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Derivation of new mass, momentum, and energy conservation equations for two-phase flows

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ABSTRACT

System codes are used to analyze nuclear reactor systems during steady state and transient operations. These codes are able to predict pressure drop, void fraction distributions and temperature distributions for various coolants, heated flow geometries, and heat configurations. They also include models for various two-phase flow regimes, but extreme flow conditions that involve significant phase change can tax the current code capabilities. Current system codes have mass, momentum, and energy conservation equations for two fields (liquid and vapor), resulting in a model with six conservation equations. Recent developments in limited applications of a few of these codes have added a separate droplet field from the continuous liquid. This is part of a trend toward the inclusion of more fields (and requisite conservation equations) in system codes. The representation of two phase flow phenomena is improved by increasing the number of fields. Conservation equations based on six fields (liquid, vapor, small bubble, large bubble, small droplet and large droplet) are derived in this work.

1. Introduction

Nuclear reactor systems are complex, and require detailed analysis to evaluate reactor performance during normal operations as well as accident or transient conditions. Nuclear Pressurized Water Reactor (PWR) systems include steam generators, pressurizers, vessels where the reactor fuel is utilized, pumps, valves, and many pipe fittings and components. Boiling Water (BWR) systems such as that as depicted schematically in Fig. 1 are similar to PWR systems, but do not require pressurizers (or steam generators, for some BWR designs). Computer codes that are used to analyze these complex reactor systems are called "system codes".

System codes include detailed models of reactor components, such as pipes, pressurizers, valves, and pumps. These hydrodynamic models have frequently been extended to include a code capability to model multiple phase flows (Roth and Aydogan; Roth and Aydogan, 2014). The interaction between phases in the coolant is modeled in order to capture heat transfer properties and mass exchange between the phases.

Conservation equations are used to balance the mass, momentum, and energy within a control volume or phase. Mass, momentum, and energy balances are computed to account for convective effects, heat added to or removed from the control volume or phase, and other characteristics such as energy loss to diffusion or viscous effects. For two phase systems, mass, momentum, and energy may also be exchanged by a change in phase. Jump models are often used to capture these effects. Complete characterization of a phase requires an equation for the mass, momentum, and energy balance, along with the closure relationships for that phase. Some system codes include the capability to model noncondensable gas mixed with the vapor or dissolved solutes (such as boron) mixed with the liquid (Roth and Aydogan, 2014). However, these additional phases are often only represented by a single mass balance equation, effectively assuming that the solute or gas is at the same temperature and moves at the same velocity as the surrounding phase (Roth and Aydogan).

System codes begin to differentiate when considering the number of modeled fields. Generally, the code models include just two fields, one for each phase. Such a model is limited to capturing the characteristics of a liquid and vapor by using the lumped capacitance approximation. This approximation applies to two fields by assuming that all the liquid (continuous liquid and droplets) are only one field having the same temperature, pressure, and velocity. The same approximation applies to the vapor field, where the continuous vapor and the bubbles are both covered by a single field and share a single velocity, temperature, and pressure.

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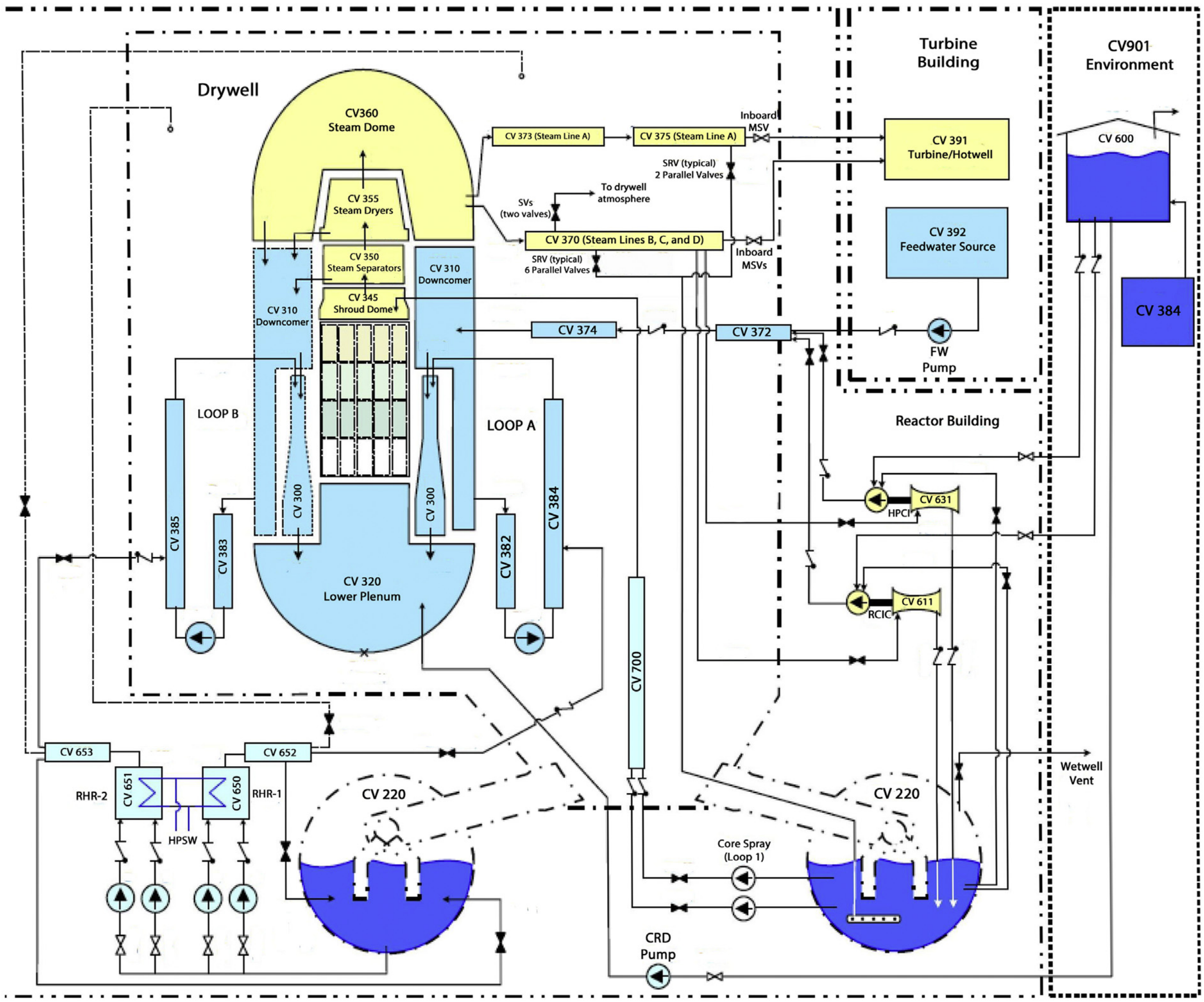

Fig. 1. Nuclear reactor system.

Almost all system codes have a two-phase, two-field model that is adequate for many anticipated flow regimes (Roth and Aydogan). Vertical flow regimes that are present before the point of Critical Heat Flux (CHF) are shown in Fig. 2. Some nuclear reactor designs, in particular Boiling Water Reactors (BWRs), operate at steady state with coolant that ranges from subcooled liquid to saturated steam. Other reactor designs can experience severe accident scenarios (such as core reflood, blowdown, or rapid depressurization) where rapid and extreme changes in coolant vapor content will tax the capabilities of a two-field model. The two-field model is limited to the assumption of only one vapor field to represent all sizes of bubbles and continuous vapor and a single liquid field representing all sizes of liquid droplets and continuous liquid. The steady state BWR conditions and severe accident scenarios can involve bubbles and droplets of varying size. Reactor system characteristics and accident progress are affected by the heat transfer between these additional fields. For example, droplet formation and evaporation remove significant amounts of heat from the bulk coolant.

COBRA/TRAC and WCOBRA/TRAC have three fields in the vessel (3D) component. The three fields are continuous liquid, continuous vapor, and a droplet field (Roth and Aydogan). The third field is only available in the 3D components. COBRA-TF is a subchannel code for rod bundle analysis that has three fields: continuous liquid, continuous vapor, and large droplets. An additional field for small droplets was added as described in Ergun (May 2006). The TRACE code will include an additional (droplet) field in a future version (U.S. Nuclear Regulatory Commission, 2008). The capability of the CATHARE code to predict dryout and rewetting is improved by increasing the number of fields that are modeled (Jayanti and Valette, 2004).

The limitations of a two-fluid six-equation model were cited as a weakness of current system codes during the development of the

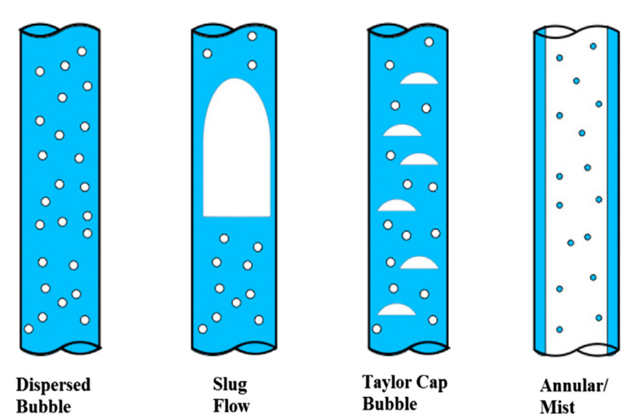

Fig. 2. Pre-CHF vertical two-phase flow regimes.