-model is based on the selection of a single control volume coinciding with the entire pressurizer.

A moving boundary splits this control volume into two different zones, an upper one containing only vapour and a lower one for water. Vapour and water can experiment all the possible stable thermodynamic state and not only the equilibrium one. Vapour can be saturated or superheated, whereas water can be saturated or subcooled, but no phase can exist in metastable form.

The TRDV and the TRTV sub-models are based on the selection of additional fixed boundary control volumes for the liquid zone. The water filling these control volumes is always treated as subcooled. In this way, axial temperature distributions inside the liquid region can be taken into account. On the contrary, the single volume approach can only compute a global mean temperature for the liquid phase, since it applies a zero-dimensional approximation of the region. Axial temperature distributions can arise during in-surge transients (see Section 4) and can impair the simulation if they are not considered. The three sub-models are not mutually exclusive. At the beginning of every simulation, the global routine selects the TRTV sub-model (Fig. 1c) by assuming that the moving-boundary region ③ is filled with saturated vapour and water and regions, ② and ① with subcooled water. If the subcooled liquid region ② empties or reaches the saturation condition, the TRDV is chosen (Fig. 1b). Similarly, if the subcooled liquid region ① becomes saturated or empty, the TRSV sub-model is picked (Fig. 1a). Of course, the procedure is reversible, from TRSV it is possible to switch to TRDV and then to TRTV. A conceptual flow chart is reported in Fig. 2, where L1, L2 and L3 are length related to the water level inside the pressurizer.

4. Jump conditions and governing equations

The governing equations of the COM-MCV model are represented by mass and energy balances and jump conditions. In this regard, jump conditions are balance equations for mass and energy transfer across vapour liquid interfaces. Since no mass and energy sources or sinks exist at each interface, jump conditions assert that the sum of all mass and energy transfer rates across the interface must be equal to zero.

[3] Vapour which is condensing on the pressurizer wall is evaluated by applying the Nusselt theory following Incropera and Dewitt (1996).

[4] The "in-surge" term specifies a water mass flow rate coming from the primary system into the pressurizer volume. Conversely, "out-surge" term is adopted to indicate water mass flow rate coming out by the pressurizer volume.