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Mass closure models for a system code based on six fields

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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, geometries, and configurations. They also include models for various two-phase flow regimes. However, extreme flow conditions that involve significant phase change can tax the current code capabilities. A set of governing equations for a six-field model have been developed to improve the two-phase modeling capabilities of system codes. The six-field model includes continuous liquid, continuous vapor, large bubble, small bubble, large droplet, and small droplet fields. The governing equations derived previously track the mass, momentum, and energy balances for each of these fields. The mass closure relationships provide necessary components of the governing equations - the source terms for small droplets generated due to large droplet breakup, large bubble generation by coalescence, mass transfer due to phase change, and other physical mechanisms. The six field equations add several new variables to the system of governing equations. The closure models solve for these variables. Therefore, the increased number of governing equations requires several additional closure equations for solution. These closure equations are challenging to define for two-phase flow problem conditions. The necessary closure models to solve the six-field mass balance equations are defined in this work. For the case of some bubble interactions, suitable models have not been identified. For these cases, substitute models are recommended from the droplet closure models.

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 systems include steam generators, pressurizers, vessels where the reactor fuel is utilized, pumps, valves, and many pipe fittings and components. Computer codes that are used to analyze these complex reactor systems are called “system codes”.

System codes include a code capability to model multiple phase flows (Roth and Aydogan, 2014a, 2014b). 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. Complete characterization of a phase requires additional equations to close the governing equations for that phase.

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.

Increasing the number of fields improves the modeling capabilities of system codes. More complex models increase the number of fields by including liquid droplets or bubbles as additional fields (Roth and Aydogan, 2014a). 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, 2014a). 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 Reference (Ergun, 2006). The TRACE code will include

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an additional (droplet) field in a future version (Nuclear Regulatory C, 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 NEPTUNE code (Guelfi and Bestion, 2007). Multifield models are being developed for CATHARE3 under the NEPTUNE project (Valette et al., 2011), since they were found to be necessary for key applications, including steam generators and heat exchangers (Guelfi and Bestion, 2007).

Two-phase Computational Fluid Dynamics (CFD) models are more capable and much improved by the addition of bubble and droplet fields (Lahey and Drew, 2000). More complex models increase the number of fields, including liquid droplets or bubbles as additional fields (Roth and Aydogan, 2014a). As with the inclusion of additional phases, each field requires additional conservation equations and closure relationships to be modeled effectively by the code.

Further progress in system codes is expected to come from multifield modeling (Guelfi and Bestion, 2007). The current trends in system code development include the improvement of the two phase models by increasing the number of fields.

Some nuclear reactor designs, in particular Boiling Water Reactors (BWRs), operate at steady state with coolant that ranges from single phase liquid to high vapor fraction. 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 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 removes significant amounts of heat from the bulk coolant. Small droplets leaving the large droplet field increase the effective surface area, which increases the thermal activity of the droplets. As these small droplets evaporate, they increase the steam flow and convective heat transfer while reducing the total liquid volume. A set of governing equations for a six-field model has been developed in Roth and Aydogan, 2015. The six fields included in the model are: continuous liquid, continuous vapor, large droplets, small droplets, large bubbles and small bubbles.

In realistic flows, all six fields will not be present in all flow regimes. For example, bubbly flow will be made up mostly of smaller bubbles, while slug flow will consist of large bubbles. Droplets will most likely not be present in bubbly flow. The six field equations developed in Roth and Aydogan, 2015 establish a framework for balancing the interactions between the six fields. The volume fraction of each field is tracked by the governing equations. For a bubbly regime, the effect of the droplet field will be reduced by the balance equations, until it can be eliminated from the calculation. Each field included in the model requires additional conservation equations and closure relationships to be modeled effectively by the code. The mass governing equations can not be solved without these closure models. The six field equations add several new variables to the system of governing equations. The closure models solve for these variables. The closure relationships track interactions between the fields, allowing the code to determine when a particular field will no longer be included in the flow. Selection of insufficient closure models will result in a system that gives incorrect results. Two field models do not have this problem, since they lump the liquid and vapor into two separate fields that differ only in temperature, not physical arrangement.

Governing equations for mass balance include terms for the source of small droplets generated by large droplet breakup, the source of large bubbles due to small bubble coalescence, the mass exchange resulting from phase change, and other physical phenomena (Roth and Aydogan, 2015). For instance, large droplets may be entrained from the continuous liquid field due to high vapor field flow rates or turbulent effects. The large droplets leaving the continuous field represent a loss from the continuous field and a source to the large droplet field. Similarly, when the large droplets impact a spacer grid or break up due to vapor flow effects, they leave the large droplet field, and enter the small droplet field. These sources and sinks of material from one field to another due to physical effects must be modeled by closure relationships.

The closure relationships that are necessary for solution of the mass balance equations in the six-field model presented in Roth and Aydogan, 2015 are presented herein. They were selected from closure relations that were found in a wide literature search. The selected models meet the following criteria:

1. The closure model must be adaptable to produce a mass generation rate per unit volume, so that it can be consistent with the existing governing equations.
2. The closure model must be applicable to a flow field. Models of individual interactions between droplets or bubbles are not useful, since the system code does not track individual bubbles or droplets.
3. Sufficient information must be available in the literature to allow use of the model.

2. Closure models for mass balance of liquid phase

The mass balance equations for six fields are documented in Roth and Aydogan, 2015. The three equations for the liquid phase are:

Continuous Liquid:

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f\right) + \nabla\cdot\left(\alpha_f \rho_f \vec{v}_f\right) = -\Gamma_L - S'''_{LD,E} - S'''_{SD,E} + S'''_{LD,DE} + S'''_{SD,DE} \tag{2.0.1}$$

Large Drop:

$$\frac{\partial}{\partial t}\left(\alpha_{LD} \rho_f\right) + \nabla\cdot\left(\alpha_{LD} \rho_f \vec{v}_{LD}\right) = -\Gamma_{LD} + S'''_{LD,E} - S'''_{LD,DE} - S'''_{LD,SB} - S'''_{LD,FB} + S'''_{SD,C} \tag{2.0.2}$$

Small Drop:

$$\frac{\partial}{\partial t}\left(\alpha_{SD} \rho_f\right) + \nabla\cdot\left(\alpha_{SD} \rho_f \vec{v}_{SD}\right) = -\Gamma_{SD} + S'''_{SD,E} + S'''_{LD,SB} + S'''_{LD,FB} - S'''_{SD,DE} - S'''_{SD,C} \tag{2.0.3}$$

The source terms (S''' - terms) in the mass conservation equations represent the physical phenomena that cause the liquid coolant to change from one field to another. Such mechanisms include breakup on spacer grids and breakup due to shear with the vapor phase. The source terms are determined using multiple correlations and have units of kg/m^3s. It is impossible to solve the six field equations without adequate closure models that solve for the source terms.

The key source terms related to the six field model in the above equations are: